Appendix H

Heathrow Airport Emission Inventory 2008/9. Report by AEA Energy & Environment on behalf of BAA, July 2010. AEAT/ENV/R/2906 Issue 2



Heathrow
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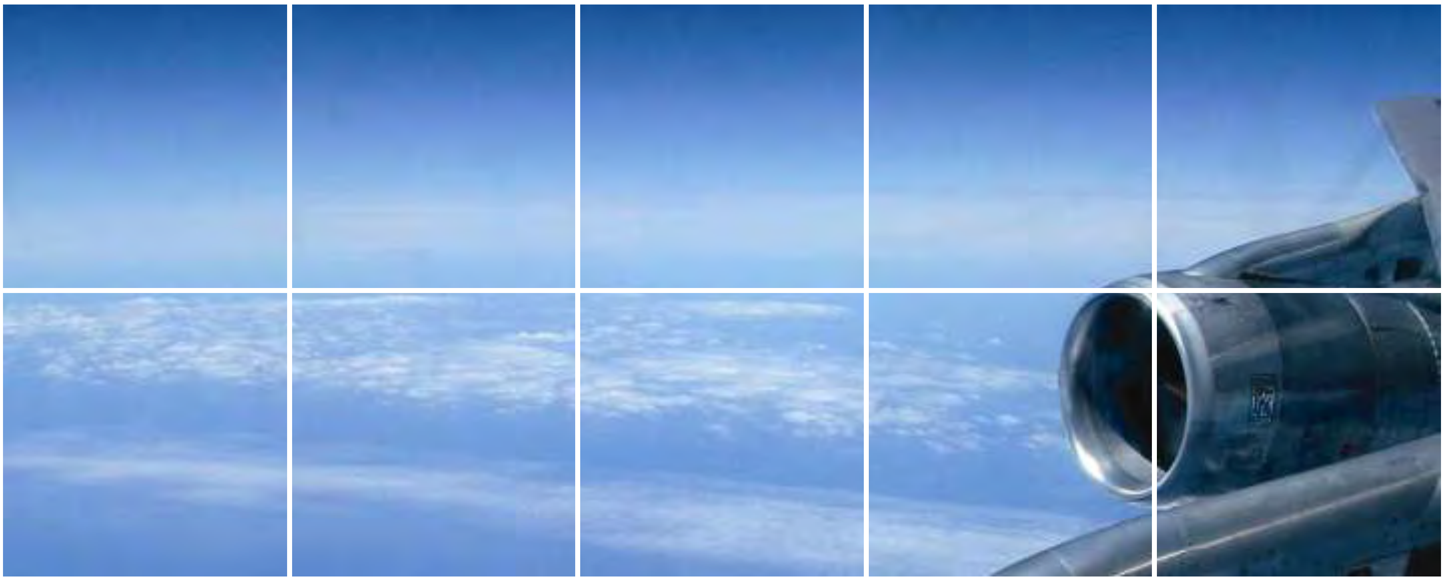

Heathrow Airport Emission Inventory 2008/9

Report to BAA

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Executive Summary

E.1 An emissions inventory has been compiled for London Heathrow Airport using airport activity data for the 12-month period from 1st April 2008 to 31st March 2009, including the pollutants NO_x (oxides of nitrogen, $NO+NO_2$), PM_{10} (particulate matter with aerodynamic diameter less than 10 microns) and $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 microns). The split year was chosen principally to reflect the opening of T5 in March 2008.

E.2 For airport sources, the methodology used for the 2008/9 inventory is essentially that applied in the PSDH (Project for the Sustainable Development of Heathrow) air quality work (i.e. the work underpinning the UK government's consultation on 'Adding Capacity at Heathrow'), thereby presenting the opportunity to track the influence on aircraft emissions of operational and activity changes between 2002 (the PSDH base year) and 2008/9, without the confounding influence of changes to methodology. For vehicle emissions on the near-Heathrow road network, the national set of emission factors (and associated traffic composition projections) released in 2009 have been used.

Methodology and Data

E.3 Airport activity data specific to the 2008/9 period were obtained, including

- aircraft movements (on a flight-by-flight basis),
- the quantities of fuel supplied for airside use,
- a recent version of the Airside Vehicle Pass database,
- transaction data for car parks, car rental and taxis;
- the quantities of fuel used in heating plant, and
- a statistical summary of engine ground runs carried out in the period.

E.4 Given the key importance of engine running times, aircraft times-in-mode for the various LTO (Landing and Take-Off) flight phases have been reassessed for the 2008/9 inventory. For the first time at Heathrow, ground-movement times-in-mode (taxi, holding and roll times) for the inventory have been derived from flight-by-flight information supplied by NATS (National Air Traffic Services), based on ground-radar data. Times-in-mode for elevated modes have been derived from NTK (Noise and Track-Keeping) radar data.

E.5 Taxiing times derived from 2008/9 data are significantly shorter than those used for the 2002 PSDH inventory. A principal reason for this is the impact that the opening of T5 has made on the ground-movement patterns on the airfield. In addition, there have been initiatives in recent years to improve ground-movement efficiency. It is not clear what fraction of this improvement will be retained in future years, when the airfield reaches a stable operational configuration.

E.6 APU (Auxiliary Power Unit) running times have been derived from a modest sample of observations taken in 2007-2009, leading to lower estimated times than those used for the 2002 PSDH inventory. There are indications that analysed running times may still be overestimates, but this cannot be confirmed. The current data set does not allow identification of any specific influence of the use of Pre-Conditioned Air (PCA) on aprons where it has been fitted.

E.7 There has been some improvement in the characterisation of airside operations since the last inventory, via the availability of a data set giving average speeds and fraction of time spent idling, for vehicles in various categories.

E.8 There has been a significant evolution in the aircraft fleet mix (relative number of movements by aircraft type) between 2002 and 2008/9, with a major increase in the percentage of Airbus A319/320/321 types and a decrease in Boeing B737 aircraft types. In relation to large jets, there has been a significant increase in the percentage of A340 and B777 types, with a slight decrease in the B747 percentage. Overall, the large-jet fraction has increased, which is reflected in an increase in the average number of passengers per movement from 135.1 in 2002 to 140.3 in 2008/9.

E.9 Emissions from traffic on the near-Heathrow road network have been quantified using a set of traffic data derived from an 'interim' traffic model. This represents a partial update of the PSDH traffic modelling, taking account of the opening of T5 (Terminal 5). Although some comparisons with traffic count data have been reported for sections of the M25 and M4, the results of the interim model have not been subjected to the usual level of validation.

E.10 The traffic data set (which is similar in format to that used for the PSDH air quality assessment) differs in some important respects from data used for pre-PSDH emission inventories. The model output does not distinguish airport-related and non-airport trips, so the specific contribution to emissions from airport-related traffic cannot be evaluated. In addition, junction delays and queue lengths are not provided in the hourly traffic flow data, whereas queuing was modelled separately in earlier inventories. On the other hand, traffic speed information has been provided separately for each hour of the day, whereas the earlier data sets gave speeds for representative morning peak, afternoon peak and inter-peak hours only. How important these differences are from an air quality perspective will be considered in the model evaluation exercise to be reported separately. A new traffic model is currently being developed, with the intention that the specific requirements of air quality modelling be considered from the outset.

Results

E.11 Table E.1 gives a summary of airport and road-network emissions, comparing the results for the 2008/9 inventory with those from the PSDH version of the 2002 inventory.

Table E.1 Summary of emissions

	NO_x		PM_{10}		$PM_{2.5}$
Source category	Emissions in 2008/9 (tonnes/year)	FD[a] %	Emissions in 2008/9 (tonnes/year)	FD[a] %	Emissions in 2008/9 (tonnes/year)
Aircraft ground level	1619	-3	35.9	-3	28.6
Aircraft elevated	2806	13	14.7	36	14.7
Airside vehicles/plant	260	10	21.0	16	18.8
Car parks etc	18	-31	1.6	0	1.1
Stationary sources	284	59	26.1	15	26.1
Landside road vehicles	2464	-31	239.3	-43[b]	156.1

[a] Fractional Difference=(2008/9 value-2002 (PSDH) value)/2002 (PSDH) value.
[b] Difference relates only to exhaust emissions (fugitive emissions not quantified for 2002), but preceding column is total including fugitive emissions.

NO_x

E.12 From the perspective of the impact of airport emissions on off-airport air quality, ground-level aircraft emissions are likely to be much more significant than the emissions from airside vehicles, car parking and heating plant. However, the differential effect of plume rise may attenuate the relative importance of aircraft emissions for receptors close to the airport: this will be taken into account in the dispersion modelling study.

E.13 For ground-level aircraft emissions, take-off roll gives the largest contribution because of the high thrust setting of the engines (but the influence of plume rise is also greater for take-off roll). APU emissions are a significant contributor to total ground-level aircraft NO_x emissions, generating about the same amount of NO_x as taxi-in and taxi-out combined.

E.14 For airside vehicle emissions, road vehicles and off-road vehicles give nearly equal contributions to the total, with rigid HGVs providing over a half of the road-vehicle contribution and the vehicles in the large-engine category (130-560 kW) accounting for over half of the off-road contribution. On the landside road network, Heavy Duty Vehicles (HDVs, including HGVs and buses) emit about the same amount of NO_x as Light Duty Vehicles (LGVs, including cars and Light Goods Vehicles), despite HDVs accounting for around 14 times fewer vehicle-km travelled on the designated network, reflecting the much larger NO_x emission factors (g/km) for HDVs.

E.15 The total (LTO cycle) aircraft NO_x emissions at Heathrow (up to 1000 m) represent 35% of the total NO_x emission from UK aviation (Domestic and International LTO) and 0.3% of the total NO_x emissions from all UK sources, as given in the 2008 version of the National Atmospheric Emission Inventory.

E.16 The estimated average amount of NO_x per passenger emitted in the LTO cycle up to 1000 m height (including APU and engine testing emissions) increased by 2.5% between the 2002 PSDH and 2008/9 inventories. Excluding APU and engine testing emissions, the estimated increase is 4%. This increase in NO_x/passenger as the average size of aircraft in the fleet increases has been noted in studies at other airports, but is specific to the types of engines in current aircraft fleets and may not be a feature that persists indefinitely into the future.

E.17 For local air quality, ground-level emissions are much more important than elevated emissions. The estimate of ground-level aircraft NO_x emissions for 2008/9 is 2.6% lower than for 2002. Excluding APU and engine testing emissions, the change becomes an increase of 0.7%, showing the impact of the decrease in the estimated APU running times. This small change in total ground-level (aircraft) emissions is the net effect of larger changes for the individual modes (taxiing, roll etc), both negative and positive, typically of magnitude 10-20%. Some of the change for individual modes is the result of minor revisions to times-in-mode, with the remaining change chiefly reflecting the difference in fleet mix.

E.18 The estimate of the total emissions from aircraft taxiing for 2008/9 is significantly lower than for 2002, despite a greater number of movements in 2008/9, principally reflecting the significant decrease in taxiing times in 2008/9 compared to those used for the 2002 inventory. Taxi-out emissions are lower by 22% and taxi-in emissions lower by 11%. Similarly the estimate of the total emissions from APU running is 10% lower for 2008/9 than for 2002, reflecting the lower running times noted above.

E.19 In terms of the relative contribution from various aircraft types, Airbus A319/320/321 aircraft accounted for a significant fraction (21%) of the ground-level aircraft NO_x emissions in 2008/9 (excluding APU and engine testing), reflecting their dominant contribution (48%) to the total movements. However, the larger aircraft types, A340, B747 and B777, together contributed nearly 60% of the NO_x emissions, despite accounting for only 26% of the movements.

E.20 Aircraft emissions normalised by number of movements varied across aircraft types in 2008/9 by over a factor of six. Even after allowing for different passenger capacities, the larger jets (such as the A340, B747 and B777) have significantly higher emissions than the medium jets (such as the A320), which results from the way that the ICAO (International Civil Aviation Organisation) engine certification limits are currently framed. This finding indicates that the change in total airport NO_x emissions over time is sensitive to the details of the fleet composition, particularly in relation to large aircraft types.

E.21 The calculated value of total NO_x emissions from airside vehicles in the 2008/9 inventory is 10% higher than the equivalent value in the 2002 inventory, for an estimated 31% increase in the mass of fuel used airside (although the latter may not reflect a real increase in usage, given the major uncertainties in the fuel-accounting methodology). The effective NO_x emission factor in g/kg (defined as total emissions divided by total fuel mass irrespective of fuel type) for airside road vehicles decreased from 24.2 g/kg in 2002 to 18.9 g/kg in 2008/9. For airside off-road vehicles, the effective NO_x emission factor decreased from 49.4 g/kg for 2002 to 37.8 g/kg for 2008/9.

E.22 The estimate of the total NO_x emissions on the near-Heathrow road network for 2008/9 is 31% lower than the published PSDH value for 2002, with only a small component of the change attributable to the slightly smaller road network area for the 2008/9 calculation. The major component of the emissions reduction between the two periods is the penetration into the fleet of higher Euro-standard vehicles, but a component of the difference derives from the change in the national emission factor data base for road vehicles.

E.23 Fig E.1 shows the spatial density of ground-level airport NO_x emissions (i.e. excluding elevated aircraft emissions and heating plant emissions) at a spatial resolution of 100 m. This spatial pattern of emissions, together with the dominance of south-westerly winds, is a key factor in determining the airport contribution to NO_x (and NO_2) concentrations in the residential areas immediately north of the airport. The influence of emissions on the runway from take-off roll is clearly visible, although there is also significant emission density in some apron areas.

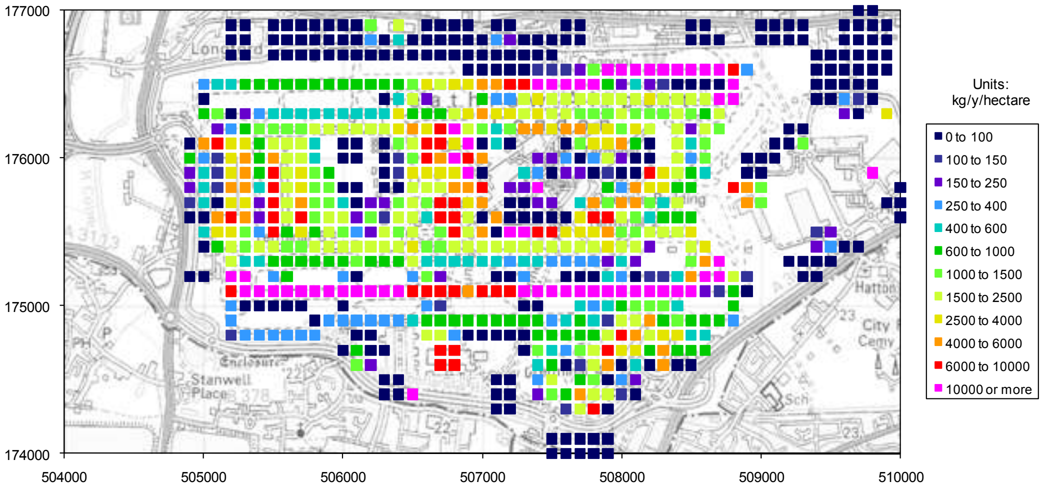

Fig E.1 Spatial density of ground-level airport NO_x emissions

PM_{10} and $PM_{2.5}$

E.24 As for NO_x, ground-level PM (particulate matter, either PM_{10} or $PM_{2.5}$) aircraft emissions are likely to be much more significant than the emissions from airside vehicles, car parking and heating plant from a local air quality perspective, although the differential effect of plume rise may attenuate their relative importance for receptors close to the airport.

E.25 In contrast to the situation for NO_x, take-off roll is not a dominant contributor to the total ground-level aircraft exhaust PM emissions. In this case, the calculated emission rate at higher thrust does not compensate for the shorter time-in-mode. The contribution from APU running is comparable to that from taxiing (taxi-in and taxi-out). Estimated brake and tyre wear emissions are major contributors to total ground-level aircraft PM emissions, together accounting for 41% (27%) of the ground-level PM_{10} ($PM_{2.5}$) emissions, although the estimates are subject to large uncertainties.

E.26 For airside vehicles, the contribution from exhaust emissions is much higher than for fugitive emissions, although there are large uncertainties attached to the latter. For exhaust emissions, off-road vehicles are estimated to have contributed 69% (70%) of the total whereas for fugitive emissions off-road vehicles are estimated to have contributed only 19% of the total (for both PM_{10} and $PM_{2.5}$).

E.27 On the landside road network, estimated PM emission from fugitive sources (brake wear, tyre wear and re-suspension) are higher than from vehicle exhaust. This is increasingly the case over time as exhaust emissions fall in response to emissions control. For PM, HDVs give a smaller contribution to exhaust emissions than do LDVs: for this pollutant the higher emission factors (g/km) for HDVs are not enough to offset the lower vehicle-km travelled by

HDVs on the network.

E.28 The LTO cycle (exhaust) PM_{10} emissions at Heathrow (up to 1000 m) represent 37% of the total from UK aviation (Domestic and International LTO exhaust emissions), and 0.03% of the total PM_{10} emissions from all UK sources, as given in the 2008 version of the National Atmospheric Emission Inventory.

E.29 The estimated average amount of PM_{10} per passenger emitted in the LTO cycle up to 1000 m height (including APU, engine testing, brake wear and tyre wear emissions) increased by 2.4% between the 2002 PSDH and 2008/9 inventories.

E.30 The estimated value of total ground-level aircraft PM_{10} emissions for 2008/9 is 1.4% lower than the equivalent for 2002. This small change is the net effect of larger fractional changes (both positive and negative) in the contributions from components such as taxiing and APUs. As noted earlier, these changes reflect the combined influence of time-in-mode changes and aircraft movement/fleet mix changes. The 2008/9 estimates for taxiing and APU emissions are significantly lower than for 2002, reflecting the lower times-in-mode used for the inventory.

E.31 In terms of the relative contribution from various aircraft types, Airbus A319/320/321 aircraft accounted for a significant fraction (37%) of the ground-level aircraft PM_{10} emissions in 2008/9 (excluding APU, engine testing, brake wear and tyre wear), reflecting their dominant contribution (48%) to the total movements. However, the larger aircraft types, A340, B747 and B777, together contributed nearly 46% of the exhaust PM_{10} emissions, despite accounting for only 26% of the movements.

E.32 Modern jet engines usually have Smoke Numbers well below the CAEP (the ICAO Committed on Aviation Environmental Protection) limit, and thus there is no regulatory driver for continuous improvement. As a result, there can be large non-systematic variations (albeit below the limit) from engine to engine, so the variation in total airport PM emissions over time is sensitive to the specific engines fitted to the principal aircraft types in the fleet.

E.33 The increase in the estimated brake-wear PM_{10} emissions between 2002 and 2008/9 by 15% is a direct reflection of the larger average aircraft size in the 2008/9 fleet, given that brake wear is assumed to scale with MTOW (Maximum Take-Off Weight). The corresponding increase for tyre wear is 20%, reflecting a difference in the assumed dependence on MTOW.

E.34 The calculated value of total PM_{10} emissions from airside vehicles in the 2008/9 inventory is 16% higher than the equivalent value in the 2002 inventory, for a 31% increase in the estimated total mass of fuel used airside for the 2008/9 inventory, reflecting the lower average emission factors in 2008/9. For airside road vehicles, the effective exhaust PM_{10} emission factor in g/kg (defined as total emissions divided by total fuel mass irrespective of fuel type) has decreased from 1.24 g/kg in 2002 to 0.74 g/kg in 2008/9. For off-road vehicles, the effective exhaust PM_{10} emission factor in g/kg has decreased from 4.04 g/kg in 2002 to 3.81 g/kg in 2008/9.

E.35 The estimate of the total exhaust PM_{10} emissions on the near-Heathrow road network for 2008/9 is 43% lower than the published PSDH value for 2002, with only a small component of the change attributable to the slightly smaller road network area for the 2008/9 calculation. The major component of the reduction in emissions between the two periods is the penetration into the fleet of higher Euro-standard vehicles, but a component of the difference derives from the change in the national emission factor data base for road vehicles.

E.36 Fig E.2 shows the spatial density of ground-level airport PM_{10} emissions (i.e. excluding elevated aircraft emissions and heating plant emissions) at a spatial resolution of 100 m the relative distribution for $PM_{2.5}$ is similar. The influence of emissions on the runway from take-off roll is clearly visible, although there is also significant emission density in some apron areas. The peaks in spatial density on the runways are principally a reflection of the brake and tyre wear contribution, which has been focused in the touchdown zone.

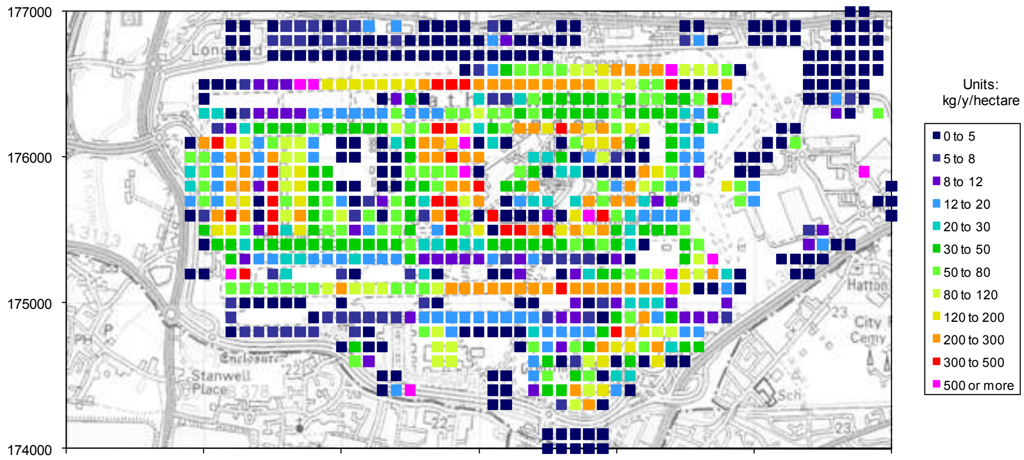

Fig E.2 Spatial density of ground-level airport PM_{10} emissions

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Abbreviations

ADMS	Atmospheric Dispersion Modelling System
AEA	A business name of AEA Technology plc
AFR	Air to Fuel Ratio
APT	Airport Playback Tool
APU	Auxiliary Power Unit
AQLVR	Air Quality Limit Value Regulations
AQMA	Air Quality Management Area
AQS	Air Quality Strategy (for England, Scotland, Wales and Northern Ireland)
AQEG	Air Quality Expert Group
ATOW	Actual Take-Off Weight
ATWP	Air Transport White Paper
AVP	Airside Vehicle Pass
BA	British Airways
BOSS	Business Objective Search System
CAA	(UK) Civil Aviation Authority
CAEP	(ICAO) Committee on Aviation Environmental Protection
CHP	Combined Heat and Power
CLB	A ‘push-button’ thrust setting for aircraft climb
CORINAIR	CO-oRdinated INformation on the Environment in the European Community – AIR
DfT	Department for Transport
DPF	Diesel Particulate Filter
ECS	Environmental Control Systems
EIS	Entry into Service (date)
EMEP	Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (UN Convention on Long-Range Transboundary Air Pollution)
EU	European Union
FAA	(US) Federal Aviation Administration
FDR	Flight Data Recorder
FOI	Swedish Defence Research Agency
FTG	Fire-Training Ground
FP2009	The set of fleet proportions released by the NAEI to accompany TRL2009
HDV	Heavy Duty Vehicles (HGV and buses)
HESAM	Heathrow Employee Surface Access Model
HGV	Heavy Goods Vehicle
ICAO	International Civil Aviation Organisation
ISA	International Standard Atmosphere
LAEI	London Atmospheric Emissions Inventory
LASAM	London Airports Surface Access Model
LDV	Light Duty Vehicles (cars and LGV)
LGV	Light Goods Vehicle
LGW	London Gatwick Airport
LHR	London Heathrow Airport
LPG	Liquefied Petroleum Gas
LTO	Landing and Take-Off
MES	Main Engine Start
mppa	million passengers per annum
MRW	Maximum Ramp Weight
MTOW	Maximum Take-Off Weight
mvt	(aircraft) movement
NADM	Non-Airport Demand Model
NAEI	National Atmospheric Emission Inventory
NATS	National Air Traffic Services
NCAR	(US) National Centre for Atmospheric Research
NO_x	Nitrogen Oxides ($NO+NO_2$)
NRMM	Non-Road Mobile Machinery
NTK	Noise and Track-Keeping system
OAT	Outside Air Temperature

OPR	Overall Pressure Ratio
OS	Ordnance Survey
PAH	Polycyclic Aromatic Hydrocarbons
PLTOW	Performance Limited Take-Off Weight
PM_{10}	Particulate Matter with aerodynamic diameter less than 10 μm*
$PM_{2.5}$	Particulate Matter with aerodynamic diameter less than 2.5 μm*
PPC	(Pollution) Prevention and Control
PSDH	Project for the Sustainable Development of Heathrow
RRTM	Regional Road Traffic Model
SCR	Selective Catalytic Reduction
SN	Smoke Number
STP	Standard Temperature and Pressure
T5	(LHR) Terminal 5
TEMPRO	(DfT) Trip End Model Presentation Program
TFP	Taxi Feeder Park
TRL	Transport Research Laboratory
TRL2009	The new set of emission factors released by the DfT in 2009
UCAR	University Cooperation for Atmospheric Research
UNECE	United Nations Economic Commission for Europe
VR	Velocity of Rotation
WV	Wake Vortex

* To be precise, PM_{10} ($PM_{2.5}$) 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 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 compile an inventory of atmospheric emissions 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). This report describes the methodology and data used to compile the inventory, and presents the results.

1.3 The last published Heathrow inventory based on recorded (rather than forecast) activity data was for the calendar year 2002. An inventory for that year was first compiled in 2004[1] in the context of the periodic updating process noted above. The long gap between that inventory and the present 2008/9 inventory can be traced partly to the decision to await the final recommendations of the Project for the Sustainable Development of Heathrow (PSDH)[2] before the next inventory update. However, as part of the modelling work underpinning the government consultation on 'Adding Capacity at Heathrow', the 2002 inventory was revised[3] using a methodology that implemented the PSDH recommendations, and was subsequently published[4] in one of the technical documents accompanying the consultation. The revised inventory will be referred to as the '2002 PSDH inventory'.

1.4 The 2008/9 inventory has been compiled using the same methodology as that implemented for the 2002 PSDH inventory, thus presenting the opportunity to track the influence on emissions of operational and activity changes between the two periods, without the confounding influence of changes to methodology. Only the key features of the PSDH methodology will be summarised in this report, given that a detailed description has been given in earlier reports[2],[3].

1.5 In carrying out an inventory and modelling study, it is usually more convenient to consider a calendar year than a split year, given that air quality objectives and limits for annual mean concentrations are usually framed in terms of averages over a calendar year. However, in the present case, Heathrow Terminal 5 (T5) opened on 27th March 2008, so there was a preference to use a 12-month period with five-terminal operation throughout. Of course, activity at T5 built up during the remainder of 2008, so the period does not represent 12 months of stabilised five-terminal operation, but the chosen period was judged the best compromise, to avoid a further long delay before updating the Heathrow inventory. Calculated mean concentrations for this period will give a good indication of the recent situation around Heathrow in relation to the annual mean NO_2 limit value.

1.6 The Heathrow inventory feeds into the London Atmospheric Emission Inventory (LAEI)[5] and the National Atmospheric Emission Inventory (NAEI)[6] via the normal updating cycle for these inventories, although there may be a delay due to a phasing mismatch*. It also provides information to the local authorities in administrative areas around Heathrow to assist them in discharging their responsibilities under Part IV of the Environment Act 1995, whereby they are required to review periodically the concentrations of designated pollutants

* The 2008/9 Heathrow inventory was not finished in time to be included in the 2008 version of the London Atmoshperic Emissions Inventory.

within their areas against air quality objectives set at the national level in the Air Quality Strategy for England, Scotland, Wales and Northern Ireland (AQS)[7]. Where it is expected that an objective cannot be met by the required date, the local authority is required to declare an Air Quality Management Area (AQMA) and to bring forward an Air Quality Action Plan to reduce concentrations, to the extent that the sources responsible for the failure to meet objectives are within its control.

1.7 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 AQS objective, 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 meeting the limit becomes mandatory). Although there are forecast to be widespread exceedences of the limit value in London in 2010[8] – for which the government is likely to seek a time extension from the European Commission – the Mayor's draft air quality[8] 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 AQMAs for NO_2.

1.8 Similarly, in its *'Future of Air Transport'* White Paper (ATWP)[9] the government's support of a third runway at Heathrow was provisional on it being confident that the 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[10], the Secretary of State announced his support for a third runway[11], again emphasising in his decision document the need to meet air quality limits. In the responses to the consultation[12], a majority did not believe that the air quality criterion could be met if a third runway was built.

1.9 In light of the above, there is a vital interest in understanding what 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 contribution to the concentrations 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.

1.10 In this respect, a Heathrow emission inventory acts as an intermediate step to the quantification of airborne concentrations around the airport. The 2008/9 inventory represents the output of the first phase of a three-phase programme of work commissioned by BAA, in which the second phase will be a dispersion modelling study using the 2008/9 inventory, followed by a model evaluation exercise in which the results of the modelling are compared with measured concentrations around the airport. These subsequent phases of the work will be reported separately.

Scope

Pollutants Included

1.11 As noted above, ambient air quality in the UK is managed by reference to the Air Quality Strategy (AQS) for England, Scotland, Wales and Northern Ireland[7], 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 Limit Value Regulations[13](AQLVR). Although there is considerable overlap between the AQS and AQLVR, there are some differences in detail, particularly in relation to dates of applicability.

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

1.12 In common with most activities involving the combustion of fuel, an airport releases a wide variety of pollutants but, for most of the regulated pollutants, airport emissions (even from a large airport) do not have the potential to be a significant factor in whether or not current air quality objectives and limit values can be met around the airport. The relevant evidence was reviewed by the air quality technical panels set up by the Project for the Sustainable Development of Heathrow[2]. Based on the available monitoring and modelling data, it was concluded that benzene, 1,3-butadiene, carbon monoxide, lead, polycyclic aromatic hydrocarbons (PAHs) and sulphur dioxide were not priority pollutants at airports, leading to a focus on NO_x, particulate matter and ozone. Ozone is not a primary airport pollutant, although airports contribute precursors (volatile organic compounds and NO_2) to the formation of ozone on a regional and trans-national scale. Thus, ozone is not currently included in the regulations for local air quality management[14]. The relevant objectives and limit values for NO_2 and PM are shown in Table 1.1.

1.13 PM_{10} is included on the grounds that the EU limit value for daily mean PM_{10} concentrations is still regularly exceeded close to major roads in London. In addition, the no-threshold assumption* is made in assessing the impact of PM_{10} pollution, so increments in concentration due to airport operation are of interest even if total concentrations are below limit values. In past Heathrow inventories, the focus on particulate matter was restricted to the PM_{10} size fraction, but the most recent AQS and EU Directive[15] set targets and limits for $PM_{2.5}$ also, so this size fraction is included as a separate pollutant in the current inventory.

1.14 Further clarification is needed in relation to NO_x and NO_2. The oxides of nitrogen ($NO+NO_2$) emitted from combustion sources are principally in the form of nitric oxide (NO), with usually only a small percentage of nitrogen dioxide, whereas the key pollutant of interest from the viewpoint of human health is nitrogen dioxide (NO_2). After release, however, further NO_2 is formed in the atmosphere by transformation of NO, principally as a result of the reaction with ambient ozone. In the interaction 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 at any given location separately from the question of how much NO_x is released. Consequently, in this report emissions are quoted in terms of NO_x (with the convention that molecular concentrations are converted to mass units as if all the NO_x were NO_2). The fraction of NO_x that is NO_2 will be addressed as part of the modelling study, which is reported separately.

Sources Included

1.15 Usually, an emissions inventory relates to a specific spatial domain, for example a given city, region or country. However, in the case of an airport, the relevant spatial domain is more difficult to define. For example, aircraft leaving the airport emit pollutants beyond the airport perimeter and road vehicles bringing passengers to the airport may start their journeys a long way from the airport. The key perspective in the present work is that the quantification of emissions is one stage in the process of evaluating the impact of the airport on pollutant concentrations close to the airport, so all sources that contribute to concentrations there must be included by one means or another. The way in which sources are categorised then becomes a matter of definition.

1.16 From this perspective, a distinction is drawn in the modelling methodology[16] between the concentration contribution from sources that are included explicitly in the dispersion modelling exercise and the 'background' contribution. In the former category, a further distinction is drawn between

(a) emissions that are calculated in this work from 'raw' activity data (e.g. aircraft movement data, road traffic data) and
(b) emissions imported from other inventories (such as the LAEI or NAEI).

The current report focuses on (a), whereas emissions imported from the LAEI and NAEI are discussed as in the modelling methodology report.

* This assumes that there is no concentration below which the probability of adverse health impacts becomes zero.

1.17 For (a), it is convenient in later modelling discussions to introduce a further distinction between the 'airport' inventory and the emissions on the road network. The following sources are included in the airport inventory:

- aircraft in the LTO flight phases, including APU (Auxiliary Power Unit) emissions and emissions from engine testing;
- airside vehicles/plant;
- car parks and taxi queues;
- stationary sources, including heating plant and the fire-training ground.

1.18 In Heathrow inventories prior to the PSDH, emissions from airport-related traffic on a near-Heathrow road network were included in a 'Heathrow-related' inventory, but the traffic data available for the current inventory did not distinguish airport from non-airport traffic (also true for the PSDH work), although the model was developed using specific Heathrow information on passenger, staff and business trips.

1.19 It is tempting to relate the 'airport' inventory to emissions that arise within the airport boundary, but for aircraft the inventory includes emissions in all the Landing and Take-Off (LTO) flight phases, adopting the cut-off at 1000 m height used in previous airport emission inventories. In practice, the impact on ground-level concentrations per unit emission decreases rapidly with the height of emission, such that aircraft emissions arising once the aircraft is outside the airport perimeter have a much smaller impact on local air quality than those emitted within the perimeter of the airport. To reflect this, the tabulated inventory summary in Section 5 will show both the total emissions to 1000 m - to conform with past modes of presentation - and also just the ground-level emissions. Dispersion modelling will automatically ensure that emissions at different heights are properly weighted in their contribution to ground-level concentrations.

1.20 As discussed in Section 2, road vehicle emissions are calculated for the major roads within a square of side length 11 km, aligned with the OS grid, with SW corner at OS co-ordinates (502000,171000). The cut-off distance is somewhat arbitrary, but the resulting network closely conforms to the 'near-Heathrow' network used in the PSDH work. Road vehicle emissions outside of this area will be included via emissions imported from the LAEI and NAEI inventories (see the modelling methodology report). The near-Heathrow network is distinguished by the fact that the traffic model providing the relevant traffic data is built using detailed airport-related activity data, such that the impact on traffic characteristics (and thence on air quality) of airport operational changes and airport-related highway modifications can be assessed. The assumption is that traffic-related emissions outside the near-Heathrow network area can be quantified using more generic airport information, without incurring significant error in calculated concentrations close to the airport.

1.21 For PM_{10} and $PM_{2.5}$, the inventory includes not only exhaust emissions but also fugitive emissions from brake and tyre wear (for aircraft and road-vehicles) and from re-suspended road dust. Any construction sources of PM_{10} or $PM_{2.5}$ on the airport during the period of interest are not included. Wind-blown contributions to suspended particulate matter on the airport are counted as part of the modelled background concentration, and not counted as part of the airport inventory.

Report Structure

1.22 Section 2 describes the data and methodology used to quantify total airport and road-network emissions in the 2008/9 inventory period. Section 3 explains how the spatial distribution of the emissions is characterised for each source category, and Section 4 explains how temporal profiles are assigned. Section 5 presents and discusses the results, including a comparison with the 2002 PSDH inventory; and Section 6 draws conclusions.

2 Emissions for 2008/9

Overall Approach

2.1 The evaluation of emissions essentially involves the multiplication of an activity statistic, for example fuel usage or distance travelled, by an emission factor (expressed as mass of pollutant emitted per kg of fuel burned or per km travelled respectively). Emission factors are usually derived from measurements, but often a limited sample of measurements have to be generalised to a broad activity type. An optimum route to developing an emission inventory is to have activity statistics broken down at the same level of detail as that available in the emission factors, but this is not always possible.

2.2 The aim of the current work is to quantify the Heathrow emission inventory using the best operational data currently available. The aim of the inventory methodology is to generate a realistic best estimate of the emissions for use in a comparison between model outputs and corresponding monitoring data.

2.3 Activity data for the actual 12-month period of interest were obtained wherever possible. Where such activity data were not available, statistics for the nearest period were used, and adjusted as necessary.

Aircraft LTO Exhaust Emissions

2.4 The dominant aircraft source of emissions is main-engine exhaust during the LTO flight phases (modes), and this will be the principal focus of the discussion below. However, separate consideration is also given to emissions from aircraft APUs (Auxiliary Power Units) and engine testing (engine ground runs).

2.5 Schematically, a contribution to aircraft exhaust emissions (in kg) arising from a given mode of aircraft operation (taxiing, for example) from a single engine is given by the product of the duration (seconds) of the operation, the engine fuel flow rate at the appropriate thrust setting (kg fuel per second) and the emission factor for the pollutant of interest (kg pollutant per kg fuel). The annual emissions total for the mode (kg per year) is obtained by summing contributions over all engines for all aircraft movements in the year.

LTO Flight Phases (Modes)

2.6 The following 'modes' (phases) of the LTO cycle are distinguished for the purpose of emissions quantification

(1) taxi-out;
(2) hold at runway head;
(3) take-off roll (from start-of-roll to wheels-off);
(4) initial climb (i.e., wheels-off to throttle-back);
(5) climb-out (from throttle-back to 1000 m altitude);
(6) approach (from 1000 m altitude to runway threshold);
(7) landing roll (from threshold to runway exit);
(8) taxi-in.

2.7 'Taxi-out' commences at stand (so includes pushback) and ends when the aircraft joins the departure queue; 'taxi-in' commences when the aircraft leaves the runway and ends when the aircraft reaches the stand. There may be some overestimation of taxi-out emissions from assuming all engines are lit during pushback, but there is a lack of systematic information on when engines are lit as a function of aircraft type and operator. On the other hand, it is assumed that all engines are shut down immediately the aircraft reaches the stand. It is judged that, on average, any potential underestimation of aircraft emissions from this assumption is more than compensated by the assumption that all engines are lit during pushback.

2.8 Helicopters do not have take-off roll nor landing roll, and a single mode covers the climb from ground to 1000 m.

Movement Data and Fleet Mix

2.9 As a starting point for the quantification of aircraft emissions in the LTO cycle, BAA provided an extract from their BOSS (Business Objective Search System) database, giving a flight-by-flight record for the period 1st April 2008 to 31st March 2009, including the following data fields of interest:

(a) aircraft registration number;
(b) flight date and time;
(c) runway identifier (and whether arrival or departure);
(d) stand number.

2.10 The movement data are too voluminous to be reproduced here, but a statistical summary is provided in Table 2.1, which gives a breakdown by major aircraft type compared with the equivalent for 2002. The total number of aircraft movements in 2008/9 was 470,029, which represents an increase of 0.75% on the total for 2002 (466,554). In relation to fleet mix, for medium-sized jets there has been a significant reduction in the B737 fraction, with a corresponding increase in the A319/320/321 fractions. For large jets, there has been a significant increase in the A340 and B777 fractions, with a slight decrease in the B747 fraction. Overall, the large-jet fraction has increased, which is reflected in the average passengers/movement (see below).

2.11 The total number of passengers served by the airport in the 2008/9 period was 65.93 mppa (million passengers per annum), compared to 63.01 mppa in 2002, an increase of 4.6%. Thus, the average number of passengers/movement has increased from 135.1 in 2002 to 140.3 in 2008/9.

Engine Assignment

2.12 The BOSS flight-by-flight aircraft movement database includes aircraft tail number, which in previous inventories has been used to determine the engine fit for individual aircraft using the BUCHair (JP Airline Fleets) compilation of aircraft fleet data (which is updated regularly). In the 2008/9 BOSS data set, however, engine model was specified explicitly, although there were some data gaps. Nevertheless, a recent version BUCHair[17] was used to cross-check the engine assignments given in BOSS. Although largely consistent, there were some discrepancies in the engine model recorded for a given tail number in the two data sets. Other data fields usually favoured the BUCHair assignment, so the latter was given preference, but where an assignment could not be made from BUCHair (a rare occurrence), the BOSS assignment was used. This process yielded engine assignments for around 98% of the movements in the 2008/9 period. For illustrative purposes, the most common engine model for each aircraft type is shown in Table 2.1, but it should be noted that most aircraft types have a range of engine types in the LHR fleet.

2.13 In the relatively few instances where no specific engine assignment could be made, the most common engine for the aircraft type in the 2008/9 data set was used. Where there was no instance in the 2008/9 data giving an engine assignment for a particular aircraft type (a rare occurrence), a typical engine was chosen according to standard aircraft reference sources.

Exhaust Emission Factors

2.14 The emission factors (sometimes termed ‘emission indices’) for aircraft engines vary from one engine type to another, and, for a given engine, depend on thrust setting. The chief source of emission factors (and fuel flow rates) used in the present work is the ICAO databank[18], which gives certification test results for most of the jet engines in service, at four thrust settings (7%, 30%, 85% and 100%). Data for the few turboprops in use at Heathrow were taken from the FOI (Swedish Defence Research Agency) compilation[19].

2.15 Some engines in the ICAO emissions databank (see later) have a number of variants with the same engine model identifier but with substantially different emission rates, the variants being distinguished by different certification test dates. For example, for older engines a later combustor variant may have been introduced to reduce smoke emissions; more recently, variants may be introduced to reduce NO_x emissions. BUCHair does not give direct information on the variant fitted if the different versions do not have different engine model identifiers. However, it does give year of aircraft entry into service (EIS), and the assumption was made that an aircraft would be fitted with the engine variant with the latest test date prior to its EIS date. For engines that have SAC (Single Annular Combustor) and DAC (Dual Annular Combustor) variants (with the latter having significantly lower NO_x emissions), such as the CFM56-5B3 and –5B6, the DAC version engine ID is given a '/2' suffix, so can be identified separately in the LHR fleet.

2.16 Over a period of years BA have been modifying the RB524-211G engines on their B747 fleet to the 'G-T' version, which has different emission characteristics. Although the BUCHair database recognises the G-T version as a different engine, it was not clear if its fleet information would represent the specific situation in 2008/9. Thus, additional information was requested directly from BA, who provided a detailed list of which tail numbers had the G-T version.

2.17 Certification data in the ICAO databank are based on tests carried out using new or nearly-new production engines, with certification data corrected to production standard. Thus the applicability of certification data to in-service engines requires consideration. For reasons of safety and fuel efficiency, aircraft engines operate within closely-monitored ranges of tolerance and are subject to strict maintenance schedules. In early airport emission inventories, uncertainties in emission rate related to engine ageing were judged small compared to other uncertainties, and were not taken into account. Nevertheless, at any particular time the engines in the fleet operating at an airport will be, on average, part-way through the maintenance cycle; in addition, there will be some longer-term degradation not restored by maintenance that will be restored only at refurbishment. Thus, there may be a systematic bias in emissions estimates based on certification data.

2.18 The available data on this issue were reviewed by QinetiQ for the PSDH[20], in particular distinguishing whole-flight deterioration values from LTO-only values, leading to a recommendation of a 4.3% increase in fuel flow rates in the LTO cycle compared to certification values and a 4.5% increase in NO_x emission rates (the product of fuel flow rate and emission index) compared to certification values. Although there was some indication in the available data of variation with engine type, the data were not detailed enough to support engine-specific recommendations: the values given are appropriate averages for the fleet as a whole, bearing in mind the range of engine age in the fleet at any given time. These fleet-averaged values have been applied in calculating the 2008/9 inventory.

2.19 The available data are also not detailed enough to make a distinction amongst the various phases of the LTO cycle (taxiing, take-off etc) so, in applying these values in the PSDH work, the percentage NO_x increase noted above was applied equally to the NO_x emissions from all phases. It was recommended that the fuel increase be applied to PM_{10} emission rates, recognising the major uncertainties in PM_{10} emission indices (see below). These recommendations have been applied to the 2008/9 inventory.

2.20 The ICAO databank does not contain emission factors for PM_{10} directly, but does include 'smoke number' (SN), an indirect measure of particulate emissions calculated from the reflectance of a filter paper measured before and after the passage of a known quantity of smoke-bearing gas. For earlier versions of the LHR inventory, a method developed by AEA was used to derive PM_{10} emission indices from SN data. Although the approach used was refined over a number of years, it was recognised that it was subject to significant uncertainties, For the PSDH, methods and data for deriving aircraft exhaust PM_{10} emission indices were reviewed by QinetiQ, and recommendations were made for an interim methodology to be used while further data are being collected from various programmes in a number of countries. Appendix 1 gives a summary of the PSDH methodology, which has been applied in the 2008/9 inventory. A closely similar methodology has been advocated in a recent CAEP document giving guidance on the calculation of airport emission inventories[21].

2.21 Data on the size distribution of aircraft exhaust particulate matter[22] indicates that virtually all of the mass is associated with particles of less than 2.5 μm in diameter. Thus the assumption was made in the present assessment that the mass of $PM_{2.5}$ in aircraft exhaust equals the mass of PM_{10} (for both volatile and non-volatile components).

2.22 The ICAO certification test results are given at the four standard thrust settings (7%, 30%, 85% and 100% of engine rating), whereas recent airport inventories take account of differences between actual thrust settings and the ICAO set points, particularly for take-off thrust. Given that the actual take-off thrust (see later) is usually not far from 85%, the precise method of interpolation is not critical. Nevertheless, the ICAO CAEP (Committee on Aviation Environmental Protection) committee issued a guidance note[23] on the use of the ICAO database in assessing airport emissions, and included advice on calculating emission indices at intermediate thrust settings. Of course, if the fuel flow rate at the intermediate setting is known, the preferred method of interpolation is the 'Boeing fuel flow method'[24], which interpolates emission index as a function of fuel flow rate; however, actual take-off fuel flow rates are not generally available for Heathrow operations. In this case, CAEP gives guidance on how to interpolate emission index on the basis of thrust value, suggesting a multi-order polynomial for NO_x (but also noting that linear interpolation between 100% and 85% thrust has good accuracy in this range). The PSDH[2] report endorsed the multi-order polynomial approach for NO_x in the absence of actual fuel flow rate data, and this approach has been used for the 2008/9 LHR inventory.

2.23 In implementing this recommendation, a fourth-order polynomial (not constrained to pass through the origin) was fitted to the four data points (NO_x emission index versus thrust) in the ICAO databank. Neither CAEP not the PSDH made a recommendation for interpolating fuel flow rate, and the piece-wise linear interpolation used previously was retained. Similarly, neither CAEP nor the PSDH made a recommendation for interpolating SN values, and piece-wise linear interpolation was used.

Effect of Ambient Conditions

2.24 Aircraft engine emissions, particularly those of NO_x, vary with ambient temperature, pressure and humidity, whereas the certification test results in the ICAO databank are corrected to sea-level ISA (International Standard Atmosphere) conditions[25]. The CAEP guidance note referred to earlier[23] considered the effect of variations in ambient conditions, noting that variations in ambient pressure and temperature will be reflected primarily in changes in operating conditions and will therefore be largely taken into account if actual thrust settings are used (see later) rather than notional thrust settings; thus, no additional adjustment was recommended.

2.25 However, even after accounting for thrust changes, there will be some variation in NO_x emission rates (i.e. the product of fuel flow rate and emission index) with hour-to-hour variations in ambient conditions because of the associated changes in engine operating point. This was examined by QinetiQ as part of the PSDH work, leading to a technical report[26], which recommends a method for adjusting NO_x emission rates at a given thrust to ambient temperature and pressure. The sensitivity to ambient temperature and pressure variations was found to be significantly greater for the higher OPR (overall pressure ratio) engines (around 40:1) that are becoming common on modern large jets. QinetiQ estimated that the impact on total ground-level NO_x emissions over the year, using weather data for LHR in 2002, is typically of order a few percent. However, annual-average emission rate is not the only parameter of interest in air quality assessment, even when calculating annual-mean concentrations: the diurnal and seasonal variation in emissions is also important, given that the frequency of meteorological conditions leading to better (or worse) atmospheric dispersion varies with hour of day and month of year. QinetiQ found that, for the most sensitive type of engine, the hourly NO_x emission rate at a given thrust varied over the year by up to ±50% from the value calculated assuming ISA conditions.

2.26 QinetiQ found that it was not possible to condense the results of their analysis into simple expressions applicable to a small number of engine type categories because of wide variations from one individual engine to another. Thus, for the purpose of applying the temperature and pressure dependence across the whole fleet at Heathrow, QinetiQ worked out the ambient effect separately for the 55 engine types with the highest utilisation (product of number of aircraft movements and number of engines per aircraft) at Heathrow in 2002. The results of the QinetiQ analysis were thus represented as a look-up table for 56 engine types (55 specific types plus one representative type) covering the temperature range –5 °C to 35 °C in 2 °C steps and covering the pressure range 960 mbar to 1040 mbar in 4 mbar steps. These tables have been made available by QinetiQ under license for use in the 2008/9 LHR inventory. Although the tables were devised on the basis of the 2002 LHR aircraft fleet, they include a large number of the engines appearing in the LHR movement data for 2008/9, with data for the specific type available for around 70% of the movements; for the remainder, the QinetiQ default parameters were used.

2.27 For illustration, Figs 2.1 and 2.2 show the temperature and pressure variation of the NO_x emission rate for two common engines with widely differing OPR, the IAE V2522-A5 with an OPR of 25.6 fitted to some A319-100 aircraft and the RR Trent 892 with an OPR of 41.4 fitted to some B777-200 aircraft. These show clearly the larger predicted sensitivity of NO_x emission rate to ambient temperature and pressure for the higher OPR engines. The results are shown separately for take-off and idle thrust settings, with both temperature and pressure effects greater for the higher thrust. It should be recognised that the values for the sensitivities shown here are based on generic assumptions. Although these are applicable on a fleet basis, they are not intended to represent the exact sensitivity of each particular engine, which would require specific engine data that is not publicly available.

2.28 In light of the relatively poor characterisation of aircraft PM_{10} emissions, the PSDH report recommended that no adjustment for variations in ambient conditions (nor for the forward speed effect – see later) be applied to PM_{10} emission rates.

2.29 Of course, the temperature and pressure variation with altitude will affect emission rates during climb and approach for an individual flight. As the aircraft climbs or descends, there are continuous changes in forward speed, temperature and pressure to which the engine control system will respond appropriately. However, emissions at increasing height have a decreasing impact on ground-level concentrations, which are the principal focus of interest in local air quality assessment. Even bearing in mind the potential impact of trailing vortices in transporting exhaust gases downwards, it is unlikely that emissions above 200 m height have a significant impact on ground-level concentrations. For this reason, greater effort has been put into representing realistically the emission rates for the lowest few hundred metres in height than for greater heights.

2.30 With this in mind, in applying the ambient-condition adjustment to the emissions inventory as a whole, the NO_x emission rate during the initial-climb phase of the LTO cycle (from wheels-off to engine cut-back, typically at 1000 ft to 1500 ft) was worked out using ground-level temperature and pressure. This ensures that the emission rate in the lowest part of the initial climb is not underestimated, accepting that there will be some slight overestimation of the average emission in the initial climb taken over the whole year. For the climb-out phase (from cut-back height to 3281 ft (1000 m)), the hourly surface temperature and pressure values were adjusted using simple representative profiles of temperature and pressure. Temperature was assumed to decrease with height from its surface (screen) value in line with the dry adiabatic lapse rate of -9.8 °C per km (which would only strictly be the case for zero heat flux to/from the ground); the temperature adjustment to climb-out emissions was worked out using the mid-height temperature for the climb-out phase. Pressure was assumed to vary with height in a manner consistent with the adiabatic lapse rate for an atmosphere in hydrostatic equilibrium. This simpler procedure for climb-out emissions is judged adequate for emissions in this part of the LTO cycle, which have an insignificant impact on ground-level concentrations.

2.31 Similar simple procedures were used to account for the temperature/pressure variation with altitude during approach.

2.32 For correcting from NO_x test results in the databank to actual humidity, the CAEP document referred to earlier[23] advocates using in reverse the expression provided by ICAO Annex 16 Vol II[25] to adjust test results to ISA conditions, albeit correcting a slight error in the reference specific humidity quoted in Annex 16. This adjustment is engine independent. Typically, this leads to hourly variations in the ground-level NO_x emission rate over the year for a given thrust setting of around ±5%, although the net effect on total annual emissions is much less. The adjustment for relative humidity is given by

$$EI(NO_x)_{adjusted} = EI(NO_x)_{ICAO}\ \exp\left(-19(H_{ref} - H)\right)$$

2.33 For elevated emissions, it was assumed that the specific humidity is constant with height, which is strictly true only in the absence of condensation and evaporation.

2.34 The hourly surface temperature and humidity data used in the above methodology was taken from the data set obtained under licence from the UK Meteorological Office for the dispersion modelling study that will be based on the 2008/9 inventory. This data set does not include surface pressure, which was downloaded from the UCAR/NCAR web site[27].

Forward-Speed Effect

2.35 Emission indices and fuel flow rates in the ICAO data bank are measured on a stationary engine in a test cell. Generally there will be a difference in the emission rate (the product of fuel flow rate and emission index) at a selected take-off thrust when the aircraft is moving at speed with respect to the air drawn into the engine compared to the emission rate for an aircraft that is stationary.

2.36 To estimate the effect of forward speed on NO_x emission rate, the approach by QinetiQ was similar to that for estimating the effect of ambient temperature and pressure variations, with the key influence being the effect of fluid velocity on the relative temperature and pressure at the engine inlet. The results of the analysis are given in QinetiQ report referred to earlier[26]. The principal effect of interest from a local air quality viewpoint is the change in emission rate during the take-off roll, although consideration was also given to the effect of forward speed on climb and approach emissions. Of course, the aircraft engine management system will respond to the inlet changes experienced. For example, QinetiQ assumed a representative 1.1% increase in fuel flow over the roll, based on samples of FDR (Flight Data Recorder) data. Thus the forward-speed adjustment to emission rates is the combined effect of changes in fuel flow rate and changes in emission indices.

2.37 The net impact of these changes is that the NO_x emission rate increases with increasing speed during the take-off roll, with the fractional increase tending to be greater for engines with higher OPR. Table 2.2 gives the calculated ratio of emission rate at the end of the roll to the static emission rate at full thrust for a sample of engine types common at LHR in 2002. For engines with OPR around 40 the factor at the end of roll is around 1.15 (i.e., a 15% higher emission rate).

2.38 For PSDH work, QinetiQ provided the forward speed factors for NO_x explicitly for the 56 engine types referred to above in the discussion of ambient conditions. For each engine type, the factor was provided in terms of the four coefficients of a cubic polynomial representing the emission rate as a function of time from start-of-roll, with the emission rate expressed relative to the static emission rate at the selected take-off thrust and the time expressed as a fraction of total roll time. In principle, this normalised emission profile depends on the actual take-off thrust selected, but QinetiQ found that the relevant factors for 85% thrust were close to those for 100% thrust. Thus a single normalised profile is assumed to apply for a given engine to all take-off thrust values. For illustration Fig 2.3 shows the profile for two common engines of widely different OPR*.

2.39 As discussed earlier for variation with ambient conditions, forward-speed effects are also operative during the initial climb, climb out and approach phases of the LTO cycle. For the initial climb phase, the forward-speed factor worked out for the end of the take-off roll was applied. For the climb-out and approach phases, QinetiQ supplied forward-speed factors for each of the 56 engine types (55 specific engines plus one representative engine) worked out using a representative speed and thrust level for each phase. Thus, the forward-speed adjustments for these phases were treated more approximately than for the take-off roll, with the same justification as that given above in the context of adjustment for ambient conditions.

2.40 As discussed for ambient effects, the QinetiQ forward-speed tables were devised in relation to the 2002 LHR fleet but they include a large number of the engines in use at LHR in 2008/9, with data for the specific type was available for around 70% of the movements; for the remainder, the QinetiQ default parameters were used.

2.41 There was insufficient information available to the PSDH quantify the effect of forward speed on PM_{10} emission rates and it recommended that the effect is ignored for this pollutant; correspondingly, the impact on $PM_{2.5}$ emissions was also ignored.

Engine Spool-Up

2.42 In the compilation of emission inventories prior to the PSDH work, it was assumed that the selected take-off thrust is applied immediately at the start of take-off roll. In practice, there is a period of engine ‘spool-up’ during which fuel flow rates and thrust levels are significantly less than the take-off values. The duration of this initial phase depends on aircraft type, and for large aircraft may be of order 10 seconds, which is a significant portion of the total roll time (around 40 seconds).

2.43 Although the engine thrust is significantly less than take-off thrust during this phase, the engine is not at equilibrium, and it is difficult to predict what the effective emission index (kg pollutant per kg fuel burned) will be, even if the fuel flow rate is known. Thus, the PSDH made an interim recommendation that the NO_x emission index be held the same during the transient phase as that applicable at take-off thrust, so the net effect of spool-up on estimated emission rate derives solely from the lower fuel flow rate.

2.44 QinetiQ[26] examined FDR data obtained during take-off for a number of aircraft types, and found that the data on fuel flow rate versus time since start-of-roll collapsed reasonably well onto a single curve when fuel flow rate was expressed as a fraction of the flow rate at take-off thrust and time was expressed as a fraction of total roll time. For ease of implementation, this curve was fitted by QinetiQ using a simple analytic expression of the form

$$f(t) = a\tanh(bt + c) + d$$

where *f(t)* is the fuel flow rate expressed as a fraction of flow rate at take-off thrust and *t* is time expressed as a fraction of total roll time. *tanh* denotes the hyperbolic tangent function; *a*, *b*, *c* and *d* are constant, with the values *a*= 0.405; *b*=8.720; *c*=-1.282; *d*=0.595. This form, which is shown in Fig 2.4, was adopted by the PSDH and has been applied to all engines and aircraft types in compiling the 2008/9 LHR inventory of NO_x emissions.

2.45 For PM_{10}, there are even greater uncertainties in Smoke Number during the transient spool-up phase than in the NO_x emission index. Given the overall uncertainties surrounding the calculation of PM_{10} emission rates, the PSDH recommended that the effect of spool-up be ignored for this pollutant, i.e. take-off thrust is assumed to apply from the start of roll. This recommendation has been followed for the 2008/9 LHR inventory, and extended to $PM_{2.5}$ emissions.

* The relative emission rates shown in the Fig 2.3 account solely for the effect of forward speed and do not include the effect of engine spool-up (see later). In implementation, both effects are taken into account.

Thrust Settings

Take-Off Thrust

2.46 The four thrust settings used in the ICAO databank were chosen to be representative of actual thrusts in the principal LTO flight phases, and early methodologies for calculating aircraft emissions simply assigned each LTO flight phase to one of the settings (with the exception of landing roll, where periods of reverse thrust were identified for some aircraft types), as shown in Table 2.3. However, more recent airport emission inventories recognise that large jets usually do not take off at 100% thrust, with the actual thrust selected depending on, *inter alia*, take-off weight and air temperature. Typically, for large jets, actual take-off thrust lies between 75% and 90% of maximum thrust*.

2.47 NO_x emissions from take-off roll are a major component of the total ground-level NO_x emissions from aircraft at an airport, and the emission rate during roll is strongly dependent on thrust: not only does fuel flow rate increase with thrust but the NO_x emissions index (g NO_x per kg fuel burned) also increases with thrust. Furthermore, there is large variability in the NO_x emission indices from one engine type to another. Thus it is important to make realistic estimates of the thrust settings for those operator/aircraft type/engine combinations that have high utilisation at LHR.

2.48 Actual take-off thrust settings are not routinely available on a flight-by-flight basis, although they can be extracted from FDR data. In recent years, BA has developed a methodology that enables information on take-off thrust to be derived from information on actual take-off weight. The methodology is based on their analysis of an extensive set of take-off thrust (FDR) and weight data for their fleet at LHR[28]. BA found that, to a reasonable approximation, when flexible thrust† is being used the ratio of actual take-off thrust to maximum take-off thrust is given by the ratio of actual take-off weight (ATOW) to Performance Limited Take-Off Weight (PLTOW)‡, subject to a lower limit set by regulation, normally 75%.

2.49 Prior to the PSDH work, BAA carried out a survey of the major airlines operating at LHR to obtain average values of ATOW and PLTOW for each major aircraft type in the operator's fleet at LHR, with the data representative of the situation in 2004. Where average PLTOW values were not known, the airline was asked to substitute the PLTOW for zero wind and 15°C OAT (Outside Air Temperature) for runway 09R, as obtained from the flight data manual for the relevant aircraft. Based on the availability of this data set, the PSDH report of the expert panels[2] recommended that, where available, the ratio of average ATOW to average PLTOW for a given airline and aircraft type is applied to all flights of that aircraft type for that airline. Recommendations were also made for filling gaps in the data.

2.50 A detailed description of how these recommendations were implemented for the 2002 inventory was given in an ancillary PSDH technical document[3], which was made publicly available at the time of the 'Adding Capacity at Heathrow' consultation, and will not be repeated here. No new survey data were available for the 2008/9 inventory, so the methodology for estimating take-off thrust was unchanged from that used for the PSDH work.

2.51 Even if it is an airline's policy to use reduced thrust where possible, there are circumstances when 100% thrust is mandated even if the aircraft is not at its limiting take-off weight, for example when the runway is icy or there is excessive low-level wind shear. Typically the annual fraction of departures at 100% lies in the range 2-10%. Data on this fraction was also requested in the BAA survey, and this fraction was treated separately in the emissions

* All thrusts in the following text are expressed as a percentage of the rated output (F_{00}), the maximum thrust available for take-off under normal operating conditions at ISA sea level static conditions.

† 'Flexible' thrust is a term used to contrast with push-button de-rated thrust, and is typically applied via the 'Assumed Temperature Method'. In the latter, the aircraft flight management system is supplied with the value of the maximum air temperature at which the aircraft could take off with its actual take-off weight, according to the flight manual. This is an approved method that maintains safety margins.

‡ PLTOW is the maximum take off weight for a flight given by the aircraft flight manual, with due account taken of outside air temperature (OAT), wind speed/direction, runway characteristics (elevation, length, slope) and obstacle clearances. If it is higher than the maximum take-off weight determined by structural considerations (MTOW) then MTOW will set the limiting take-off weight for the flight.

analysis.

2.52 Under the terms of the BAA survey, the detailed results provided by the airlines are not reproduced here, but Table 2.4 shows the mean take-off thrust for each main aircraft type, with the average taken over the calculated values for all movements of that type in the 2008/9 period. The assumed fraction of departures at full thrust is also shown.

2.53 The above procedure gives thrust values based on annual average values of weight. In principle, PLTOW is influenced by ambient temperature, so that the take-off thrust for aircraft of a given take-off weight could show systematic diurnal and seasonal variations. However, modern commercial aircraft show little dependence of PLTOW on ambient temperature across the range of temperatures commonly experienced in the UK, so the influence of ambient temperature on take-off thrust for a given aircraft weight is not expected to be major. Of course, actual take-off weights for a given aircraft type operated by a given airline may also vary with time of day and season due to systematic variation in load factors or routes served, but the detailed ATOW data are not available to take this into account. The use of average weight data is unlikely to introduce significant error in the estimates of annual take-off emissions, but could influence the diurnal and seasonal profile of emissions.

Climb-Out

2.54 Between wheels-off and 1000 m height, two flight phases are distinguished: initial climb from wheels-off to cut-back height (normally 305 m (1000 ft) or 457 m (1500 ft)*); and climb-out from cut-back to 1000 m. In the standard ICAO LTO cycle, the thrust after cut-back is 85%, but in practice aircraft use a range of thrust settings, with the value for a particular flight linked in part to the take-off thrust. In particular, the aircraft will not climb out at a thrust setting higher than at take off. In LHR emission inventories prior to the PSDH, the influence of reduced-thrust take-off was recognised simply in terms of a constraint that if the take-off thrust is less than 85% the climb-out thrust is set at take-off thrust; otherwise it was set at 85%. It was recognised that this procedure was likely to overestimate climb-out NO_x emissions, but emissions above the cut-back height have an insignificant influence on ground-level annual-mean concentrations (even when the potential influence of trailing vortices is taken into account), so the approximation was considered acceptable from a local air quality viewpoint.

2.55 However, the PSDH recognised that total emissions in the LTO cycle are also of interest beyond the local air quality perspective, and made recommendations aimed at improving estimates of elevated emissions, including recommendations on climb-out thrust, which are summarised below.

2.56 Large commercial jets usually have several pre-set climb thrust settings, typically the maximum climb setting (CLB) and two lower settings, CLB1 and CLB2 (nominally 10% and 20%, respectively, lower thrust than CLB). The actual climb settings depend on aircraft type and engine fit, but for most types CLB does indeed appear to be close to 85% of the full engine rating, with CLB1 and CLB2 at around 78% and 70% of full rating. Thus, the PSDH report recommends the following procedure for setting climb-out thrust:

- use 85% for take-off thrust settings between 100% and 90%;
- use 78% for take-off thrust settings between 90% and 80%;
- use 70% for take-off thrust settings between 80% and 75% (the normal lower limit on take-off thrust);
- set climb-out thrust equal to take-off thrust if take-off thrust is less than 75% (for particular cases where an aircraft type is specifically certificated for take-off at less than 75%).

2.57 These recommendations have been adopted for the 2008/9 LHR inventory.

* Conventionally, aircraft elevation is measured in feet

Approach

2.58 In the standard ICAO LTO cycle, approach thrust is set at 30% throughout the descent from 3000 ft (914 m) to touchdown, as shown in Table 2.3. Although some FDR data analysed in the EU AEROCERT programme[29] indicated that in practice thrust levels were often less than 25% (and variable during the approach), it was considered adequate from a local air quality perspective to retain the 30% value in airport emission inventories, given that most of the approach emissions are well above the ground; 30% approach thrust was used in the 2002/3 inventory.

2.59 In line with its intention of improving estimates of elevated LTO emissions as well as near-ground emissions, however, the PSDH defined a typical approach procedure at LHR as follows. Aircraft follow a 3° glide path (as in previous assessments) with power levels of 15% of maximum thrust from 3000 ft (914 m) down to 2000 ft (610 m) and 30% of maximum thrust from 2000 ft (610 m) to touchdown. This requires the approach to be treated in two sections with differing emission rates.

Taxiing

2.60 Taxiing is assigned a thrust setting of 7% in the standard ICAO LTO cycle. There has been evidence available for some years (e.g. the Loughborough study at LGW[30]) that actual taxiing thrust settings are on average less than this. However, it was unclear how emission indices would behave at lower thrust settings. For the products of incomplete combustion, such as CO and HC, the emission indices (g pollutant per kg fuel burned) are likely to be higher for lower thrust settings, with the reverse likely to be true for NO_x; the position for SN and PM_{10} emission indices is unclear. Lower taxiing thrust was partly taken into account in LHR emission inventories from 2000 onwards in that taxiing fuel flow rates were provided by BA for all the major aircraft types in their fleet, derived from information in their fuel management databases. These data confirmed that aircraft were on average taxiing at less than 7% thrust. However, it was not clear if the BA data could be extended to other airlines so, prior to the PSDH work, the lower taxiing thrust was applied only to BA movements. Emission indices (g/kg) were held at the values for 7% thrust, recognising that this might lead to overestimation of NO_x emissions.

2.61 The estimation of taxiing emissions is made potentially more complex by the practice of shutting down one engine on taxi-in, which is favoured by some operators for some aircraft types. There are no robust statistical data on the practice at LHR, although the PSDH expert panel report estimates it is used for around 25% or less of arrivals. Analysis of the impact of engine-out taxiing on emissions suggests that it will yield no significant overall reduction in NO_x emissions because the other engine(s) generally has(have) to be operated at higher thrust setting(s) (and the APU may be running for longer), but potentially significant reduction in exhaust hydrocarbon emissions. In light of this, the PSDH report made no specific recommendation at the present for taking account of engine-out taxiing on NO_x and PM emissions.

2.62 However, for taxi-out and for taxi-in on all engines, the PSDH recommended that idle thrust settings lower than 7% should be taken into account for all aircraft movements. FDR data compiled for the PSDH indicate that in most cases the ground-idle thrust setting used during most of taxiing and hold is around 5% except for aircraft fitted with Rolls Royce engines, for which 3% thrust is nearer the mark. Clearly, there will be brief periods of higher thrust (perhaps 10% to 15%) to get the aircraft rolling or to negotiate sharp turns, but superimposed on much longer periods at the ground idle setting, so the average thrust level will be significantly below 7%.

2.63 It is easier to estimate the impact of these lower thrust settings on fuel flow than on emission indices. Considering the available data as a whole, the PSDH recommended that fuel flow rates for engine types other than Rolls Royce be set 15% - 20% lower than the ICAO 7% value and for Rolls Royce engines be set 30% - 35% lower than the ICAO 7% value, and these recommendations were implemented for LHR by using the mid-point of the ranges, i.e. 17.5% and 32.5% respectively, with the values applied to all periods of taxiing and hold. The PSDH further recommended that the NO_x and PM_{10} emission indices at the lower fuel flow rate be held the same as the value at 7% thrust. As noted earlier, this is likely to yield a somewhat conservative estimate (i.e. overestimate) of taxiing NO_x emissions; current information[31], albeit more uncertain, suggests that this assumption is also likely to be conservative for PM_{10}. These recommendations have been applied in the 2008/9 LHR inventory.

Reverse Thrust on Landing

2.64 Some arriving aircraft deploy thrust reversers at thrust levels above idle on landing whereas other aircraft, although they may deploy the reversers, use only idle thrust and rely on the wheel brakes to slow down the aircraft. In the following, to ‘use reverse thrust’ implies a thrust level above idle. There are three key parameters determining the total annual emissions from landing roll: the fraction of aircraft of a given type that use reverse thrust on landing; the duration of reverse-thrust deployment; and the thrust level engaged.

2.65 Prior to the PSDH work, all aircraft types in the ‘Heavy’ and ‘Medium’ wake-vortex categories (which account for most of the movements at LHR) were assumed always to use reverse thrust, with short periods at 85% thrust and 30% thrust, based on data supplied by BAA for the LHR T5 Public Inquiry. For LHR inventories after 2000, however, the thrust level was restricted to 30%, based on advice from major airlines and airport operators. In addition, BA advised that for those aircraft in their fleet fitted with carbon brakes (A319, A320-111, A320-211, B747-436, B767-336, B777-236 IGW, B777-236ER) reverse thrust above idle is not normally used.

2.66 Two additional sources of data on reverse thrust were made available to the PSDH. First BA provided the results of observations made on a sample of 174 arriving aircraft (all airlines, not just BA) at LHR, which quantified the fraction of arriving aircraft employing reverse thrust as a function of aircraft type, together with the average duration of the period of reverse-thrust. Although the sample size is modest, this data set was judged to give a more reliable indication of reverse-thrust usage than earlier data. The sample size was not large enough to give a robust indication of variability amongst airlines for a given aircraft type, so it was recommended that the average over all airlines was applied to all arrivals of that aircraft type. In implementing this recommendation, BA was treated separately in view of the additional information supplied for their fleet on the use of carbon brakes. Table 2.5 gives the fractions and durations used; for those types with carbon brakes in the BA fleet, the entry in the table applies to non-BA aircraft.

2.67 Aircraft types not appearing in the PSDH landing-roll data set were assigned a surrogate or, in the absence of any obvious surrogate, were assigned values from the older T5 data set: these aircraft types, however, account for a small fraction of the overall emissions.

2.68 A second type of data made available to the PSDH was samples of FDR data held by the CAA and BA for a variety of common aircraft types, which indicated that reverse thrust levels were rarely above 30%, leading to a recommendation that reverse thrust above idle be retained at the 30% level (as used for earlier post-2000 LHR inventories).

Times-in-Mode

2.69 The PSDH report did not make any specific recommendations on how times-in-mode for the LTO flight phases should be assessed, but endorsed the AEA approach of utilising ground-radar and NTK (Noise and Track-Keeping) data where available.

Ground-Movement Times

2.70 In recent years NATS has developed systems for extracting ground-movement time information from ground-radar data via its Airport Playback Tool (APT). At LHR, this facility benefits from the multi-lateration system that enables aircraft to be tracked to/from the stand despite radar ‘clutter’ from buildings.

2.71 For the PSDH update of the LHR 2002 inventory[3], BAA made available a set of ground movement times derived from radar data in 2004/5, comprising around 50,000 departures and nearly 70,000 arrivals. These data were already partly processed, in that averages had been taken over sets of flights in various categories. For example average taxi-out times were provided as a function of aircraft type (expressed in terms of the 3-letter IATA code), originating stand and departure runway (but not specifying the turn-on block on the runway). Average taxi-in times were provided as a function of runway exit, stand and aircraft type; holding times at runway head were given as a function of aircraft type, originating stand and departure runway (but not hold point).

2.72 For the 2008/9 inventory, BAA provided flight-by-flight APT information for the specific period of interest. Use of flight-specific times-in-mode provides a more accurate way of quantifying aircraft emissions since it will take account automatically of correlations (if any) between time-in-mode and, for example, hour-of-day or the emissions performance of the particular engines on an aircraft. However, the APT data set was incomplete, with entries for around 65% of arrivals and 67% of departures. The procedure followed, therefore, was to first reconcile individual flights in the APT with the corresponding BOSS record and to apply flight-specific times for these reconciled flights. Then the set of times for these reconciled flights was used as a basis for assigning times to the remaining flights by identifying the key parameters on which a particular time in mode depends. Appendix 2 describes this process in more detail for each ground-movement time-in-mode.

Initial Climb and Climb-Out

2.73 Initial-climb (from wheels off to cut-back) and climb-out (cut-back to 1000 m height) times are based on data extracted from the NTK radar system. The current NTK system at Heathrow is different to that used for the 2002 inventory, and the analysis of times-in-mode for the 2008/9 inventory has been based on samples of individual flight trajectories rather than on a statistical analysis performed internally within the NTK system. NTK output was provided for a sample of flights in 2008/9, separately for each of the 17 aircraft types listed in Table 2.6, with these types accounting for the great majority of flights at Heathrow in the relevant period. Other aircraft types are assigned a surrogate from the set of 16, based on aircraft size and type of operation. For each aircraft type, a sample of 12 flights was provided, with one flight taken from each month of the year. The size of the sample was restricted by practical constraints, but the standard error on the mean time-in-mode values obtained from the samples proved to be acceptably small.

2.74 For each flight trajectory, output was provided from the NTK system at typically four-second intervals, giving the lat/long of the aircraft's position, its height and the time elapsed since the first radar 'squawk'*. Typically there are around 10-20 trajectory points below 1000 m height. The data set also provides a (horizontal) 'speed' value at each trajectory point; however, this is not an instantaneous speed but an average speed calculated from distance and time between two trajectory points. From this trajectory information, the time to cut-back - either 1000 ft (305 m) or 1500 ft (457 m), see below - and the time from cut-back to 1000 m were worked out. It is worth noting that the aircraft may be below or above cut-back height when the first squawk is detected.

2.75 In principle, the time between lift-off and first squawk can be derived from the difference between absolute times in the BOSS data and the NTK data, but the synchronisation between the times the two systems could not be relied on to the precision required. Thus this time difference was calculated from an estimate of the lift-off speed (which is a representative speed for each aircraft type), lift-off location (derived from the length of roll, calculated as in Section 3), position at first squawk and speed at first squawk, assuming uniform acceleration from lift-off to first squawk.

2.76 The speed information in the NTK data displays spurious variability deriving from finite precision of the positional information from which it was derived, so it was not treated as primary data. Instead, the speed at first squawk was estimated based on the (smoothed) shape of the trajectory points after first squawk. A quadratic relationship was assumed

* The aircraft height at which the first signal (squawk) from the aircaft is detected varies from flight to flight.

between horizontal speed and time (i.e. constant acceleration), which was used to derive the average acceleration (up to 1000 m) and the speed at first squawk.

2.77 If the first squawk is detected before cut-back, the time from first squawk to the pertinent cut-back height (either 305 m or 457 m) was the obtained by finding the two trajectory points that bracket the cut-back height and assuming linear interpolation in height (effectively assuming constant vertical speed). If the cut-back was below first squawk (as sometimes happened), the time to first squawk was obtained by assuming constant vertical speed between lift-off and first squawk.

2.78 Average times to cut-back and to 1000 m taken over the 12 flights for each aircraft type group, together with corresponding standard errors are shown in Table 2.6. These times can be compared at the NATS Group level with those used for the PSDH, as shown in Table 2.7. NATS Groups are a broader categorisation of aircraft types used in runway utilisation studies, with the assignment of aircraft types to NATS Groups as shown in Table 2.8. The times for the two years are broadly comparable. The initial climb time is somewhat higher (by 14%) for the larger aircraft (NATS Group 1), which may result from fleet differences or operational differences, although it cannot be ruled out that it is an artefact of the different procedures required to extract the relevant information from the two types of NTK data.

2.79 In relation to cut-back height, a specific improvement introduced for the PSDH work was to recognise that some operators/aircraft types normally cut back at around 1000 ft (305 m) rather than 1500 ft (457 m) at LHR for noise-compliance reasons. Advice from the CAA (Environmental Research and Consultancy Department) at the time indicated that the lower cut-back was used by most aircraft in the ‘Heavy’ wake-vortex category (typically B777, B747, B767, A340, A310, A300, MD11) and by aircraft in the ‘Medium’ wake-vortex category (typically B737, A319, A320, A321) for particular operators.

Approach

2.80 For the PSDH work, approach times at LHR were based on a defined representative approach procedure, which recognised two phases, namely from 3000 ft (914 m) down to 2000 ft (610 m) and from 2000 ft to threshold. In the first phase, the speed was assumed constant at 160 kt, whereas in the second phase the aircraft decelerated from this speed to a specified landing speed that was a function of aircraft size. In both phases, the aircraft is assumed to be on a 3° glide slope. Given that aircraft on standard approach paths operate within narrow ranges of speed, approach times are not subject to high variability; in addition approach emissions contribute little to the annual-mean ground-level concentrations of the key pollutants. Thus, the use of a representative approach trajectory was judged adequate.

2.81 However, the NTK system also provides actual approach data, so the opportunity was taken to use these data to estimate LHR approach times, for comparison with those derived from the PSDH representative-approach procedure. BAA provided flight-by-flight data on the time that the aircraft crosses a ‘gate’ (a hypothetical vertical plane perpendicular to the runway direction) at 10 nautical miles from runway threshold (and the co-ordinates of the point of crossing), together with the time of crossing the runway threshold. Given that aircraft on a standard approach path (a 3° glide slope) are close to a height of 1000 m at 10 nautical miles (18.5 km), this provides an accurate estimate of approach time (from 1000 m height to threshold) on a flight-by-flight basis. A sample was provided of around 8000 arrivals in 2009. The variability with aircraft type is not large for reasons outlined above, so it was judged that the appropriate level of aircraft-type categorisation was the wake-vortex (WV) category (a broader level of categorisation of aircraft type than the NATS Group). The assignment of aircraft types to WV categories is shown in Table 2.8.

2.82 The analysis retains the assumption of a two-phase approach (down to 2000 ft then 2000 ft to threshold), together with the assumptions of a constant speed in the upper section and constant decelerations in the lower section, and retains the landing speeds (as a function of WV) used in the PSDH protocol. However, the speed in the upper section is then fixed by the other assumptions. This analysis allows the time from 1000 m to 610 m (2000 ft) and from 610 m to threshold to be worked out. If 1000 m is above the height at which the aircraft intersects plane, the upper constant-speed region is assumed to extends up to 1000 m along the 3° glide path. Table 2.9 compares the resulting approach times by WV category of times with those given by the PSDH protocol. The new times are on average around 6% lower those used previously, but the differences will have an insignificant impact on ground-level concentrations.

APU Emissions

2.83 APU emissions (kg) from a given aircraft movement were calculated as the product of the APU running time (s), the fuel consumption (kg/s) and the emission factor (kg pollutant per kg fuel consumed) appropriate to the APU model fitted on the aircraft.

2.84 There are relatively few openly-available sources of information giving APU emission factors (kg pollutant per kg fuel burned) and fuel flow rates (kg/hour), principally because APUs are not included in the ICAO certification process. The release of detailed APU emission indices is controlled by the APU manufacturers, but data are released to aircraft operators for the purposes of generating emission inventories, provided the values for individual APU models are not published. For the work of the PSDH, a compromise was worked out whereby BA derived from the detailed manufacturer's data supplied to them a set of representative modal emission indices for general use in compiling inventories. This approach allowed greater realism to be reflected in the emission factors used for airport emission inventories whilst maintaining the level of confidentiality required by the manufacturers. The key elements of this methodology have been adopted in the recent CAEP guidance report on airport emission inventories referred to earlier[21].

2.85 Potentially there is a wide range of APU operating conditions for which differing fuel flow rates and emission factors apply, ranging from 'no load' through to the starting of main engines together with the provision of electrical power to the aircraft systems. Other load conditions include the supply of electrical power and/or the provision of air conditioning. However, inspection of the data revealed that it is adequate to characterise APU operations in terms of three modes: (a) no load; (b) air conditioning plus electrical power (labelled ECS – environmental control systems - for convenience below) and (c) main engine start plus electrical power (labelled MES below).

2.86 For NO_x emissions, BA defined six APU classes that adequately span the range of values found in the detailed data; each aircraft type was assigned to one of the six classes for the purpose of calculating APU NO_x emissions. The modal NO_x emission rates (product of fuel flow rate and emission index) for the six classes are given in Table 2.10, together with the principal aircraft types assigned to the classes. It will be seen later that APU running times are dominated by the 'ECS' mode so overall emission indices will be similar to those in this column of Table 2.10. As expected, these values span much the same range as the cycle-average values used in earlier inventories.

2.87 The detailed data on PM_{10} emission indices proved more difficult to generalise, but BA found that the large variability in modal PM_{10} emission rates could be reduced if the emission rates were expressed as a function of the corresponding NO_x emission index. In this way, BA distinguished three classes of APU for which a different functional form of the relationship between PM_{10} emission rate and NO_x emission rate was appropriate, with each aircraft type assigned to one of these classes. The forms of the relationships thus derived are shown in Table 2.11, together with the principal aircraft types assigned to the classes. $PM_{2.5}$ emission indices were set equal to the corresponding PM_{10} indices.

2.88 For the 2002 inventory, APU running times were based on information from 'compliance audits', in which spot checks are carried out on the status of an APU (whether off or on) against the requirements of the OSI (Operational Safety Instruction) for APU running at Heathrow. There are uncertainties in extracting actual running times from the spot-check information. For the 2008/9 inventory, an updated analysis of compliance audit data was provided by BAA, providing running times based on 163 departure and 43 arrival observations from 2008 and 2009. In addition, however, a separate set of data was made available from 'turnaround' surveys (carried out in 2007 and 2009) in which individual flights were monitored to record the specific times of switching on and off of the APU; these were then related to the time of arrival/departure of the aircraft. This set of data included 121 departure observations and 159 arrival observations.

2.89 The 'turnaround' data set was not a representative sample, with observations missing in the summer period. Also, the sample contained few example of APU running prior to departure for wide-bodied jets. On the other hand, the compliance data had observations for a wider range of months and complemented the turnaround data in having more wide-body departure data points. Thus the decision was taken to pool the compliance-audit and turnaround data sets. Taken on their own, the turnaround data would lead to significantly lower average APU running times (by around 20-30%), suggesting that APU emissions in the 2008/9 inventory may be overestimated, but this cannot be confirmed until better running-time information is available.

2.90 The combined data set was still not large enough to identify a systematic dependence on operator or specific aircraft type, but did show the expected distinction between wide-bodied* and narrow-bodied aircraft. Consequently, average times were formed separately for the two aircraft type categories. The data were initially averaged separately by terminal, but within the precision allowed by the sampling statistics, no clear systematic dependence on terminal could be identified, so the data for all terminals were pooled, leading to a single airport-wide average for wide-bodied aircraft and a single average for narrow-bodied aircraft. This data set, therefore, is unable to identify any specific influence of the use of Pre-Conditioned Air on aprons where it has been fitted.

2.91 The resulting times† are shown in Table 2.12, which also shows the corresponding averages for the 2002 PSDH inventory‡. The 2008/9 running times are generally lower than the 2002 values, by 13% for wide-bodied aircraft and 41% for narrow-bodied aircraft.

2.92 The above analysis leads to total APU running time, whereas the PSDH methodology distinguishes three operating modes, namely (a) no load, (b) air conditioning plus electrical power (labelled ECS) and (c) main engine start plus electrical power (labelled MES), so the total time needs to be partitioned amongst these three modes. BA provided estimates of the typical times for the no-load and MES modes, with the former given as 180 seconds (all aircraft types) and the latter as 35 seconds for 2-engined aircraft or 140 seconds for 4-engined aircraft. These times, which were applied to LHR in the PSDH work, have been adopted in the CAEP guidance report[21] and have therefore been adopted for the 2008/9 inventory. Thus, for arrivals, the time assigned to the ECS mode was set equal to the difference between total arrival running time and no-load time. For departures, the time assigned to the ECS mode was set equal to the time remaining after subtraction of no-load and MES times from the total departure running time.

Engine Testing Emissions

2.93 The emissions from engine ground runs (engine testing) represent a small contribution to total ground-level emissions, so a simplified methodology was judged adequate.

2.94 The estimate of emissions was based on recorded information on ground runs carried out in the 2008/9 period, which provided a statistical summary for each month of the period, giving both the number of tests and the total number of engine-minutes of running, separately for high-power and idle operation.

2.95 The data were provided separately for daytime (07:00 to 23:00) and night-time runs and, for the latter, separately by aircraft type and by location (which may be in the ground-run pens or out on the airfield)§. It was assumed that the distributions of runs by aircraft type (and by location) in the night were reasonably representative of the corresponding distributions for all

* Wide-bodied types include B747, B767, B777, A300, A310, A330, A340 and A380
† Where aircraft had the APU running for the whole turnaround, the time was partitioned between arrival and departure in the ratio 1/3 to 2/3.
‡ Running tmes were terminal dependent in the PSDH work, although the variation was not large, the numbers in the table are movement averages over the whole year.
§ The greater level of detail is not available for daytime runs.

runs during both day and night.

2.96 A variety of engines may be fitted to a given aircraft type, and information on engine model was not recorded in the ground-run data provided. Therefore, an average emission rate was worked out for each aircraft type on the assumption that the engine types for a given aircraft type would be represented in the tests in the same proportion as they are represented in the total aircraft movement data for the 2008/9 period. PM_{10} and $PM_{2.5}$ emission factors were derived from Smoke Number values using the methodology described in Appendix 1. Adjustments were then made to the emission rates to account for engine deterioration, as explained earlier in the context of LTO-cycle aircraft emissions.

2.97 For the running time at idle, emission rates for a thrust setting of 7% (of engine rating) were used but with the adjustment to the ICAO fuel flow rates recommended by the PSDH expert panel on emissions, as described earlier in the context of LTO-cycle aircraft emissions. For the running time at high power, emission rates for the 30% thrust setting were used, in line with PSDH recommendations. This calculation procedure leads to engine test emissions for each pollutant for each month of the period.

Aircraft Brake and Tyre Wear

2.98 Prior to the PSDH, LHR emissions inventories included an estimate of the contribution to PM_{10} emissions from aircraft brake and tyre wear based on the generalisation of sparse information obtained from operators at Stansted airport, which gave the quantity of material eroded from brakes and tyres per landing for particular aircraft types common at that airport. In addition, data on tyre wear was obtained from aircraft tyre manufacturers. It was assumed that *all* eroded material would end up as suspended particulate matter in the PM_{10} size range, recognising that this would almost certainly lead to an overestimation of PM_{10} mass (given the blackening of runways and aircraft undercarriages). In order to estimate emissions from the whole fleet at at an airport based on this limited information, it was assumed that the PM_{10} mass per landing would scale with the size of the aircraft, as represented by its maximum take-off weight (MTOW), although there were no specific data to support this assumption.

2.99 For the PSDH, QinetiQ[32] reviewed all the available data on brake and tyre wear, including additional information on tyre wear compiled by BA for a number of the aircraft types in their fleet at LHR, and recommended a methodology for making best use of the information. For brake wear, the earlier assumption that all the eroded mass ends up as suspended PM_{10} particulate matter was retained - partly by analogy to road-vehicle data indicating that a significant fraction of the eroded mass can end up as PM_{10} - but with continuing recognition that this is likely to lead to an overestimation of the PM_{10} mass. Similarly, the assumption that the emitted PM_{10} mass per landing scales with aircraft weight was retained. For brake wear this gave an emission factor of $2.53\text{x } 10^{-7}$ kg PM_{10} per kg MTOW (with the factor very similar if maximum take-off weight (MTOW) is used rather than MRW).

2.100 For tyre wear, QinetiQ based the methodology principally on the BA information, which covered a wider range of aircraft size than previous data. This gave support to a linear dependence of mass eroded per landing on aircraft weight (represented as MTOW), and a linear regression of the data yielded the following relationship:

amount lost per landing (kg)= $2.23 \times 10^{-6} \times$ (MRW in kg) - 0.0874 kg

for MTOW>50,000kg.

2.101 The QinetiQ report gave no recommendation for MTOW<50,000 kg, and it has been assumed that the eroded mass per landing varied linearly from the value at MTOW=50,000 kg given by the above to zero at MTOW=0.

2.102 Judging by analogy to road-vehicle data, QinetiQ considered it over-conservative to assume that all the eroded mass from tyre wear is suspended as particulate matter, and a PM_{10} fraction of 10% was assumed, which is at the upper end of the range observed for road-vehicle tyres. This contrasts with the earlier assumption that all eroded tyre material contributes to suspended PM_{10} mass.

2.103 The above PSDH methodology has been adopted for the 2008/9 LHR emission inventory. It is recognised that there remain significant uncertainties in estimating PM_{10} emissions from brake and tyre wear, but these will only be reduced when more aircraft-specific data become available.

2.104 The mean size of particles from attrition processes such as brake and tyre wear tends to be much higher than from combustion processes, so in this case setting $PM_{2.5}$ emission factors equal to PM_{10} emission factors is likely to significantly overestimate $PM_{2.5}$ emissions. There are no specific data on the $PM_{2.5}/PM_{10}$ mass ratio for aircraft brake and tyres, so equivalent data for road vehicles were used, adding to the uncertainty in the $PM_{2.5}$ estimates. The road-vehicle values were taken from a recent review of brake and tyre wear carried out for the UNECE (United Nations Economic Commission for Europe)[33]; further details are given in the section on landside road vehicle emissions below. This estimates that the $PM_{2.5}/PM_{10}$ mass ratio for brake wear is 0.4 and for tyre wear is 0.7; these ratios were adopted for aircraft brake and tyre wear for the 2008/9 LHR inventory.

Airside Support Vehicle Emissions

Activity (Fuel per Vehicle Type)

2.105 This source category includes all vehicles and plant that generate exhaust emissions airside, principally vehicles associated with aircraft turn-around (vehicles operated by caterers, cleaners and fuel handlers, Ground Power Units, buses etc) but also vehicles associated with runway maintenance etc. For convenience, the term ‘airside vehicles’ will be taken to include non-vehicular plant burning fuel airside.

2.106 As discussed later, annual emissions from vehicles on the landside road network were calculated from the annual vehicle-km travelled in various vehicle categories, together with vehicle speed information, with emission factors then expressed as grams pollutant per vehicle-km. For airside vehicles, however, the number of miles travelled airside by vehicles with permits to operate airside is more difficult to estimate from available information (although some mileage information is given in the Airside Vehicle Pass database). In addition, some types of vehicles operating airside (loaders for example) are stationary (but with engines running) for much of their operation, so mileage is not a good basis for estimating their emissions. For specialist vehicles operating airside, the number of kW-hr of operation per year would be a useful starting point for an emissions estimate but, again, information on this for individual vehicles operating airside is patchy. For this reason, airside emissions estimates in previous Heathrow emission inventories have been based on estimates of the amount of fuel used. Emission factors expressed in g/kg are less variable with vehicle type and size than when expressed in g/km.

2.107 A number of additional data sources on airside activity have recently been identified[34], but these had not been sufficiently well developed at the time of this inventory to serve as an alternative basis for estimating airside vehicle emissions. Thus a methodology based on fuel use was retained for the 2008/9 inventory, with the expectation that more detailed airside activity data may be available for the next inventory update.

2.108 For past inventories, a number of suppliers of fuel for airside use provided data on annual fuel throughput, but airside fuel supply is now managed principally by a single company, AIRES. AIRES supplied data on the total quantity of fuel supplied in the 2008/9 period for 4 supply sources, separately for each fuel type. The totals are shown in Table 2.13. The predominant fuel is (Ultra Low Sulphur) gasoil (untaxed diesel), followed in importance by taxed diesel and petrol; small quantities of LPG were supplied. The AIRES data also included the total amount of AdBlue additive supplied in the year. AdBlue is the registered trade mark for AUS32, a 32.5% solution of high purity urea in demineralised water that is used in vehicles (principally Euro IV and V goods vehicles) fitted with Selective Catalytic Reduction (SCR) technology. (The AdBlue is held in a separate tank on the vehicle and sprayed into the exhaust stream at rate of around 5% of diesel fuel usage). It was assumed that the impact of SCR technology is already included in the emission factors for the relevant vehicle types, so no further use was made of the AdBlue data.

2.109 A key issue in a fuel-based methodology is identifying what fraction of the fuel supplied is actually consumed airside. Some of the fuel dispensed to vehicles operating airside is consumed landside (and this applies even to gasoil, which can be used on airport-owned landside roads). Similarly, fuel is brought onto the airport from off-airport bases, in some instances in bowsers. A detailed record of these 'losses' and 'gains' to the fuel consumed airside is not available, but the AIRES manager offered approximate estimates. Bus operations along the perimeter road were estimated to account for 1.5 million litres of gasoil per year not used airside. All other fuel in the AIRES total was assumed to be consumed airside. It was estimated that 2.7 million litres gasoil per year was supplied from off-airport sources for airside use in mobile units.

2.110 With these adjustments, the total mass of fuel of each type consumed airside in the 2008/9 period was estimated as in Table 2.14. These quantities are compared with the equivalent estimates made for the 2002 inventory, showing that the 2008/9 estimate of total gasoil plus diesel is 36% higher than the 2002 estimate. This is less likely to represent a genuine increase in the amount of fuel used than to reflect the uncertainties in the fuel estimation methodology. It is now considered likely that the fuel supplied from off-airport sources was underestimated in 2002.

2.111 The next stage of the methodology was to partition the total amount of fuel (of each type) amongst vehicle categories with different emission factors (g pollutant per kg fuel burned). To assist in this process, BAA supplied a recent version of their Airside Vehicle Pass (AVP*) database (March 2009), in which the data entries had been partly 'cleaned' by another consultant to remove anomalies and fill in some data gaps.

2.112 As a first step, all vehicles in the AVP (airside vehicle pass) database were identified as either road vehicles or off-road vehicles. For these two broad classes of vehicle, the engines have to conform to a different set of emissions standards, and there are significant differences in the published emission factors for the two classes. Both have emission standards that are tightening over time, but starting from a different baseline and with different staged reductions. For the road/off-road identification process, all the vehicles/plant in the database were assigned to a number of categories (around 40 in total), based on the type of activity for which the vehicle/plant is used airside (for example, baggage tug, belt loader, push-back tug, airstart, high-loader, coach). Each of these categories was then designated as either road vehicle or off-road vehicle/plant based on background knowledge of the types of vehicle involved in the particular activity. Where this assignment was not obvious, more detailed information was collected on the specific vehicles involved.

2.113 The next step was to partition the fuel amongst major vehicle categories recognised in the emission factor databases. For road vehicles, these were taken to be car, LGV, rigid HGV, articulated HGV and buses/coaches; for off-road vehicles, the power ranges used in the off-road emission factor data set (see Table 2.18) were used as the categories. To put road vehicles and off-road vehicles on a common footing, each of the road-vehicle categories was assigned to one of the power ranges used for off-road vehicles based on engine size. The fraction of fuel assigned to each power range was then take to be the proportional to the product of the number of vehicles in the category and the mid-range power of the category.

2.114 Essentially this corresponds to assuming that the average usage (hours of operation per year) is the same for all vehicle types using a given fuel type (if the mid-range power is indicative of fuel consumed per second). This assumption represents a significant approximation and, correspondingly, the partitioning of fuel amongst the major vehicle categories is a principal source of uncertainty in the methodology. In mitigation, emission factors in g/kg are not strongly varying with vehicle category for the same level of engine technology; however, the distribution of vehicle age (and thence Euro standard) may be quite different for vehicles in different categories, so partitioning by category is still

* Contains information on all vehicles with permanent passes to operate airside.

necessary. The resulting estimates of the mass of fuel consumed airside per vehicle category are shown in Table 2.15.

2.115 The next step was to partition the fuel used in each major vehicle category amongst a set of further sub-divisions corresponding to ‘engine technology’ (defined by the emission standard to which the engine conforms, termed Euro standard below), which has a significant impact on the emissions expressed as g pollutant per kg of fuel burned. The distribution of the airside vehicles by Euro standard was constructed by comparing the age data in the airside database with the introduction years for the various emissions standards. Using vehicle age as a surrogate for engine emissions technology does not take into account instances where environmentally-enhanced vehicles were purchased or vehicles were retro-fitted with exhaust after-treatment technology. Anecdotal information suggested that this is not a significant deficiency, but there was insufficient information to quantify the impact.

(Hot) Exhaust Emission Factors

2.116 The above process gives the amount of fuel consumed airside as a function of fuel type, major vehicle type and Euro standard. For road vehicles, exhaust emission factors in g/kg were derived from the national set recently released by the DfT - labelled in the section below on landside road vehicles as ‘TRL2009’ - together with traffic composition data released by the NAEI (labelled FP2009). Further information on these data sets is given in the later section and will not be repeated here. The description there relates to emission factors in g/km, but TRL2009 provides fuel consumption (in kg/km) on a equal footing, enabling emission factors in g/kg to be derived for the airside methodology.

2.117 For a given fuel type (petrol or diesel)/major vehicle type/Euro standard, TRL2009 gives emission factors for further sub-divisions of the vehicle fleet. For cars, there is a distinction by car size (separating ‘large’ cars, in the weight range 2.5 tonne to 3.5 tonne from cars of weight less than 2.5 tonnes) and by engine size (<1400 cc, 1400 cc to 2000 cc, >2000 cc). In line with the methodology developed for landside road vehicles, all cars are assumed to be in the <2.5 tonne weight class. The information on engine size in the AVP database is patchy, and the assumption was made that the distribution of car engine sizes airside was the same as in the national fleet, as described in the section on landside road emissions.

2.118 Similarly, the LGV and HGV categories, the emission factors distinguish weight classes. The information on vehicle weight in the AVP is sparse, and the assumption was made that the frequency distribution of vehicle weight was the same as in the national fleet, as described in the section on landside road vehicle (see Table 2.22, ‘Average’).

2.119 These additional assumptions allow a weighted-average emission factor in g/kg to be derived for each of the major road-vehicle categories for each fuel type, to be applied to the annual fuel assigned to each category. Road-vehicle emission factors are speed-dependent, and in previous inventories speed was set at the airside speed limit (20 mph, 32 kph) in the absence of detailed data. However, a recent assessment of airside vehicle operations presented speed information derived from duty-cycle investigations by Millbrook. The information came in two parts, namely the fraction of time spent idling and the average speed when moving, for a number of vehicle categories, as shown in Table 2.16. To apply this to the emission inventory, each road vehicle category was associated with one of the ‘duty-cycle’ categories in the table, with LDV and rigid HGV associated with the ‘catering vehicles’ category, artic HGV associated with ‘cargo lorry’ category and bus/coach associated with the ‘coach’ category.

2.120 A weighted average emission factor for each duty-cycle category was derived as follows: an effective idling emission rate (g/s) was worked out as the emission factor (in g/km) at the lowest point on the speed-emission curve (usually 5 kph) multiplied by the speed (in km/s); similarly an effective emission rate was worked out for the duty-cycle category moving speed in a similar way. The weighted average emission rate (g/s) was formed using the specified fraction of time spent idling. A similar procedure was applied to fuel consumption to get a weighted average fuel consumption in kg/s, which thus enables a weighted average emission factor in g/kg to be derived.

2.121 The vehicle tests on which the road vehicle exhaust emission factors are based were carried out using fuel specifications appropriate at the time, and the new set of emission factors also include scaling factors to correct for different fuel sulphur content. All diesel and gasoil used airside is ultra-low sulphur content, in conformance with airport requirements, but in 2008/9 this did not differ from the specification of public fuel supplies, so appropriate corrections are already included in the TRL2009 data set.

2.122 The above process allows an effective emission factor (g/kg) to be derived for each of the major road vehicle categories, with the values shown in Table 2.17. The fraction of PM that is PM_{10} or $PM_{2.5}$ is discussed below in the section on landside road vehicle emissions.

2.123 For off-road (specialist) vehicles, exhaust emission factors for Uncontrolled, Stage I, Stage II and Stage IIIA diesel vehicles for NO_x and PM (taken to be PM_{10}) and $PM_{2.5}$ were taken from the latest issue of the EMEP/CORINAIR Guidebook, available on the European Environment Agency website[35], although the values for Stages I to IIIA there are simply based on the emission limits in the EU Directive[36] (with a few simplifications). Although no emission factors are quoted there for the later stages of emissions control already agreed for off-road vehicles (Stage IIIB and Stage IV), these have introduction dates after the inventory period of interest here. The Guidebook also includes recommended degradation factors of 1% per year for fuel consumption and 3% per year for PM (0% for NO_x), which have been included in the emission factors for each Stage using the average age of vehicles in the Heathrow airside fleet for each Stage.

2.124 The resulting emission factors, expressed in g pollutant per kg fuel used, are given in Table 2.18. The small variation in emissions factors expressed in these units as a function of power ranges for vehicles of the same age and fuel type indicates the utility of basing emission estimates on fuel data, at least whilst the emission factors for off-road vehicles are still so coarsely characterised. (Of course, as noted earlier, there will still be an indirect dependence on power range if the distribution of age – and hence Euro Stage – varies with power range.)

2.125 Data sources for LPG emission factors are sparser than for diesel and petrol factors, but the quantity of LPG used airside was small in 2008/9. Only a total of 86 LPG-fuelled vehicles were identified, principally in the LGV or specialist 37-75 kW categories (with a few cars and HGV). TRL2009 gives LPG emission factors for cars (in the <2.5 tonne weight range) as a function of Euro standard, and these factors were applied to airside LPG-fuelled cars and LGV vehicles (worked out at the speed and idling fraction for 'catering vehicles').

2.126 Some of the LPG fuel was assigned to specialist vehicles in the 37-75 kW range. The NRMM (Non-Road Mobile Machinery) section of the EMEP/CORINAIR Guidebook[35] gives a (speed-independent) NO_x emission factor for uncontrolled 4-stroke LPG engines irrespective of power output of 10 g/kW-hr)and a single value for fuel consumption of 350 g/kW-hr, and these were used to work out an emission factor in g/kg fuel consumed. In the absence of alternative data, this value was also applied to LPG-fuelled HGVs. The resulting set of emission factors are shown in Table 2.19.

Cold Starts

2.127 For NO_x and PM_{10}, the NAEI emission factor compilation contains data on 'cold starts' for LDVs expressed as a quantity of pollutant per trip[37]. This represents the additional (integrated) amount of pollutant generated near the start of a trip, incurred during the period when the engine (and catalyst if fitted) has not yet reached its normal operating temperature range; this is particularly significant for catalyst-equipped vehicles. Updated factors have not yet been released to accompany TRL2009. There are currently no cold start emission factors for HGVs.

2.128 It is difficult to estimate the number of cold starts associated with airside fuel use because of the wide range of duty cycles for airside vehicles and plant. However, even if every airside LDV had two cold starts every day, the contribution to annual NO_x and PM emissions would be around 1%-2% of the total hot-running emissions. Thus, emissions from airside cold starts were ignored.

Fugitive PM_{10} and $PM_{2.5}$ Emissions

2.129 Three sources of fugitive PM_{10} and $PM_{2.5}$ emissions from road vehicles have been included in the inventory: brake wear, tyre wear and re-suspended road dust; these sources were also included in the 2002 inventory. For the PSDH revision of the 2002 inventory, the methodology for estimating emissions from brake and tyre wear was updated to that described in the section below on landside road vehicle emissions. It is worth noting that fugitive emissions are becoming a significant component of total PM_{10} and $PM_{2.5}$ emissions from road vehicles as exhaust emissions fall in response to tightening EU vehicle emission limits.

2.130 The fugitive-PM emission factors are expressed in terms of g/km, and vary with vehicle category. For road vehicles operating airside, therefore, an estimate of the vehicle-km travelled for each vehicle category was derived from category-specific airside fuel amount by using the weighted-average specific fuel consumption for the category calculated at the category-specific airside speed (discussed earlier), taking care not to count the fuel spent idling when working out the distance. For off-road vehicles, an approximate estimate of km travelled was derived by associating each specialist category with a road vehicle category for the purpose of assigning a specific fuel consumption in kg/km: the 37-75 kW category was associated with the LGV category; the 75-130 kW category was associated with the rigid-HGV category and the 130-560 kW category was associated with the articulated-HGV category.

Landside Road Network Emissions

2.131 Emission from road vehicles over a large area contribute to pollutant concentrations close to Heathrow, and can be viewed as having two components:

(a) emissions from traffic on a near-Heathrow road network, where airport-related flows make a substantial contribution to total traffic flows; and

(b) emissions from the more distant road network.

2.132 Typically, for airport air quality studies, the traffic flows and speeds on the network for component (a) are derived from a traffic model, which uses airport-specific information on passenger, employee and business trips, together with information on non-airport traffic flows. The model is calibrated against count data collected on the network. In principle, the use of a traffic model allows the total flow on any link to be partitioned between airport-related and non-airport components, which is necessary to enable airborne pollutant concentrations to be apportioned between airport-related and non-airport sources. The model also forms the basis for forecasting what will happen to traffic flows and speeds on the network in response to developments on the airport or changes to the near-airport network layout.

2.133 For (b), road-vehicle emissions are expected to be dominated by the contribution from non-airport traffic, and emissions can be taken from existing regional and national emission inventories. These may use count data directly rather than traffic model outputs if the spatial density of count sites is adequate.

2.134 For the 2008/9 inventory, traffic model output has been used for the road network within an ‘inner’ square area of side length 11 km, aligned with the OS grid, with SW corner at OS co-ordinates (502000,171000), as shown on Fig 2.5(a) . For emissions from traffic within (and including) the M25 to the east of this area, the London Atmospheric Emission Inventory was used, providing emissions on a 1 km square basis; in addition, traffic emissions in a 40 km square centred on Heathrow (but outside the M25) were taken (at 1 km resolution) from the National Atmospheric Emission Inventory. The relationship of these geographical areas is shown on Fig 2.5(b): the rationale for this choice is linked to the methodology for estimating the concentration contribution from ‘background’, i.e. from sources not included explicitly in the dispersion modelling, and will be discussed further in the 2008/9 modelling methodology report[16].

2.135 Below, the traffic data and emission factors used to estimate emissions in the designated road network area are described.

Traffic Data

2.136 The 2008/9 inventory needs a set of traffic data for the ‘inner’ network area that takes account of the opening of T5 in March 2008 and its consequent impact on road traffic around the airport. The most recent published surface-access modelling for Heathrow prior to starting the 2008/9 inventory was that carried out by Hyder Consulting Ltd for the PSDH[38]. This model was calibrated and validated using 2004 traffic data, and used to forecast traffic for postulated airport development scenarios in 2010, 2015, 2020 and 2030. There was no forecast available for the situation immediately after the opening of T5 and, anyway, it is preferable to have a traffic model that has been informed by actual airport activity data for the 2008/9 period rather than a forecast made some years ago.

2.137 Fortunately, transport consultants AECOM were engaged in a limited update of the Hyder traffic modelling to generate a post-T5-opening baseline from which to carry out a number of sensitivity studies and scenario tests related to future development of the airport[39]. This was viewed as an interim model for use until a fuller set of surveys for 2009 had been completed. This update involved using some 2008/9 airport-related activity data to revise inputs, but the basic structure of model was not changed, so that the comparisons carried out to calibrate and validate the 2004 model were still pertinent. A limited number of additional comparisons were made for the updated model using count data for 2009 on the M4 and M25. Of course, activity in T5 was growing during 2008 and the resulting traffic model is more representative of the situation the latter part of the 12-month period than in the period as a whole, thus overstating the specific T5 impact.

2.138 Unfortunately, the Hyder data did not retain a split between airport-related and non-airport traffic*, so the AECOM update was also unable to provide this split.

2.139 The original PSDH traffic data were generated by Hyder using the RRTM (Regional Road Traffic Model) version 2a, which took inputs from a number of other models, including NADM (Non-Airport Demand Model) version 2, LASAM (London Airports Surface Access Model) version 2a and HESAM (Heathrow Employee Surface Access Model) version 1. In principle, the RRTM model covers a large area of the country, but the focus of attention in the validation of RRTM for use in the PSDH work was the vicinity of Heathrow (typically within about 10 km of the airport).

2.140 The RRTM2a model is implemented in the SATURN highway assignment and simulation package. In this framework, the model domain is divided into spatial zones and SATURN takes as input a set of matrices representing the number of trips between pairs of zones for various classes of trips, then assigns this ‘demand’ to the specified road network using modelling assumptions about driver behaviour etc. Junction models allow queuing delays as a function of traffic volume to be represented and, away from junctions, capacity constraints are represented in terms of speed/flow curves. An optimisation process is carried out to ensure that traffic reaches a ‘least cost’ equilibrium (with ‘least cost’ defined in a specific way).

2.141 The AECOM update of the model included

- 2009 outputs from LASAM2a based on an analysis of 2008/9 CAA data,
- the allocation of air passenger vehicle (car and taxi) trips to the airport parking zones based on current count data,
- an update of airport employee trips based on 2009 employment statistics (although

* Air passengers were recognised as a separate User Class (see text for explanation) but not airport employees and commercial trips.

detailed employee surveys for 2009 were not completed in time for this update),
- an updated distribution of employee trips to airport car parking zones based on 2009 HESAM1 output and allocation techniques developed for the PSDH and
- an update of trip end data in NADM2 using TEMPRO 5.4 data.

The model gave a good fit to count data on the M4 (including the M4 Spur), with the flow discrepancies generally less than 10%, but larger discrepancies were found for the M25 (particularly for anticlockwise flows), especially in the evening peak hour, where discrepancies of order 20% were found on some links. The interim model, therefore, has been subject to only a limited amount of validation.

2.142 Annual emissions based on the resulting set of traffic data may be more appropriate to a whole year of five-terminal operation rather than for the transitional situation that existed in 2008/9, but this is accepted as a limitation of the available traffic data.

2.143 For the PSDH air quality modelling, RRTM2a traffic data were used for an area including the whole of Greater London, albeit with the road network represented in more detail in the inner area around Heathrow referred to earlier. As noted above, for the present Heathrow 2008/9 work, AECOM traffic model output was used for the inner area only, with other data sources used to obtain road-vehicle emissions outside this area.

2.144 Data from the AECOM traffic modelling was provided to AEA in the same format as that supplied by Hyder (to Cambridge Environmental Research Consultants) for the PSDH modelling. This data set included flows and speeds for each hour of the day for a representative weekday (Mon-Fri) and for each hour of the weekend (termed below the ‘traffic hours’). The data are generated in two steps: first the SATURN process is run separately for three representative model hours: an AM peak hour, an inter-peak hour and a PM peak hour. Then, in a post-processing step, flows for these three representative model hours are used to generate flows in each of the traffic hours, using supplementary data on traffic profiles; speeds are then derived for each of the traffic hours using flow-speed relationships. In the past AEA has used the model output for the three representative model hours directly in quantifying road vehicle emissions on the network, making simplifying assumptions about the variation of speed during the day, whereas the AECOM process now provides the speed variation as an explicit output.

2.145 Conventionally, two types of link-specific speed information are available for the network. ‘Free-flowing speed’ refers to the speed of vehicles not taking account of any delays that may occur, for example at junctions; the model output gives separately the average time spent queuing at nodes of the network (principally road junctions) and the associated queue length. In an alternative representation, the total time taken to transit the link (including delay time) is used to calculate an effective link speed. Emission can be quantified using either representation, in the one case adding emission contributions from free flowing to emissions from queuing and in the other case just using the emission factors for the effective speed. It is not clear which route is preferable, bearing in mind that the basic speed-emission curves relate to *average* speed and derive from measurements taken over drive cycles having a given average speed. These drive cycles may include periods of queuing, depending on the average speed. On the other hand, a specific link may have queuing delays much higher than the average for relevant drive cycles, and the use of the effective speed may not be appropriate (particularly if the emission factor is not a monotonic function of speed).

2.146 For the PSDH air quality modelling, the effective-speed representation was used, and the post-processing steps to generate hourly data carried over by AECOM from Hyder were designed around this representation, so the data provided for the 2008/9 inventory were of this form. In this representation, the impact of junction delays is spread uniformly along the link, so the emissions per unit length of road may be under-represented close to the junction (with a compensating overestimation elsewhere), which needs to be borne in mind at the dispersion modelling stage.

2.147 The hourly AECOM data were supplied for two vehicle categories, LDV (Light Duty Vehicles) and HDV (Heavy Duty Vehicles). The LDV category includes cars and Light Goods Vehicles (goods vehicles with a gross weight of less than 3.5 tonne); the HDV category includes Heavy Goods Vehicles (gross weight > 3.5 tonne) and buses/coaches. The emission factor database has separate factors for finer sub-divisions of these two broad vehicle categories, and there can be quite substantial differences in factors from one sub-category to another. Thus it is necessary to supplement the traffic model output with additional data or assumptions to estimate the sub-category proportions within the LDV and HDV categories.

2.148 The assignment of sub-category proportions was carried out in two steps. First, it was noted that the SATURN modelling had been carried out for more 'User Classes' than just LDV and HDV but the finer detail had not been retained in the post-processing step of generating data for each traffic hour (i.e. hour of the weekday and weekend).This more detailed information allowed a distinction to be made between car and LGV (for the LDV category) and between HGV and buses/coaches (for the HDV category) on a link-by-link basis, for the three representative model hours. The relative proportions of the sub-categories for each traffic hour was thence derived by associating each of the traffic hours with one of the three model hours: hours 7 am to 10 am (3 hours) were assigned the relative proportions of the morning peak hour; hours 4 pm to 7 pm (3 hours) were assigned the relative proportions of the afternoon peak hour and all other hours were assigned the relative proportions of the inter-peak hour.

2.149 This process, therefore, generated link-by-link traffic data for four vehicles classes, termed below the 'traffic' categories, namely cars, LGVs, HGVs and buses/coaches. Further sub-divisions of these categories are discussed in the following section on emission factors.

Emission Factors

Exhaust Emission Factors

2.150 A new set of emission factors has recently been compiled by TRL[40] and, after a period of consultation, has been released by the DfT[41] for use in quantifying road vehicle emissions at both the national and local level. This set (referred to below as TRL2009) contains separate speed-related emission factors for more vehicle categories than in previous datasets, including a sub-division of HGVs, buses and coaches by weight category, an additional sub-division of LGVs (by weight category), the introduction of a 'large' car/minibus category and the recognition of taxis as a separate category.

2.151 Accompanying the new emission factors, the NAEI (National Atmospheric Emissions Inventory) team has generated a new set of 'fleet projections' (relative number of vehicle-km travelled by sub-categories of vehicle type recognised in the TRL2009 emission factor data set), referred to below as FP2009[42]. TRL2009 is based on 2007 licensing data. For cars, the fleet proportions are based on national statistical data whereas for LGV, HGV and buses separate sets of proportions are given for within-London and outside-London areas, with the former sets including the effects of the London LEZ (Low Emission Zone)*. For 2008/9, however, the within-London LGV and outside-London LGV proportions do not differ, with differences arising only in later years.

2.152 The FP2009 data set has been used in the Heathrow 2008/9 inventory to further subdivide the four traffic categories introduced earlier into the finer categories for which separate emission factors are given in the TRL2009 emission factor set. There is an implicit assumption that relative proportions within a given traffic category are much the same around Heathrow as they are for national traffic (for cars) or for London traffic (for LGVs and HDVs).

2.153 A key sub-categorisation relates to the Euro standard to which vehicles conform. FP2009 gives the relative proportions by Euro standard separately for the following vehicle categories (termed 'Euro-proportion categories' below for convenience):

* For 2008/9, the impact of LEZ Phases 1 and 2 will be included.

- petrol cars;
- diesel cars;
- petrol LGVs;
- diesel LGVs;
- rigid HGVs;
- articulated HGVs; and
- buses and coaches.

The distribution of Euro standards for each of these categories evolves from year to year as vehicles conforming to later standards penetrate the fleet and vehicles conforming to earlier standards are scrapped. The relevant distributions for the 2008/9 period are shown in Table 2.20, formed by taking a weighted average of the FP2009 distributions for 2008 and 2009 (with weighting factors 0.75 and 0.25 respectively). For LGVs and HGVs, where Euro distributions are given separately for 'London' and 'outside London', the 'London' distribution was chosen for the area around Heathrow (based on guidance from the NAEI team), except for traffic on, and outside, the M25. For buses, however, the distribution given for 'outside London, but entering London' was considered more appropriate.

2.154 For Euro 3 and Euro 4 diesel cars, vehicles with/without a Diesel Particulate Filter (DPF) are recognised separately in FP2009, but do not correspond to separate categories in TRL2009. For pollutants other than PM it is assumed that emission factors are the same for the with/without DPF categories. For PM, the TRL2009 emission factors were assumed to apply to 'without DPF' vehicles and for 'with DPF' vehicles a 90% reduction on the 'without DPF' values was assumed, on advice from the NAEI team.

2.155 For petrol cars and LGVs, Table 2.20 shows for each Euro standard the estimated fraction of vehicle-km travelled by cars of that standard with failed catalysts (before being replaced at the next MOT test). The relative fraction increases with vehicle age and is correspondingly greater for lower Euro standards. It is assumed that petrol vehicles with a failed catalyst revert to having the corresponding Pre-Euro 1 emission factor. FP2009 also takes account of catalyst failure for Euro 5 and 6 diesel cars, but the year-of-introduction of these categories is later than 2009.

2.156 To apply these distributions of Euro standard to the four traffic categories in the network traffic data requires the following additional information:

- for cars and LGVs, the split between diesel and petrol vehicles;
- for HGVs, the split between rigid and articulated vehicles; and
- for cars, the split between taxis (black cabs) and other cars.

2.157 The splits between petrol/diesel cars, between petrol/diesel LGVs and between rigid and articulated HGVs are provided within the FP2009 data package as a function of year and road type, with the latter distinguishing urban roads, rural roads and motorways. Separate 'London' and 'outside London' splits are given, and the 'London' splits were chosen for the Heathrow area. The relevant fractions for 2008/9 (formed from the 2008 and 2009 distributions, as explained earlier) are given in Table 2.21. It is assumed that these splits are independent of Euro standard. The splits are applied to the AECOM traffic data by assigning each link of the network to one of the three road types, using ancillary information supplied by AECOM.

2.158 The FP2009 data package provides information to enable a black cab fraction to be distinguished within the 'car' category for London urban roads. This is an average value for London, whereas more detailed data show a significant gradient in this fraction between inner and outer London. The fraction of black cabs on the road network in the immediate vicinity of Heathrow is unlikely to be typical of either central London or outer London, with Heathrow acting as a focus for black cabs used by air passengers. In the absence of Heathrow-specific information, the London-average fraction (for 2008/9) was used for the whole road-network area, as shown in Table 2.21.

2.159 Although the seven Euro-proportion categories listed above represent the most detailed level of traffic breakdown for which separate Euro-standard distributions are given, the emission-factor database has separate factors for a number of subdivisions of these categories. The relevant subdivisions and relative proportions are discussed below, with the tacit assumption made that the Euro-standard distribution is the same for all subdivisions of a given Euro-proportion category[*].

2.160 For the TRL2009 'car' category (which includes minibuses), a new sub-categorisation has been introduced in terms of vehicle weight, separating cars/minibuses of less than 2.5 tonne from cars/minibuses in the weight range 2.5 tonnes to 3.5 tonnes. However, the current version of FP2009 recommends that all cars are treated as < 2.5 tonne until more detailed data become available. Within this weight range, three categories of engine size are distinguished: less than 1400 cc; between 1400 cc and 2000 cc; and greater than 2000 cc. FP2000 gives the relative proportions of these three engine-size categories separately for petrol and diesel cars, as shown in Table 2.22, with the assumption that the proportions are independent of year (and road type).

2.161 For LGVs, TRL2009 recognises three weight classes as used in the type-approval process:

- N1(I) – less than 1305 kg;
- N1(II) - between 1305 kg and 1760 kg; and
- N1(III) - greater than 1760 kg.

Emission factors for the N1(I) weight class are assumed to be the same as for cars in the < 2.5 tonne weight class, <1400 cc engine-size class. FP2009 gives the relative proportions of these three weight classes in the national LGV fleet, with proportions 6%, 26% and 68% for N1(I), N1(II) and N1(III) respectively for both petrol and diesel LGVs, as shown in Table 2.22. These proportion are assumed independent of year and road type.

2.162 For HGVs, TRL2009 gives emission factors separately for a number of vehicle weight categories. Correspondingly, FP2009 gives the relative proportions by weight class separately for rigid and articulated HGVs for each of the three road type classes, based on national data, as shown in Table 2.22. These proportions are assumed independent of year.

2.163 For the bus/coach Euro-standard category, TRL 2009 gives separate emission factors for buses and coaches and, for each, distinguishes a number of weight categories. The national vehicle-km data on which to base estimates of the relative proportions of the sub-categories is relatively sparse at present, but FP2009 makes interim recommendations. For the bus/coach split, the recommendation is that for motorways all vehicles in this category are treated as coaches from the perspective of TRL2009, and for non-motorway roads a 72%/28% bus/coach split is recommended. The recommended distribution by weight class is given in Table 2.22, separately for buses and coaches. These interim weight distributions are assumed independent of year and road type.

2.164 Accompanying the TRL2009 set of emission factors is a set of correction scaling factors (of order unity) to account for deterioration in average emissions performance with increased mileage and for the evolution in fuel composition standards over time. In principle the mileage scaling factors can be applied for particular mileage estimates if these are available, but in general they are applied using average mileage estimates for each vehicle category in the TRL2009 data set. Special provision has to be made in relation to mileage scaling factors for vehicles with failed catalysts: although these vehicles are assigned Pre-Euro 1 emission factors, they will have covered on average lower mileage than vehicles manufactured as Pre-Euro 1 vehicles, and a corresponding adjustment was made to the mileage scaling factor.

2.165 In terms of pollutants, the TRL2009 data set gives emission factors for total particulate matter, but also provides an ancillary table specifying the fraction of total particulate mass that lies within the PM_{10} or $PM_{2.5}$ size ranges, separately for petrol and diesel cars and LDVs, based on measurements made on Euro 2 and 3 vehicles. However, the main text

[*] With the exception of the N1(I) LGV weight band, for which FP2009 recommends the Euro-standard distribution for cars is used.

recommends that the fraction should taken as unity for both PM_{10} and $PM_{2.5}$ because of the limited data available. Further dialogue between TRL and the NAEI teams subsequent to the publication of TRL2009 has decided on a factor of 0.95[43] for the $PM_{2.5}$ fraction (for all petrol and diesel vehicles); PM_{10} has been taken as 98% of PM for petrol vehicles and 92% for diesel vehicles, in line with the table in TRL2009.

2.166 According to the above procedures, the partitioning of traffic flows for the four traffic categories for which link-by-link flow data are available (car, LGV, HGV, buses/coaches) amongst sub-categories with separate emission factors varies from link to link only by virtue of the difference in road type (and even this variation is absent for LGVs). Thus, emission factors can be most conveniently presented as composite speed-emission curves for the four traffic categories for 2008/9 for each of the 3 pollutants of interest. These are shown in Figs 2.6 (a) to Fig 2.6(l). Separate curves are required for each road type for cars (because the petrol/diesel split in the national data depends on road type), for HGVs (because the rigid/articulated split and breakdown by weight depend on road type) and for buses/coaches (because the bus/coach split depends on road type). Where applicable, the curves are shown separately for ‘London’ and ‘outside London’.

Fugitive PM Emission Factors

2.167 Three sources of fugitive PM_{10} and $PM_{2.5}$ emissions from road vehicles have been included in the inventory: brake dust; tyre wear; and re-suspended road dusts. Emission factors (in g/km) for brake and tyre wear have been revised since the original 2002 inventory and are now based on the latest methodology used in the NAEI, which is described in the AQEG (Air Quality Expert Group) report on particles[44]. The revised methodology draws on a review of brake and tyre wear carried out for the UNECE (United Nations Economic Commission for Europe), which has informed the methodology included in the recent versions of the EMEP/CORINAIR Emission Inventory Guidebook[35]. Despite the revisions to the methodology, large uncertainties in the emission factors remain.

2.168 For both tyre and brake wear, the revised methodology gives separate factors for passenger cars, LGV and HGV, as shown in Table 2.23. The factors are all speed-dependent, in contrast to the constant values in the previous methodology. For tyre wear, the values shown in Table 2.23 apply at a speed of 80 kph; the factors increase linearly with decreasing speed to a value 1.39 times higher than the 80 kph value at a speed of 40 kph, below which they remain constant. Similarly, the factors decrease linearly with increasing speed to a value of 0.902 times the 80 kph value at 90 kph, above which they remain constant. For brake wear, the values in the table apply at a speed of 65 kph; the factors increase linearly with decreasing speed to a value of 1.67 times higher than the 65 kph value at a speed of 40 kph, below which they remain constant. Similarly, the factors decrease linearly with increasing speed to a value of 0.185 times the 65 kph value at a speed of 95 kph, above which they remain constant.

2.169 In the revised methodology, HGV emission factors have a dependence on vehicle loading and, for tyre wear, are linearly proportional to the number of axles on the vehicle. In the absence of data on vehicle loading, the UNECE report recommends using the values for 50% loading, which are the values quoted in Table 2.23. The dependence on number of axles has been taken into account by using a weighted-average number of axles, with the weighting factor given by the relative number of vehicle-km travelled nationally by vehicles with the given number of axles, as given in national transport statistics*. The HGV emission factors then become road-class dependent, as shown in Table 2.23, because the weighted-average number of axles is road-type dependent. Buses were assigned the same average of number of axles as rigid HGVs (and 50% load).

2.170 As can be seen by comparison between Table 2.23 and the PM_{10} exhaust speed-emission curves, the combined fugitive emissions factors for brake and tyre wear are comparable to or greater than those from exhaust emissions.

* The distribution of number of axles by vehicle-km was given in a supplementary spreadsheet released by the DfT alongside the TRL2009 data set, namely ‘hgvfleetproportions.xls’, This distribution has been held fixed although it will vary slightly from year to year.

2.171 There are even larger uncertainties surrounding the contribution to PM_{10} and $PM_{2.5}$ emissions from traffic-induced re-suspension of particulate matter, and this contribution is usually not included in national PM emission inventories. However, the NAEI contains a PM_{10} emission factor of 0.04 g/km, also noted in the AQEG report[44], as applicable to the current UK mix of vehicle types. This value has been used in the current assessment, although the AQEG report on particles sounds a note of caution that accounting for re-suspended particles explicitly in this way may include some double counting of contributions already included elsewhere. From Table 2.23, it is clear that this factor is comparable to the combined PM_{10} factors for brake and tyre wear, so is not an insignificant addition. There is little specific information on the $PM_{2.5}/PM_{10}$ ratio for traffic-induced re-suspension in the UK, and a value of 0.5 was taken after discussions with experts in the NAEI. This value is judged more likely to overestimate than underestimate $PM_{2.5}$ emissions from this source.

Additional Emissions from Car Parks and Taxi Queues

2.172 Most of the emissions from vehicles on the landside road network are included via the methodology outlined above, based on traffic flow and speed delay data obtained from the traffic model. However, there are some additional sources of landside vehicle emissions not accounted for by that methodology, principally related to car parking on the airport.

2.173 The NAEI emission factor database[37] contains data on ‘cold starts’ for cars and LGVs, expressed as a quantity of pollutant per trip. This represents the additional (integrated) amount of pollutant generated near the start of a trip, incurred during the period when the engine (and catalyst if fitted) has not yet reached its normal operating temperature range; this is particularly significant for catalyst-equipped vehicles. There are currently no cold start emission factors for HGVs. Updated cold start emission factors have not yet been issued as part of the TRL2009 set of emission factors discussed earlier in the relation to road vehicle emissions on the landside road network, so the earlier set of factors have been retained.

2.174 Vehicles starting from cold that are leaving the airport are assumed to have parked somewhere on the airport, and the estimates of associated cold-start emissions are based on parking transaction information (including car rental and taxis in the taxi feeder park). An estimate of the annual cold-start emissions (g/year) for a given car park for a given vehicle category is derived as the product of the number of cars in that category parking (/year) and the emissions per cold start (g/start) for the vehicle category. It is assumed that all vehicles park long enough for the full cold-start ‘penalty’ to be incurred when they leave.

2.175 Also, there are additional emissions associated with vehicles finding a parking space on entry to the car park (or rental pound) and driving to the exit on departure. An estimate of the annual emissions (g/year) from a given vehicle category in a given car park is derived as the product of the number of cars parking in that car park (/year), the average distance (km) travelled within the parking area and the emission factor (at an appropriate speed) for that vehicle category (g/km).

2.176 There are additional sources of emissions from taxi waiting in the taxi feeder park (TFP) and taxis queuing at the terminal forecourts.

Cold Start Emissions

2.177 For public car parking, BAA provided data for 15 car parks marked on Fig 3.6. This data set gave the number of cars entering and leaving in each 15-minute period throughout each day of the 12-month period. This yields the total number of cars parking in the year in each car park, as given in Table 2.24. In total there were 8.60 million parking transactions in public car parks in the 2008/9 period, compared to 8.03 million in 2002. BAA also provided monthly data on car rentals for Jan-Sep 2009, by rental pound, which were scaled up to give the 12-month values shown in Table 2.24.

2.178 For staff parking, BAA provided data for 10 staff car parks marked on Fig 3.6, giving the total number of parking vehicles in the 12-month period of interest, as shown in Fig 2.24. The total number of parking vehicles in the period was 3.93 million, compared to 3.51 million in 2002.

2.179 All vehicles in car parks and rental pounds were assumed to be passenger cars. For NO_x and PM_{10}, cold start emission factors[37] are provided separately by the NAEI for diesel and petrol cars, as weighted averages over the distribution of engine technologies in the national fleet of that car type. The NAEI factors are based on an average trip length of 8.4 km, which is generally long enough for most of the potential excess emissions associated with given starting conditions to have arisen before the end of the trip. In using these factors for car parking at Heathrow, it is tacitly assumed that trips from Heathrow are also generally long enough for the engine to reach normal operating conditions before the end of the trip.

2.180 The fleet-weighted cold-start factors vary with year as the distribution of engine technologies changes over time, and a weighted-average value for 2008/9 was used (with 2008 given a weight of 0.75 and 2009 given a weight of 0.25), shown in Table 2.25. The fraction of diesel vehicles in the car fleet was taken to be the corresponding weighted-average of the values for 2008 and 2009, as given in the latest (FP2009) fleet fraction data (discussed earlier in the section on network road vehicle emissions), choosing the values for London urban roads. The $PM_{2.5}/PM_{10}$ fractions for emissions during cold running were assumed to be the same as for hot running, as discussed earlier.

Additional Distance Travelled in Car Parks

2.181 To calculate the annual total additional distance travelled within a car park or rental pound (vehicle-km/year), the number of parking cars (vehicles/year) was multiplied by an average distance of travel (km). Approximate estimates of the average distances travelled are shown in Tables 2.24, based on the physical size of the car park or car-rental pound, with an allowance for whether or not it is multi-storey.

2.182 Vehicles travel at relatively low speeds within the car parking areas, with significant amounts of acceleration and deceleration, and it was judged that the NAEI emission factors (g/vehicle-km) for a speed of 16 kph (10 mph) would be appropriate to this low speed running. Fleet-averaged values for 2008/9 (with values for the two years weighted by relative number of months, as described above for cold start emission factors) are given in Table 2.26, using the TRL2009 and FP2009 datasets discussed earlier.

Taxis

2.183 BAA provided data on the total number of taxis passing through the Taxi Feeder Park (TFP) in the 2008/9 inventory period. The length of wait in the TFP is highly variable, but it was assumed that all vehicles switch off for long enough to incur the full cold start penalty; cold start emission factors for diesel cars were used to estimate this contribution, as shown in Table 2.25. Emissions from travelling within the feeder park were based on the physical size of the park and assuming low-speed travel (16 kph), as described above for car parks. The TRL2009 emission factor data set contains separate emission factors for black cabs, which were applied to taxis at Heathrow. Similarly, the FP2009 fleet composition data gives a separate Euro-standard distribution for black cabs as a function of year. The resulting emission factors (g/km) appropriate to 2008/9 are shown in Table 2.26.

2.184 Taxis spend some time queuing on the terminal forecourts before picking up a fare. An estimate of the associated emissions (g/year) at a given forecourt was calculated as the product of the total number of taxis passing through the forecourts (/year), the average time spent queuing (s) and a queuing emission rate (g/s). It has been assumed that taxis leave their engines running for the whole of the queuing time. A queuing emission rate for taxis was derived in the manner similar to that described earlier for queuing at junctions, based on the emission factor for black cabs at the lowest speed (5 kph) on the relevant speed-emission curve, leading to the value shown in Table 2.27. No new information on average time spent queuing was available, and the earlier estimate of 7 minutes was retained.

Fugitive PM_{10} and $PM_{2.5}$ Emissions

2.185 Fugitive PM_{10} and $PM_{2.5}$ emissions arise from the additional distances travelled within car parks and the TFP. The emission factors (g/km) for brake wear, tyre wear and re-suspended road dust are discussed above in the section on landside road vehicle emissions and the appropriate distances travelled (km) have been discussed above in the context of exhaust emissions. It should be noted that the 2002 inventory used an earlier methodology (which was not updated for the PSDH revision of the 2002 inventory).

Heating Plant Emissions

2.186 Emissions from a given heating plant (g/year) were calculated as the product of the total amount of fuel used, expressed as the energy equivalent of the fuel in MJ/year, and an emission factor (g/MJ).

Fuel Used

2.187 Three types of data were supplied on fuel consumption in heating plant in 2008/9: monthly data for plant using gas as principal fuel (with gasoil as a backup fuel in some cases), with values derived from meter readings; monthly data on gasoil usage derived from information on the fuel ordered for each of a number of tanks supplying gasoil-fuelled facilities; and BA fuel usage supplied separately by BA rather than by BAA (who supplied the first two types of data).

2.188 The major (non-BA) plant on the airport fuelled by gas are the CHP, (building) 448, T5 and T4, although there are other smaller gas-fired plant. The breakdown of gas usage by facility supplied by BAA gave directly the gas use in the (Cargo) CHP and T5, but provided only a total value for the remaining plant. Ancillary data enabled the relative proportion of gas used in T4 and 448 by month to be estimated, and all gas other than that used in the CHP and T5 was split between 448 and T4 in this proportion. Although this procedure will count the gas usage from small plant in the 448 and T4 totals, this is a minor approximation judging from past information on the gas usage in the smaller plant. In terms of dispersion modelling, only the major plant are modelled explicitly, but the above procedure ensures that all the emissions are accounted for in one or other of the modelled sources.

2.189 The CHP also used a small amount of gasoil in 2008/9. For the other plant using gasoil, the quantity of fuel consumed in 2008/9 was estimated from records of fuel ordered on a monthly basis for each of a number of named tanks on the airport. The amount ordered can be equated to amount used on the grounds that the tanks tend to be filled to a fixed level.

2.190 In relation to BA energy usage, the 2002 inventory was based on data compiled for the UK Emissions Trading Scheme operating at the time. Equivalent 2008/9 data compiled for the EU Emissions Trading Scheme was made available by BA for the 2008/9 inventory. The data were provided in the form of CO_2 estimates for each of a number of named plant, but these were readily converted into amounts of fuel used, knowing the type of fuel used in each plant. By far the largest quantity of fuel used by BA (over 90%) was in the maintenance area, and only this BA plant was included explicitly in the dispersion modelling.

2.191 Table 2.28 gives the annual fuel energy input for each plant in 2008/9, expressed in MJ/year, with the total over all plant amounting to 2.75 10^9 MJ/year. This can be compared to the total of 2.21 10^9 MJ/year in 2002, representing an increase of 24% from 2002 to 2008/9. A major component of the increase derives from gas usage in the Cargo CHP, which has increased by 20% (presumably because it now supplies part of T5's energy requirements), but there are also apparent increases in the BA gas consumption. The overall increase may not reflect a genuine increase in the total energy input into heating plant between 2002 and 2008/9, with at least some of the difference possibly resulting from the different process by which the total was derived from available records for the two 12-month periods.

Emission Factors

2.192 For the PSDH work[45], NO_x emission factors were derived from efflux concentrations measured in 2005, whereas PM_{10} emission factors were based on older measurements (at the detection limit) used in the 2002 emission inventory. Although some more recent stack monitoring data were made available by BAA for the 2008/9 inventory, the information provided was not sufficient to derive updated emission factors in g/MJ. However, the stack concentrations in the later measurements were comparable with those from the 2005 measurements, so the previous factors were retained. These plant-specific factors are typically around 3-4 times lower than the default emission factors given in the NAEI for the category 'other industrial combustion', which includes large boilers (see below).

2.193 For T5, NO_x emission factors were based on the efflux concentration limits specified in the PPC (Pollution Prevention and Control) permit to operate; in the absence of an equivalent limit for PM_{10}, a generic emission factor for the relevant type of plant was taken from the NAEI.

2.194 For the Cargo CHP, the NO_x emission factor used in the 2002 inventory for gas firing was derived from measured stack concentrations. No new stack concentration data were available for the 2008/9 inventory, and it was assumed that the emission factor used previously would still apply. There are no NO_x measurement data available for gasoil firing (which accounts for a small fraction of the fuel energy input) and no PM_{10} measurements for either fuel, so default emission factors were taken from the US EPA compilation AP-42[46] for uncontrolled gas turbines*. It is worth noting that the NO_x emission factor used for gas firing of the CHP is about one half of the value given in AP-42 for uncontrolled gas turbines.

2.195 No NO_x or PM stack emission measurement data were available for the BA boilers, so default emission factors (in g/MJ) for NO_x and PM_{10} were taken from the NAEI (UK Emission Factor Database)[47]. Separate emission factors are given there for various categories of fuel usage: for natural gas burning in boilers, the category 'other industrial combustion – natural gas' was selected. It should be noted that the NO_x values given there have been revised since the 2002 and PSDH work, with the current value around 60% higher than the previous value; the corresponding PM_{10} values is around a factor of two lower.

2.196 The $PM_{2.5}/PM_{10}$ ratio for all heating plant emissions was taken as unity following advice from the NAEI.

2.197 The full set of emission factors used for heating plant are shown in Table 2.29.

Fire-Training Ground Emissions

2.198 The Fire Training Ground (FTG) is included here for the sake of completeness, although previous inventories have demonstrated that the annual emissions of the pollutants of interest from this source are very small compared to those from other airport sources.

2.199 Although there are no detailed records of the quantities of LPG used per test, estimates were provided for the 2002 inventory by the fire service at Heathrow of the approximate total volume of LPG consumed in exercises per year, given as 70,000 - 80,000 litres per year. This quantity was assumed to apply to 2008/9, with 80,000 litres used for the emissions calculations

2.200 LPG is usually a mixture of butane and propane predominantly, of varying proportions depending on the origin, but the emission factor data available are not detailed enough to vary with composition. There are no emission factors specific to the type of operation at the FTG, but it was judged that the NO_x and PM_{10}† emission factors from AP-42[48] for the burning of LPG in commercial boilers (0.1 to 3.0 MW) would be reasonably appropriate.

* For NO_x, AP-42 gives values both for uncontrolled and for water-injected turbines of a type similar to that at Heathrow. However, for reasons explained in the 2002 inventory report, the value for uncontrolled turbines was preferred. (For PM_{10}, no value is quoted in AP-42 for water-injected turbines.)
† The AP-42 value applies to 'filterable particulate matter', which is assumed to be all PM_{10}.

These are shown in Table 2.30; the factors are generally within a factor of 2 of the values in the NAEI for both domestic burning of LPG and for general industrial burning of LPG.

2.201 There are no specific data on the $PM_{2.5}/PM_{10}$ ratio for LPG burned in this type of operation, and it was conservatively assumed that the $PM_{2.5}$ mass is equal to the PM_{10} mass. Given the extremely small PM_{10} contribution from the Fire Training Ground, this approximation has insignificant impact on the estimate of the total airport-related $PM_{2.5}$ emissions.

2.202 The emissions are not uniform over the year, but it is very unlikely that more than 10% of the annual emissions would arise in a single day. It can be confirmed from the summary emission tables (Section 5) that even on this conservative estimate the maximum daily emissions from the FTG are insignificant compared to the daily emissions from other sources of the airport, for all the pollutants of interest.

3 Spatial Representation

Overall Approach

3.1 A principal aim in compiling the above emission inventory is to provide the inputs for dispersion modelling to assess the airport contribution to ground-level pollutant concentrations on and around the airport. For this purpose, the spatial distribution of the emissions is required in addition to total quantities, and it is considered part of the inventory compilation to assign spatial distributions to the sources included.

3.2 All sources are represented using combinations of three basic configurations in plan view – point, line* or area. For points, the source is specified in terms of the co-ordinates of the point and the total annual emissions; if the point is actually representative of emissions over a small area (as, for example, in the case of emissions at a stand), a specification is given of the horizontal extent represented by the 'point'. Line sources are specified in terms of the end points of the line element, a width and the total emissions for the line element, assumed to be uniformly distributed along the line unless otherwise stated. Area sources are represented as polygons, defined in terms of the co-ordinates of the vertices, and the total emissions, assumed to be uniformly distributed over the area.

3.3 The level of detail required in the spatial distributions depends on how close to the source information on concentrations is required. Broadly speaking, the resolution adopted is intended to give adequate accuracy in the concentration field at the airport boundary, and not to give detailed concentrations close to the major sources on the airport. On the other hand, if concentrations are required only at larger distances from the sources, a coarser spatial aggregation may be appropriate.

3.4 For some sources, the methodology for calculating emissions starts from spatially disaggregated operational data so the spatial distribution of emissions emerges naturally. However, for some sources (for example airside vehicles) the methodology leads to only an estimate of total emissions, and a way of 'disaggregating' the emissions spatially has to be devised, making use of a surrogate variable. This process will be described below on a source-by-source basis.

Aircraft Exhaust Emissions

Taxiing and Hold

3.5 The taxiway system on the airport was represented by a network of nodes joined by straight-line links, as shown on Fig 3.1, so each taxiing route was expressed as a series of straight-line segments.

3.6 For 'reconciled' departures (i.e. where the APT data can be used to give flight-specific ground-movement times), both stand and hold-point identifiers were known. For the purpose of devising taxiing routes, however, taxi-out from all stands in a given stand group to a given hold point were represented by a single taxiing route, taken from a representative point within the stand group. Stand groups are shown on Fig 3.4; the stands included in each group are listed in Table A2.1 of Appendix 2. Taxi-out emissions assigned to a given taxi-out route were then distributed uniformly along the route. The width of the emissions source (across the taxiway) is set by the distance between engines, in accord with the modelling procedures in ADMS-Airport.

3.7 For non-reconciled flights, hold point is not known – it is not recorded in BOSS – and, as described in Appendix 2, when calculating total taxi-out emissions the flight was assigned the mean time (derived from the data for reconciled flights) taken over all pertinent hold

* 'Point' and 'line' in this context are indicative of source shape in plan view, and do not imply zero size or width.

points for the appropriate aircraft type category, stand group and runway direction. For the spatial representation, however, taxi-out emissions for the flight were partitioned amongst the routes to each of the pertinent hold points, with a weighting determined jointly by the relative frequency of hold point usage and the relative mean taxi-out time for the hold point, both derived from the data for reconciled flights (for the appropriate aircraft type, stand group and runway direction). Effectively, therefore, each non-reconciled departure was split probabilistically into several pseudo-departures corresponding to the pertinent hold points (and thence runway entry blocks), with the 'weights' assigned to the pseudo-departures summing to unity. This procedure will give a realistic spatial distribution of emissions from non-reconciled flights when averaged over a sufficient number of departures.

3.8 This partitioning for non-reconciled departures also serves to assign runway turn-on block and thence start-of-roll position, which is a key parameter in the spatial representation of roll emissions.

3.9 A similar approach was used for taxi-in emissions. Taxi-in routes were devised for each relevant runway exit/stand group pair (see Fig 3.1). For reconciled arrivals, both runway exit and stand group are known, so the emissions were readily assigned to a route; emissions were distributed uniformly along the route. For non-reconciled arrivals, exit is not known, and in calculating total taxi-in emissions the flight was assigned the mean time taken over all pertinent exits for the appropriate aircraft type category, stand group and runway direction. For the spatial representation, however, taxi-in emissions were partitioned amongst the routes from each of the pertinent exits, with a weighting determined jointly by the relative exit frequency and the relative mean taxi-in time from the exit, both derived from the data for reconciled flights (for the appropriate aircraft type, stand group and runway direction). Effectively, therefore, each non-reconciled arrival is split probabilistically into several pseudo-arrivals corresponding to the pertinent exits. This procedure will give a realistic spatial distribution of emissions for non-reconciled flights when averaged over a sufficient number of arrivals.

3.10 Similarly, hold point is known for reconciled departures, so hold emissions were readily assigned spatially. Holding emissions for a given hold point were assigned to a short line source close to where aircraft would join the runway from that hold point, as marked on Fig 3.2. For non-reconciled departures, hold point is not known and in calculating total hold emissions* the departure was assigned the mean time (from reconciled flights) taken over all pertinent hold points, for the relevant values of the other dependent variables. For the spatial representation, however, hold emissions for the flight were partitioned amongst the pertinent hold points, with a weighting determined jointly by the relative hold-point frequency and the relative mean hold-point time, both derived from the data for reconciled flights (for the relevant values of the other dependent variables).

Take-Off Roll and Landing Roll

3.11 Take-off roll emissions for a given flight were distributed along the runway between a start-of-roll point and a wheels-off point. Prior to the PSDH work, the total roll length and the spatial distribution of the emissions along the roll were worked out by assuming uniform acceleration from a standing start to wheels off at speed VR and assuming a constant emission rate. However, as a result of engine spool-up and the forward–speed effect (see Section 2), the acceleration is not constant in practice, and this is taken into account in spatially distributing the roll emissions. In addition, engine spool-up and the forward-speed effect lead to NO_x emission rates that vary along the roll (with the detailed variation depending on aircraft engine type).

3.12 For the PSDH, QinetiQ provided a 'universal' speed curve expressing speed as a fraction of VR (speed at aircraft rotation – taken to be an adequate surrogate for lift-off speed) as a function of time expressed as a fraction of total roll time. This curve, being based on actual data, will include the influence of spool-up in the early part of the roll and the changes to thrust and drag (and thence acceleration) as the aircraft picks up speed. Of course, actual speed curves, suitably normalised, show some scatter about the universal curve but the

* For convenience, the three components of hold are not separated out in this discussion.

curve is judged an adequate representation of speed versus time for the purpose of spatially distributing emissions. For ease of use, QinetiQ represented the curve in analytic form:

$$V/VR = (At_r^2 + Bt_r + C)(D\tanh(Et_r + F) + G)$$

where t_r is the ratio of time since start-of-roll to total roll time, *tanh* is the hyperbolic tangent function and *A*-*G* are constants provided by QinetiQ, with the following values:

A= -0.232; *B*=1.061; *C*=0.0148; *D*=0.799; *E*=3.142; *F*=-0.251; *G*=0.394

The shape of the universal speed curve is shown in Fig 3.3.

3.13 The impact of engine spool-up and the forward-speed effect on NO_x emission rates has been discussed in Section 2. For the PSDH, QinetiQ provided normalised $E(t_r)$ curves for a large number of specific engines (including the main types operated at LHR in 2008/9), together with a default curve for engines not explicitly included, where *E* is the NO_x emission rate expressed as a fraction of the static emission rate at the selected take-off thrust and t_r is the normalised time from start-of-roll. QinetiQ licensed AEA to use these curves for the 2008/9 LHR emission inventory, but the detailed coefficients of the $E(t_r)$ curves cannot be given here for commercial reasons. Using the universal speed curve, emissions per unit distance along the roll can be derived from emissions per unit time along the roll.

3.14 Engine type has been assigned to all flights in the BOSS database for the inventory period (as described in Section 2), and roll time is known on a flight-by-flight basis for reconciled departures. For the latter, therefore, the spatial distribution of the roll emissions is readily derived from the flight-specific roll time and the engine-specific *E(t)* curve, coupled with the universal speed curve. Although the spatial distribution of the roll emissions varies in principle on a flight-by-flight basis, at the dispersion-modelling stage roll times for a given aircraft type are grouped into roll-time categories, with a representative spatial distribution used for each category.

3.15 For non-reconciled departures, the total roll emissions for a given flight have been calculated using the mean roll time over all relevant start-of-roll blocks (corresponding to the various hold points), for the pertinent aircraft type and stand group, as described in Appendix 2. For the purpose of spatial representation, however, the roll emissions from non-reconciled departures were partitioned amongst the appropriate start-of-roll blocks, with the share for a given block proportional to the product of the corresponding hold point probability and the mean roll time. Start-of-roll points are marked on Fig 3.2.

3.16 Similarly, for reconciled arrivals, runway exit is known, and landing-roll emissions were distributed uniformly between the touchdown point and runway exit. For non-reconciled arrivals, runway exit is not known and, as explained above for taxi-in emissions, each arrival was effectively split into several pseudo-arrivals corresponding to the pertinent exits, with an appropriate weighting factor assigned to each arrival (normalised so that the sum over all weights equals unity). Again, the landing roll emissions associated with each exit were distributed uniformly between touchdown and exit. The use of a uniform distribution is clearly an approximation, given that aircraft are decelerating and may apply reverse thrust (above idle) for part of the roll, but the approximation is judged adequate given the magnitude of landing-roll contribution to total ground level aircraft emissions.

3.17 The width of the emissions source (across the runway) is set by the distance between engines, in accord with the modelling procedures in ADMS-Airport.

Initial Climb, Climb-Out and Approach

3.18 As described in Section 2, the time to reach cut-back height and the time from cut-back to 1000 m were derived from NTK data, in order to calculate emissions for the initial-climb and climb-out phases. This analysis also provides a means of estimating average climb angles during the initial-climb and climb-out phases, as a function of aircraft type category. In practice, only emissions up to 1000 ft (305 m) are included in the dispersion modelling

3.19 The analysis of times described in Section 2 gives the horizontal speed at first squawk and the average acceleration from first squawk to 1000 m. If the cut-back height is below the first squawk, the distance to cut-back is worked out assuming uniform acceleration between lift-off and first squawk, together with uniform vertical velocity. If the first squawk is below cut-back, the distance to cut-back is worked out using the calculated speed-time curve to carry out the interpolation of horizontal distance between the two data points bracketing the specified cut-back height, assuming constant vertical velocity between the points.

3.20 For the dispersion modelling, the take-off profile up to 305 m height was stylised as a straight-line segment from the end of roll to cut-back, using the location worked out above (together with the lift-off point) to give the angle of inclination of each segment. Take-off tracks were assumed to continue in the direction of the runway at least up to 305 m height. The average angles by aircraft type category are shown in Table 3.1.

3.21 Approach emissions were represented as two co-linear line segments (from 1000 m height to 610 m height then from 610 m height to threshold) at 3° to the horizontal and aligned with the runway. The total emissions for each segment (as worked out using the methodology described in Section 2) were distributed uniformly along the corresponding line segment. However, only emissions in the lower segment (below 610 m) were included in the dispersion modelling.

APU Emissions

3.22 APU emissions were calculated separately for each stand, given that the BOSS database includes flight-by-flight stand assignment, so a ‘point’ source (in practice a 50 m area source) was located at each stand. The locations of the stands are marked on Fig 3.4 and the assignment of stands to groups is shown in Table A2.1.

Engine Testing

3.23 Information on the location of tests was provided for tests in the night but not in the day (other than for a split between BA maintenance area and elsewhere). The emissions from all tests were spatially distributed in line the spatial distribution of night time tests. Fig 3.5 shows the areas over which engine testing emissions were distributed.

Aircraft Brake and Tyre Wear PM Emissions

3.24 Aircraft tyre-wear PM emissions were distributed over the touch-down zone, whereas brake-wear PM emissions were distributed uniformly between touch-down and runway exit.

Airside Support Vehicles

3.25 Airside vehicle emission were assigned to stands in proportion to the 'airside activity' at the stands. To calculate airside activity, each aircraft movement was assigned a 'weight' to represent its contribution to airside activity in terms of demand for airside services. The weighting factor was taken to be the maximum take-off weight (MTOW) for the aircraft, as given in the BOSS database. Emissions associated with a stand were assigned to a 'point' (i.e. 50m area) source at the stand. It is an approximation to assume that all airside vehicle emissions are distributed in this manner, bearing in mind the emissions from vehicles travelling to/from the stands from other parts of the airfield. However, the impact of the approximation is expected to be small beyond the airport perimeter.

Landside Road Network Emissions

3.26 Emissions on the landside road network were calculated on a link-by-link basis (see Section 2), and the emissions on a given link were spread uniformly along the link. Road links were assigned a width corresponding to the number of carriageways.

Car Parks, Taxi Feeder Park and Terminal Forecourts

3.27 Emissions arising from the extra distance travelled in a car park, car rental pound or in the Taxi Feeder Park were distributed uniformly over a polygonal shape approximately representing the boundary of the facility on the airport layout. These areas are marked on Fig 3.6.

3.28 In past LHR inventories, cold-start emissions arising within a parking area have also been assigned to the area, albeit noting that in fact the emissions typically arise over a few km of travel. Although cold-start emissions make a relatively small contribution to total ground-level airport emissions for NO_x and PM, the simple procedure underestimates the emissions on links of the network leading away from the airport out to distances of a few km, with these links having the potential to be closer to residential population than the airport car parks. For the 2008/9 inventory, a revised representation of cold start emissions from vehicles that have parked on the airport was introduced, as follows (bearing in mind that the traffic component associated with each car park on each road link was not separately identified in the traffic data provided).

3.29 First, a fraction of the cold start emissions were assigned to the car park, as before, with the fraction given by the ratio of the estimated average distance to the exit and 2 km. The remaining total (excess) cold-start emissions from vehicles that have parked on the airport were distributed on the various links of the road network leading from car parks etc out to (but not including) the motorways in proportion to the total air-passenger vehicle-km[*] on the link. Although an approximation (partly because staff vehicle-km will have a different spatial distribution), this was judged adequate given the magnitude of the associated emissions.

3.30 Emissions from taxis queues on the forecourts were represented as line sources, as marked on Fig 3.6, and assigned a width of 5 m.

Heating Plant

3.31 As discussed in Section 2, five major gas-fuelled plant have been modelled explicitly, namely 448, T4, T5, Cargo CHP and BA Maintenance. The locations are marked on Fig 3.7.

3.32 For gasoil use (other than in the CHP), the gasoil tanks were associated with named buildings on the airport, so the emissions were assigned accordingly. The location of the plant are also marked on Fig 3.7.

[*] Although the traffic data did not separately identify airport-related from non-airport traffic in general, there was sufficient information to estimate air passenger traffic on a link-by-link basis.

4 Temporal Variation

4.1 In line with the aim of providing input to the dispersion modelling study, a temporal profile must be assigned to each source of emissions. For example, for many sources, emissions arise much less during the night than during the daytime, and this strong diurnal variation needs to be taken into account, given that meteorological conditions classified as ‘stable’ – for which ground-level concentrations from low-level emitters tend to be higher – occur less frequently during the day than in the night. Similarly mean wind speed, which also influences pollutant dispersion, may systematically differ between day and night. Similarly, there may be seasonal variations in emissions alongside seasonal trends in key meteorological parameters.

4.2 The dispersion modelling is aimed at calculating annual-mean concentrations (with shorter-period concentrations factored from the annual mean – see modelling methodology report) and the level of detail needed in the temporal profiles is judged accordingly.

Aircraft Sources

4.3 Aircraft exhaust emissions in the LTO flight phases were calculated from a flight-by-flight record, so it was straightforward to represent aircraft-related sources throughout the twelve-month period at a time resolution of one hour, which matches the temporal resolution of the meteorological data used in the dispersion modelling. Thus, the spatial distribution of emissions for each LTO mode varies from hour to hour throughout the year. This variation will automatically incorporate diurnal and seasonal changes in the number and type of aircraft movements, systematic variations in ground-movement times-in-mode[*] and the impact of diurnal and seasonal variations in ambient temperature and pressure (which affect NO_x emission rates at a given thrust now that the PSDH methodology for ambient effects – see Section 2 – has been implemented). As noted earlier, for take-off emissions it will not include any systematic variation in take-off thrust due to diurnal or seasonal variation in actual take-off weight for aircraft of a given type operated by a given airline.

4.4 The full set of hourly data is clearly too voluminous to be given in this report, but for illustration and for comparison with other temporal profiles given below, Figs 4.1 and 4.2 give some summary information. Fig 4.1 shows the hour-of-day profile of total ground-level aircraft emissions taken over the whole year and Fig 4.2 shows the monthly profile of total ground-level aircraft emissions summed over the month. The difference in the hour-of-day profiles for PM and NO_x reflects the influence of brake and tyre wear for PM, with a peak in arrivals of large (long-haul) aircraft early in the morning.

4.5 Similarly, the hourly variation of APU emissions at a stand can be derived from the record of flights using the stand. The sample of data from which APU running times were derived was not large enough to analyse for a dependence on hour of day or month of year. but any systematic variation missed as a consequence is expected to have little impact on annual-mean concentrations.

4.6 Emissions from engine testing are a small contributor, and a uniform hour-of-day profile was adopted.

Other Sources

4.7 As noted earlier, airside vehicles emissions were distributed amongst stands in proportion to the ‘airside activity’, which is derived from the breakdown of aircraft movements by stand. However, given the approximation involved in this spatial distribution, it was judged inappropriate to retain a temporal profile of airside-vehicle emissions that varied with stand.

[*] Diurnal and seasonal effects on ground-movement times-in-mode will be included automatically for flights that have been reconciled with APT records but will be averaged over for unreconciled flights (except for the hour-of-day dependence of queuing time in the holding areas).

4.8 Airside vehicle emissions, therefore, were assigned a temporal profile independent of location, with the variation determined by the summed airside 'activity' (product of movements and aircraft MTOW). Formed in this way, the temporal profile has a separate value for each hour of the year, and the data are too voluminous to be given in full here. However, Figs 4.3 and 4.4 provide two 'cross-sections' of the data, with Fig 4.3 showing relative weighting factor as a function of hour of the day, averaged over all days of the year, and Fig 4.4 shows the relative weighting factor summed over all hours of the month as a function of month of the year*.

4.9 Road vehicle emissions on the road network have been calculated separately for each hour of the weekday and weekend, and are modelled separately for each of these hours. A uniform monthly profile was assumed.

4.10 For car parking and taxi queuing, a representative diurnal profile was based on the variation of car parking transactions by hour of day, as shown in Fig 4.5. Given that the month-of-year passenger profile is fairly flat, a uniform monthly profile was used for these sources.

4.11 Fuel usage data for the major heating plant was available on a monthly basis, thereby providing the basis for assigning a monthly profile of emissions†. The diurnal profile of emissions was held constant.

* For modelling purposes, it may be judged adequate to substitute these two cross sections for the full hour-of-year profile.
† In addition, the NO_x emission factors for building 448, based measurements, distinguished summer and winter operation, although the differences turned out to be small.

5 Results and Discussion

5.1 The results are discussed below for each pollutant in turn, including a comparison with the results from the 2002 PSDH inventory[4]. The discussion focuses on total annual emissions as the best way to compare results across source categories and between inventories. Of course, for input to dispersion modelling the full set of results distributed in space and time is used.

NO_x

Emissions by Source Category

5.2 Table 5.1 gives a breakdown of the calculated annual NO_x emissions by source category. In the context of local air quality assessment, emission estimates are best viewed as intermediate results required for the modelling of airborne concentrations rather than as indicators in their own right of the comparative importance of various source categories. This is particularly true given the imposed cut-off in height (1000 m) for aircraft emissions and the truncation of the network for road vehicle emissions, which make comparisons of total emissions from aircraft and road vehicles of little value*.

5.3 Aircraft emissions at increasing height make a rapidly decreasing contribution to ground-level concentrations around the airport; similarly, road-vehicle emissions at greater distance from the airport make a decreasing contribution to ground-level concentrations around the airport. Dispersion modelling is the means by which emissions in different spatial locations are given the appropriate weight in determining concentrations at any given point, which thus makes relative concentration contribution the appropriate measure for comparing the impact of various sources.

5.4 Nevertheless, it is worthwhile to compare ground-level emissions that are localised on the airport, such as ground-level aircraft emissions and airside vehicle emissions, if the (off-airport) receptors of interest are not close to individual sources. In this case, relative annual emissions is a reasonable indicator of potential contribution to annual-mean concentration. From this viewpoint, it can be seen from Table 5.1 that ground-level aircraft emissions are much more significant than the emissions from airside vehicles, car parking and heating plant. However, the differential effect of plume rise may attenuate the relative importance of aircraft emissions for annual mean concentrations at receptors close to the airport, which will be taken into account in the dispersion modelling study.

5.5 Similarly, it is worthwhile to compare the contributions to total ground-level NO_x emissions from the various phases of the LTO cycle. As can be seen from Table 5.1, take-off roll gives the largest contribution, accounting for 44% of the total, in spite of the fact that roll times are substantially shorter than taxiing times. This results from the relatively high thrust setting on take-off, even after taking account of the thrust reductions commonly used. An increase in thrust generates a greater-than-proportional increase in NO_x emissions because it increases both the fuel flow rate and the emission index (amount of pollutant per unit amount of fuel burned). Again, however, the influence of plume rise is greater for take-off roll, as discussed in the modelling methodology report.

5.6 Taxi-out emissions are higher than taxi-in emissions, principally because taxi-out time includes pushback and any waiting time at the end of pushback†. APUs are a significant contributor to total ground-level aircraft NO_x emissions, accounting for 21% of the total, about the same as taxi-in and taxi-out combined.

* Although the 1000 m cut-off on height for aircraft emissions is arbitrary, it is certainly high enough that emissions at greater height will have an insignificant impact of ground-level concentrations. Similarly the size of the road network analysed ensures that airport-related trips at greater distance will have a small impact on concentrations in the study area.
† As noted in Section 2, it is assumed that main engines are lit at the start of pushback.

5.7 For airside vehicle emissions, road vehicles and off-road vehicles give nearly equal contributions to the total, as seen from Table 5.1. Table 5.2 gives a more detailed breakdown of the total by the major vehicle categories used in the emissions analysis. Rigid HGVs provide over half (53%) of the total for road vehicles, whereas, for off-road vehicles, the large-engine category (130-560 kW) accounts for 58% of the total.

5.8 On the road network, HDV (HGV and buses) emit about the same amount of NO_x as LDV (cars and LGV), despite HDVs accounting for a small fraction of the total vehicle-km travelled on the designated network. This reflects the much greater NO_x emission factors (g/km) for HDV compared to those for LDV (see Section 2). Table 5.3 gives the traffic average emission factor (g/km) separately for LDV and HDV, defined as the total NO_x emissions from road vehicles on the network divided by the total vehicle-km travelled on the network. The HDV factor is around 15 times higher than the LDV factor.

Comparisons with Other Inventories

5.9 Table 5.1 (final column) gives the percentage difference between the 2008/9 values and the corresponding values from the 2002 PSDH inventory. In some instances, the differences are not simply the reflection of changes in activity (aircraft movements by aircraft type, etc) between the two years, but include changes to operational parameters such as times-in-mode. These changes will be noted below, where they have a significant impact on the comparison with 2002 values.

Aircraft Emissions - Total

5.10 The estimate of total aircraft emissions, including APU and engine testing emissions, for 2008/9 is 6.8% higher for 2008/9 than for 2002. Excluding APU and engine testing emissions, the increase is 8.9%.

5.11 As noted in Section 2, the total number of passengers carried in the 12-month period increased from 63.01 mppa (million passengers per annum) in 2002 to 65.93 mppa in 2008/9, an increase of 4.6%, implying an increase in the average LTO NO_x per passenger by 2.0% (for the total including APU and engine testing emissions), from 65.8 tonnes NO_x per million passengers to 67.1 tonnes NO_x per million passengers. Excluding APU and engine testing emissions, the estimated increase is 4%. This increase in NO_x/passenger as the average size of aircraft in the fleet increases has been noted in studies at other airports (for example, Gatwick Airport[49]), but is specific to the types of engines in current aircraft fleets and may not be a feature that persists indefinitely into the future.

5.12 The total (LTO cycle) aircraft NO_x emissions at Heathrow (up to 1000 m) represent 35% of the total NO_x emission from UK aviation (Domestic and International LTO), as given in the 2008 NAEI[50]. Of course, the national and the Heathrow estimates are not independent, given that the Heathrow component of the national figure is based on operational information used in compiling a Heathrow inventory. However, the 2008 NAEI version used operational information underpinning the 2002 PSDH inventory, which has been updated in compiling the Heathrow 2008/9 inventory. The 2008/9 estimate of Heathrow total (LTO) aircraft NO_x emissions is 0.3% of the total NO_x emissions for the UK, as given in the 2008 NAEI.

5.13 It is also worth noting that the 2008/9 estimate of total (LTO) aircraft emissions is 22% lower than the equivalent value given in the PSDH forecast for 2010[4], with the major part of change resulting from fleet-mix differences.

Aircraft Emissions – Ground Level

5.14 From a local air quality perspective, ground-level emissions are much more important than elevated emissions. The estimate of ground-level aircraft NO_x emissions is 2.6% lower for 2008/9 than the equivalent value for 2002. Excluding APU and engine testing emissions, the change becomes an increase of 0.7%, showing the impact of the decrease in the estimated APU running times (discussed further below). It is clear from the last column in Table 5.1 that this small change in total ground-level (aircraft) emissions is the net effect of larger changes for the individual modes (taxiing, roll etc), both negative and positive, typically of magnitude 10-20%. The changes for the individual modes will now be discussed further.

5.15 Take-off roll is the largest contributor to ground-level aircraft NO_x emissions in the emissions breakdown given in Table 5.1, and the 2008/9 emissions estimate is 9.9% higher than the 2002 estimate. As described in Appendix 2, take-off roll times were re-calculated specifically for the 2008/9 inventory, based on flight-by-flight information derived from ground-radar data. There were no major differences between the 2008/9 times and those used for the 2002 inventory (see Appendix 2), but minor differences will have contributed to the overall difference in take-off roll emissions between 2002 and 2008/9. The remaining difference is a reflection of the (small) increase in movements and the impact of fleet-mix differences on average emission rates at high thrust.

5.16 The decrease in the estimate of taxi-out NO_x emissions, by 22%, despite an (small) increase in the number of movements, principally reflects the significant decrease in taxi-out times in 2008/9 compared to those used for the 2002 inventory (by on average about 30%), which is discussed in Appendix 2. The decrease in taxi-in times between the 2008/9 and 2002 inventories (by on average around 15%) is lower than for taxi out, which is reflected in the smaller decrease (by 11%) in total taxi-in emissions shown in Table 5.1.

5.17 The estimate of hold emissions for 2008/9 is 11.7% higher than that for 2002. The average hold time in 2008/9 was little different from (3.5% smaller than) that derived from the information used for the 2002 inventory (based on 2004/5 ground-radar data), reflecting the fact that length of the hold queue is managed by ground movement controllers. The net increase in hold emissions principally reflect the change in fleet mix between the two periods.

5.18 The estimate of landing roll (including reverse thrust) NO_x emissions for 2008/9 is 4.5% higher than that for 2002, The landing roll times for the 2008/9 inventory are on average 5% higher than those derived from the (2004/5) data set used for the 2002 inventory – see Appendix 2 – implying little additional change in emissions from fleet mix changes.

5.19 For engine testing - a small contributor to ground-level NO_x emissions - the 2008/9 estimate is 79% lower than that for 2002. However, this is more likely to reflect a change in methodology than an actual increase in emissions.

Ground-Level Emissions by Aircraft Type

5.20 Table 5.4 gives a breakdown of ground-level aircraft NO_x emissions (omitting APUs and engine testing) by aircraft type. As might be expected from the movement breakdown (Table 2.1), A319/320/321 aircraft account for a significant fraction of the NO_x emissions (21%). However, the larger aircraft types, A340, B747 and B777, together contribute nearly 60% of the NO_x emissions despite accounting for only 26% of the movements.

5.21 Table 5.4 also gives the ground-level emissions per movement (excluding APU and engine testing), showing that the value for the large aircraft types (A340, B747 and B777) is around a factor of five higher than the average for A319/320/321 aircraft. Of course, the large types carry more passengers than the A320 family, but only around twice as many, so the NO_x/passenger ratio is about double that of the A320 family. This reason for this is well known, and results principally from the way that the ICAO engine certification limits are framed, allowing aircraft with higher values of OPR (Overall Pressure Ratio) to emit more NO_x even after normalising for engine size (expressed via engine rating). This indicates that the change in total airport NO_x emissions over time is sensitive to the details of the fleet composition (and even to the specific characteristics of the engines fitted).

5.22 Equivalent information for 2002 is also provided in Table 5.4. For a given aircraft type, a change in kg/movement from 2002 to 2008/9 reflects both time-in-mode changes between the two years and the evolution (if any) in the frequency distribution of aircraft sub-series and/or specific engine types fitted to the aircraft type. Generally, the 2008/9 values are slightly lower than those in 2002, but there a few exceptions. The increase for the A340, for example, reflects the greater proportion of the A340-600 series in 2008/9. The average kg/movement taken over all aircraft types is the same for the two periods (2.7 kg/movement), with a reduction in some ground-movement times-in-mode in 2008/9 offsetting an increase in average emission rates.

Elevated Aircraft Emissions

5.23 Emissions up to 1000 m height are included in the airport inventory by convention, but elevated aircraft emissions are of less significance from a local air quality perspective. However, changes between 2002 and 2008/9 will be discussed briefly here for completeness.

5.24 Of the three elevated flight phases included, initial climb (from wheels off to cut back) is most significant because thrust settings are higher in this mode and the take-off trajectory has a segment relatively close to the ground, which may lead to a not-insignificant contribution at receptors close to the airport perimeter. Climb-out emissions arise at too great a height to contribute significantly to ground-level concentrations; similarly, a large fraction of the approach emissions arise far from the airport.

5.25 The estimate of initial climb emissions for 2008/9 is 32% higher than for 2002. Although the initial-climb time averaged over all movements in the period is only 2% higher for the 2008/9 inventory than for the 2002 inventory, the estimated time is greater (around 15% higher) for the larger jets, which account for a major fraction of emissions. The times for 2008/9 were based on a sample of NTK data specific to the period, using a finer set of aircraft type categories than for 2002. The type of NTK data provided by BAA for the analysis of times was different for 2008/9 from that for 2002 (as a result of changes to the NTK system in the intervening period) leading to differences in the methodology for extracting times to cut-back height. Thus, it cannot be ruled out that some of the increase in initial-climb time results from the methodology change, and reflects the uncertainty in extracting time-to cut-back (an event that is not directly recorded in the NTK system) from the raw data provided. Generally, the new analysis has re-partitioned the total time to 1000 m height between initial climb (wheels off to cut back) and climb out (cut back to 1000 m) whilst having a smaller effect on the total time to 1000 m.

5.26 The estimates of approach and climb-out emissions for 2008/9 are 6% higher than those for 2002, with the effect of changes to the number of movements and fleet mix having been partly offset by minor reductions in climb-out and approach times resulting from the analysis of NTK radar data carried out specifically for the 2008/9 inventory (as discussed in Section 2). Climb-out times are typically 5-10% lower and approach times around 5% lower.

APU Emissions

5.27 APU emissions are the second-largest contributor to ground-level aircraft emissions according to the breakdown given in Table 5.1. It is worth noting that no plume rise is attributed to APU emissions in the dispersion modelling so, per unit emission, APU emissions may have a greater impact on ground-level concentrations than emissions from aircraft main engines, particularly those from take-off roll.

5.28 The estimate of APU NO_x emissions for 2008/9 is 10.2% lower than that for 2002. The APU running times adopted for the 2008/9 inventory are lower on average than those used for the 2002 inventory: the significant uncertainty in these values has been noted in Section 2. Averaged over movements in the period, the estimated running time per LTO cycle (sum of arrival and departure running) for wide-bodied jets for 2008/9 was 14% lower than the equivalent value for 2002 (88 min in 2008/9 compared to 102 min in 2002); for narrow-bodied jets, the estimated average running time per LTO cycle for 2008/9 was 41% lower than the equivalent value for 2002 (33 min in 2008/9 compared to 56 min in 2002). The residual difference in the estimated APU emissions for 2008/9 and 2002 result from the (small) increase in the number of movements together with the impact of aircraft fleet mix changes (which lead to APU emission factor changes).

Airside Vehicle Emissions

5.29 The calculated value of total NO_x emissions from airside vehicles in the 2008/9 inventory is 10% higher than the equivalent value in the 2002 inventory. As noted in Section 2, the estimated total mass of fuel used airside is 31% higher for the 2008/9 inventory than for the 2002 inventory, which may not reflect a real increase in usage, given the major uncertainties in the fuel-accounting methodology. The partitioning between fuel used by road vehicles compared to that used by off-road vehicles has also changed, partly as a result of changes to the procedure for classifying vehicles based on the descriptions provided.

5.30 Taking the road vehicle and off-road contributions separately, the effective NO_x emission factor in g/kg (defined as total emissions divided by total fuel mass irrespective of fuel type) for road vehicles has decreased from 24.2 g/kg in 2002 to 18.9 g/kg in 2008/9. A reduction is expected, given the gradual penetration into the fleet of higher Euro-standard vehicles as a result of age-replacement of vehicles, but it should be noted that there has also been a change in the base emission factor data set in the intervening period (as discussed in Section 2), which contributes to the difference. For off-road vehicles, the effective NO_x emission factor in g/kg has decreased from 49.4 g/kg for 2002 to 37.8 g/kg for 2008/9. In this case, the basic emission-factor data set has not changed, and the difference reflects the gradual penetration into the fleet of higher (off-road) Euro-standard vehicles as a result of age-replacement of vehicles.

Landside Road Vehicle Emissions

5.31 The total road vehicle NO_x emissions in the 11 km square road network area (Fig 2.5) is calculated to have been 2464 tonnes for the 2008/9 period. For the PSDH work, CERC calculated emissions on the road network* as part of the modelling exercise using ADMS-Airport. The road network area extended to include the Greater London area, so emissions based on the RRTM2a traffic model were substituted for the road vehicle emissions in the 2002 LAEI in the road network area. However, CERC quoted separately[51] the emissions on a near-Heathrow major-road network that is closely similar to that used for the 2008/9 inventory†, giving a value of 3571 tonnes NO_x.

5.32 Thus, the estimate of the total NO_x emissions on the near-Heathrow network for 2008/9 is 31% lower than the PSDH value for 2002, with only a small component of the change attributable to the slightly smaller road network area used for the 2008/9 calculation. One component of the residual change between the two years derives from the change in the emission factor data base for road vehicles. As explained in Section 2, a revised national set of emission factors (and associated traffic vehicle-km fractions) was released in 2009. The 2002 emissions were compiled for the PSDH using an interim set of factors, which already incorporated some of the changes from the older national set of factors in the NAEI database. However, there were subsequent revisions to the data set (particularly relating to traffic composition) before final release, which contribute to the differences in the 2002 and 2008/9 estimates. Of course, the major component of the reduction in emissions between the two periods is the penetration into the fleet of higher Euro-standard vehicles.

Other sources

5.33 The calculated value of total additional‡ NO_x emissions from public car parks (including car rentals) for 2008/9 is 31% lower than the equivalent value for 2002, despite an increase in the estimated number of parking transactions by 7%. The reduction is principally a reflection of the decrease in NO_x emission factors for passenger cars between the two time periods as higher Euro-standard vehicles penetrate the fleet. However, the update of the national emission factor database described in Section 2 has contributed a (minor) component of the

* Airport-related emissions other than those on the road network were calculated by AEA.
† For the Heathrow 2008/9 inventory, the network was truncated at the edges of the 1 km OS squares at the outer edges of the 11 km square network area, for convenience in making the split between LAEI and non-LAEI emissions. Thus the network size in the PSDH work was slightly larger than that for the 2008/9 inventory.
‡ NB: Only the additional emissions from cold starts and moving within the car park are included here: emissions from vehicles travelling to and from car parks are included in 'road network' emissions;

difference.

5.34 The calculated value of total additional NO_x emissions from staff car parks for 2008/9 is 28% lower than the equivalent value for 2002, despite an increase in the estimated number of parking transactions by 12%. Again, the reduction is principally a reflection of the decrease in NO_x emission factors for passenger cars between the two time periods as higher Euro-standard vehicles penetrate the fleet, with the update of the national emission factor database contributing a (minor) component of the difference.

5.35 The calculated value of total additional NO_x emissions from taxis in the Taxi Feeder Park and queuing on the forecourts is 45% lower than the equivalent value for 2002, for little change in the estimate of total annual number of taxi transactions. The dominant contribution to the emissions total arises from taxi queuing, so the reduction principally reflects the reduction in queuing emission rates derived from the low-speed portion of the pertinent speed emission curve. A minor component of the decrease arises from a reduction in the estimate of the distance travelled by taxis within the TFP.

5.36 The calculated value for the total NO_x emissions from heating plant on the airport is 58.5% higher for 2008/9 than the equivalent value for 2002. As described in Section 2, the estimated quantity of input fuel energy (MJ), including both gas and gasoil, for 2008/9 is 24% higher than for 2002, although some of this difference may result from changes in the data sources available to estimate the total amounts of fuel used. The remaining component of the increase in NO_x emissions results principally from the revision of the default emission factor for boilers, taken from the NAEI emission factor database, which is applied here to gas-fuelled boilers for which no stack-emission measurement information is available.

Spatial Density of Emissions

5.37 As discussed in Section 3, dispersion modelling requires the spatial (and temporal) distribution of emissions to be specified. To give an impression of the overall spatial distribution of emissions, Fig 5.1 shows the spatial density of total ground-level airport* emissions at a spatial resolution of 100 m. This is similar to the plots produced for the PSDH work[4], except that in the latter case only aircraft emissions were included in the total.

5.38 This spatial pattern of emissions, together with the dominance of south-westerly winds, is a key factor in determining the airport contribution to NO_x (and NO_2) concentrations in the residential areas immediately north of the airport. The influence of emissions on the runway from take-off roll is clearly visible†, although there is also significant emission density in some apron areas.

Particulate Matter (PM_{10} and $PM_{2.5}$)

Emissions by Source Category

5.39 From the perspective of the relative contribution from various source categories, PM_{10} and $PM_{2.5}$ show similar profiles and will be discussed together (with the abbreviation PM used to refer to them collectively).

5.40 Table 5.5 (Table 5.6) gives a breakdown of the calculated annual PM_{10} ($PM_{2.5}$) emissions by source category. In discussing these tables, PM_{10} values are given first, with equivalent $PM_{2.5}$ values in brackets.

5.41 As for NO_x, in the local air quality context the emission estimates are best viewed as intermediate results needed for the modelling of airborne concentrations rather than as indicators in their own right of the comparative importance of various source categories. Nevertheless, it is worthwhile to compare ground-level emissions that are localised on the

* Excludes elevated aircraft emissions and heating plant emissions
† There appearance of two lines of 100 m squares with high emission density at the eastern end of the northern runway arises because the runway is not parallel to the E-W direction, whereas the 100 m squares have been aligned with the OS grid.

airport, such as ground-level aircraft emissions and airside vehicle emissions, if the (off-airport) receptors of interest are not close to individual sources. In this case, relative annual emission rate is a reasonable indicator of relative contribution to annual-mean concentration. From this viewpoint, it can be seen from Tables 5.5 and 5.6 that ground-level aircraft emissions are more significant than the emissions from airside vehicles, car parking and heating plant although, as noted for NO_x, the differential effect of plume rise may attenuate the relative importance of aircraft exhaust emissions.

5.42 In contrast to the situation for NO_x, take-off roll for PM is not a dominant contributor to the total ground-level aircraft exhaust emissions. In this case, the calculated emission rate at higher thrust does not compensate for the shorter time-in-mode, so the longer running times for taxiing and hold lead to larger contributions. APUs make a significant contribution to aircraft ground-level PM emissions, with the contribution comparable to that from taxiing (taxi-in and taxi-out): despite the typical fuel burn rates for APU engines being much lower than for main engines, their emissions are not controlled by the ICAO certification process, and manufacturer's data indicate comparatively higher PM emission indices (g pollutant per kg fuel burned). Estimated brake and tyre wear emissions are major contributors to total ground-level aircraft PM emissions, together accounting for 42% (27%) of the ground-level PM_{10} ($PM_{2.5}$) emissions, although the estimates are subject to large uncertainties (see Section 2).

5.43 The relatively smaller contribution from elevated emissions than was the case for NO_x arises because the differential between emission factors for high-thrust modes and low-thrust modes is smaller for PM than for NO_x; in addition, ground-level emissions for PM include aircraft brake and tyre wear.

5.44 For airside vehicles, the estimate of the relative contribution from exhaust emissions, 83%(90%), is significantly higher than for fugitive emissions, 17%(10%), although there are large uncertainties attached to the estimates for fugitive emissions. For exhaust emissions, off-road vehicles are estimated to have contributed 69% (70%) of the total (compared to 47% for NO_x), whereas for fugitive emissions off-road vehicles are estimated to have contributed only 19% (19%) of the total.

5.45 Table 5.7 gives a further breakdown of PM emissions from airside vehicles by the major vehicle categories used in the emissions methodology. The total for exhaust emissions from airside road vehicles has large and comparable contributions from the rigid-HGV and LGV categories (whereas for NO_x LGVs gave a much smaller contribution); for fugitive emissions from airside road vehicles, the LGV category gave the largest contribution. For off-road exhaust emissions, vehicles in the lowest and highest power-range category gave comparable contributions whereas, for fugitive emissions, vehicles in the lowest power range give the largest contribution.

5.46 For landside road vehicles, it is noteworthy that the calculated contribution from fugitive emissions (brake wear, tyre wear and re-suspension) is greater than that from exhaust emissions (by around a factor of two). This is increasingly the case over time as exhaust emissions fall in response to emissions control. For PM, HDVs give a smaller contribution to exhaust emissions than do LDV: for this pollutant the higher emission factors (g/km) for HDV are not enough to offset the lower vehicle-km travelled by HDV on the network. Table 5.8 gives the traffic average exhaust emission factor (g/km) separately for LDV and HDV, defined as the total PM exhaust emissions from road vehicles on the network divided by the total vehicle-km travelled on the network. The HDV factor is around 6 times greater than the LDV factor.

5.47 The split between exhaust and fugitive PM emissions for airside vehicles is different from that for road-vehicle emissions because there is a larger diesel fraction in the airside fleet (so the exhaust PM emissions per unit fuel are higher) and much of the fuel used airside is associated with large vehicles which have high specific fuel consumption (kg/km). It should be borne in mind that, although the methodology for estimating brake and tyre wear emissions has been updated, significant uncertainties remain for these sources.

Comparisons with Other Inventories

5.48 Tables 5.5 (final column) gives the percentage difference between the 2008/9 values and the corresponding 2002 values for PM_{10}. $PM_{2.5}$ was not included in the 2002 inventory so comparisons are not available for this pollutant. As noted for NO_x, the PM_{10} differences include the effect of changes to operational parameters (such as times in mode) as well as the changes to activity (such as the number of movements by aircraft type).

Aircraft Engine Emissions

5.49 The estimate of total (LTO) aircraft PM_{10} emissions for the Heathrow 2008/9 inventory is 6.2% higher than the equivalent value for the 2002 PSDH inventory, with the increase for elevated emissions (36.4%) being partly offset by a slight decrease in ground-level emissions (by 2.6%). As noted in the NO_x discussion, passenger throughput increased by 4.6% between the two periods, leading to a net increase in LTO PM_{10} per passenger of 1.5% (from 0.756 tonne/million passengers to 0.767 tonnes/million passengers).

5.50 The LTO cycle (exhaust) PM_{10} emissions at Heathrow represent 37% of the total from UK aviation (Domestic and International LTO exhaust emissions), as given in the 2008 NAEI[50]. As noted earlier, the national and the Heathrow estimates are not independent, given that the Heathrow component of the national figure is based on operational information used in compiling a Heathrow inventory. However, the 2008 NAEI version used the operational information underpinning the 2002 PSDH inventory, which has been updated in compiling the Heathrow 2008/9 inventory. The 2008/9 estimate of total Heathrow LTO PM_{10} emissions is 0.03% of the total PM_{10} emissions for the UK, as given in the 2008 NAEI.

5.51 The 2.6% decrease in ground-level aircraft PM_{10} emissions is the net effect of larger fractional changes (both positive and negative) in the contributions from components such as taxiing and APUs. As noted earlier, these changes reflect the combined influence of time-in-mode changes and aircraft movement/fleet mix changes.

5.52 The estimates of taxi-out and taxi-in PM_{10} emissions for 2008/9 are significantly lower (by 22.7% and 13.6% respectively) than the corresponding values for 2002, with the lower taxiing times (discussed above in the section on NO_x) more than offsetting any increase due to fleet-mix changes. Hold times have not changed much between the two years, so the 9.5% increase in hold emissions is a reasonable reflection of the change in fleet-average PM_{10} emission rates at low-thrust settings. In contrast, take-off roll emissions have increased by 33.8% despite little change in roll times. This larger change, therefore, reflects a significant increase in the fleet-average PM_{10} emission rate at high thrust.

5.53 Table 5.9 gives a breakdown of ground-level aircraft exhaust PM emissions (omitting APUs, engine testing, brake wear and tyre wear) by aircraft type. As might be expected from the movement breakdown (Table 2.1), A319/320/321 aircraft account for a major fraction of the PM_{10} emissions (37%). However, the larger aircraft types, A340, B747 and B777, together account for 46% of the PM emissions despite accounting for only 26% of the movements.

5.54 For a given aircraft type in Table 5.9, a change in kg/movement from 2002 to 2008/9 reflects time-in-mode changes between the two years, together with evolution (if any) in the frequency distribution of aircraft sub-series and/or specific engine types fitted to the aircraft. There are significant increases in kg/movement for A319/320/321 aircraft, even though they are fitted with the same engine types in the 2008/9 fleet as in the 2002 fleet (V2500 series). This can be traced to the correction of an error in the ICAO databank: the engines were classed as 'turbofans' (TF) in the version of the databank current at the time of the 2002 inventory compilation, which has been corrected to 'mixed turbofan' (MTF) in the later version. This change affects the methodology for translating Smoke Number into PM_{10} emission rate.

5.55 The maximum Smoke Number of an engine is subject to CAEP regulatory control[25] although, unlike the situation for NO_x, the standard has not become more stringent over time. Modern jet engines usually have Smoke Numbers well below the CAEP limit, and thus there is no regulatory driver for continuous improvement. As a result, there can be large non-systematic variations (albeit below the limit) from engine to engine, so the variation in total airport PM emissions over time is sensitive to the specific engines fitted to the principal aircraft types in the fleet.

5.56 The increase in the estimate aircraft exhaust PM_{10} emissions for elevated modes is largely a reflection of higher Smoke Numbers on average at high thrust levels for the 2008/9 fleet, but in the case of initial climb also includes the significant increase in initial climb times discussed in Section 2.

APU Emissions

5.57 The estimate of APU PM_{10} emissions for 2008/9 is 27.1% lower than that for 2002. As noted earlier, a major component of the change in APU emissions derives from the lower APU running times adopted for the 2008/9 inventory compared to those used for the 2002 inventory.

Aircraft Brake and Tyre Wear Emissions

5.58 In the PSDH methodology, aircraft brake wear scales as aircraft size, represented via the surrogate Maximum Take-Off Weight (MTOW). Thus, the increase in brake-wear emissions from 2002 to 2008/9 by 15% is a direct reflection of the larger average aircraft size in the 2008/9 fleet. An increase in the fraction of A319/320/321 aircraft together with a decrease in B737 aircraft leads to an increase in average aircraft MTOW. Similarly, the 2008/9 fleet had a greater percentage of large aircraft types.

5.59 Tyre wear emissions are not quite proportional to MTOW in the PSDH methodology (although nearly so), which explains the slightly different fractional increase in tyre wear emission between the 2002 and 2008/9 inventories (20.0%) .

Airside Vehicles Emissions

5.60 The calculated value of total PM_{10} emissions from airside vehicles in the 2008/9 inventory is 16% higher than the equivalent value in the 2002 inventory. As noted in Section 2, the estimated total mass of fuel used airside is 31% higher for the 2008/9 inventory than for the 2002 inventory, although this may not reflect a real increase in usage, given the major uncertainties in the fuel-accounting methodology. Thus the smaller net increase reflects the lower average emission factors in 2008/9.

5.61 Taking the road vehicle and off-road contributions separately, the effective exhaust PM_{10} emission factor in g/kg (defined as total emissions divided by total fuel mass irrespective of fuel type) for road vehicles has decreased from 1.24 g/kg in 2002 to 0.74 g/kg in 2008/9. A reduction is expected, given the gradual penetration into the fleet of higher Euro-standard vehicles as a result of age-replacement of vehicles, but it should be noted that there has also been a change in the base emission factor data set in the intervening period (as discussed in Section 2), which contributes to the difference.

5.62 For off-road vehicles, the effective exhaust PM_{10} emission factor in g/kg has decreased from 4.04 g/kg for 2002 to 3.81 g/kg for 2008/9. In this case, the basic emission-factor data set has not changed, and the difference reflects the gradual penetration into the fleet of higher (off-road) Euro-standard vehicles as a result of age-replacement of vehicles.

5.63 For fugitive emissions, the effective PM_{10} emission factor (in g/kg) for road vehicles has decreased from 0.60 g/kg in 2002 to 0.41 g/kg in 2008/9; no estimate was made of fugitive emission from off-road vehicles for the 2002 inventory. For the 2008/9 estimate, the fuel used while idling has been identified separately and not counted in estimating fugitive emissions.

Landside Road Vehicles

5.64 The total road vehicle PM_{10} emissions in the 11 km square road network area (Fig 2.5) is calculated to have been 239.3 tonnes for the 2008/9 period, with 74.8 tonnes from exhaust emissions and 164.6 from fugitive emissions. The CERC estimate[51] of exhaust PM_{10} emissions on the near-Heathrow network was 130.1 tonnes, representing a decrease of 43% in exhaust PM_{10} emissions. No further breakdown of the PSDH estimate was published.

5.65 The principal component in this decrease is the penetration into the fleet of higher Euro-standard vehicles, but some contribution arises from the revisions to the emission-factor database in the period between the two emission estimates.

Other sources

5.66 The estimate of total PM_{10} emissions (exhaust and fugitive) from car parks and taxi queuing is the same for 2008/9 as for 2002 (1.64 tonnes), resulting from a decrease in exhaust emissions by 18% being offset by an increase in fugitive emissions by 21%. The estimate for exhaust emissions has fallen despite an increase in parking transactions, principally as a result of the penetration into the LDV fleet of higher Euro-standard vehicles although the change in emission factor database has contributed to the change. The increased estimate for fugitive emissions is principally a reflection of the change in the methodology noted in Section 2, which has increased the emission factor for brake and tyre wear.

5.67 The calculated value for the total PM_{10} emissions from heating plant on the airport is 14.6% higher for 2008/9 than the equivalent value for 2002. As described in Section 2, the estimated quantity of input fuel energy (MJ), including both gas and gasoil, for 2008/9 is 23% higher than for 2002, although some of this difference may result from changes in the data sources available to track the total amounts of fuel used. The residual difference results from the change in default emission factors extracted from the NAEI database.

Spatial Density of Emissions

5.68 To give an impression of the overall spatial distribution of PM_{10} emissions. Fig 5.2 shows the spatial density of total ground-level airport* emissions at a spatial resolution of 100 m, in a similar format to that described earlier for NO_x; the relative distribution for $PM_{2.5}$ is similar.

5.69 The peaks in spatial density on the runways in Fig 5.2 are principally a reflection of the brake and tyre wear contribution, which has been focused in the touchdown zone.

* Excludes elevated aircraft emissions and heating plant emissions

6 Summary and Conclusions

6.1 An emissions inventory has been compiled for London Heathrow Airport from airport activity data for the 12-month period from 1st April 2008 to 31st March 2009, including the pollutants NO_x, PM_{10} and $PM_{2.5}$. The split year was chosen principally to reflect the opening of T5 in March 2008.

6.2 For airport sources, the methodology used for the 2008/9 inventory is essentially that applied in the PSDH air quality work (i.e. the work underpinning the UK government's consultation on 'Adding Capacity at Heathrow'), thereby presenting the opportunity to track the influence on aircraft emissions of operational and activity changes between 2002 (the PSDH base year) and 2008/9, without the confounding influence of changes to methodology. For vehicle emissions on the near-Heathrow road network, the national set of emission factors (and associated traffic composition projections) released in 2009 have been used.

6.3 Airport activity data specific to the 2008/9 period were obtained, including aircraft movements (on a flight-by-flight basis), the quantities of fuel supplied for airside use, transaction data for car parks, car rental and taxis and the quantities of fuel used in heating plant. Activity on the airside is still poorly characterised with respect to how the fuel used is distributed amongst vehicles with different emission factors. New data sets are becoming available to address this gap, but were not sufficiently well developed to include in the present inventory.

6.4 Given the key importance of engine running times, aircraft times-in-mode for the various LTO flight phases have been reassessed for the 2008/9 inventory. For the first time at Heathrow, ground-movement times-in-mode (taxi, holding and roll times) for the inventory have been derived from flight-by-flight information supplied by NATS, based on ground-radar data. Times-in-mode for elevated modes have been derived from NTK (Noise and Track-Keeping) radar data.

6.5 Taxiing times derived from 2008/9 data are significantly shorter than those used for the 2002 PSDH inventory. A principal reason for this is the impact that the opening of T5 has made on the ground-movement patterns on the airfield. In addition, there have been initiatives in recent years to improve ground-movement efficiency. It is not clear what fraction of this improvement will be retained in future years, when the airfield reaches a stable operational configuration.

6.6 On current estimates, APU emissions are a significant contributor to the total ground level emissions on the airport. APU running times have been derived from a modest sample of observations taken in 2007-2009, leading to lower times than those used for the 2002 PSDH inventory. There are indications that analysed running times may still be overestimates, but this cannot be confirmed. The current data set does not identify any specific influence of the use of Pre-Conditioned Air on aprons where it has been fitted.

6.7 There has been some improvement in the characterisation of airside operations, via the availability of a data set giving average speeds and fraction of time spent idling, for vehicles in various categories. However, the emission factors for off-road vehicles are still quite coarsely characterised.

6.8 There has been a significant evolution in the aircraft 'fleet mix' (relative number of movements by aircraft type) between 2002 and 2008/9, with a major increase in the percentage of Airbus A319/320/321 types and a decrease in Boeing B737 aircraft types. For large jets, there has been a significant increase in the percentage of A340 and B777 types, with a slight decrease in the B747 percentage. Overall, the large-jet fraction has increased, which is reflected in an increase in the average number of passengers per movement from 135.1 in 2002 to 140.3 in 2008/9.

6.9 Emissions from traffic on the near-Heathrow road network have been quantified using a set of traffic data derived from an 'interim' traffic model. This represents a partial update of the

PSDH traffic modelling, taking account of the opening of T5. Although some comparisons with traffic count data have been reported for sections of the M25 and M4, the results of the interim model have not been subjected to the usual level of validation.

6.10 The traffic data set (which is similar in format to that used for the PSDH air quality assessment) differs in some important respects from data used for pre-PSDH emission inventories. For example, the model output does not distinguish airport-related and non-airport trips, so the specific contribution to emissions from airport-related traffic cannot be evaluated. In addition, junction delays and queue lengths are not provided in the hourly traffic flow data, whereas queuing was modelled separately in earlier inventories. On the other hand, traffic speed information has been provided separately for each hour of the day, whereas the earlier data sets gave speeds for representative AM peak, PM peak and inter-peak hours only. How important these differences are from an air quality perspective will be further discussed in the model evaluation report. It is worth noting that a new traffic model is currently being developed, with the intention that the specific requirements of air quality modelling be considered from the outset.

6.11 Airport heating plant make an appreciable contribution to total airport emissions near the ground, although past studies have shown that they make only a small contribution to ground-level concentrations at off-airport receptors, given their specific conditions of release.

6.12 The following set of conclusions are pollutant specific.

NO_x

6.13 From the perspective of the impact of airport emissions on off-airport air quality, ground-level aircraft emissions are likely to be much more significant than the emissions from airside vehicles, car parking and heating plant. However, the differential effect of plume rise may attenuate the relative importance of aircraft emissions for receptors close to the airport: this will be taken into account in the dispersion modelling study.

6.14 For ground-level aircraft emissions, take-off roll gives the largest contribution because of the high thrust setting of the engines (but the influence of plume rise is also greater for take-off roll). APU emissions are a significant contributor to total ground-level aircraft NO_x emissions, generating about the same amount of NO_x as taxi-in and taxi-out combined.

6.15 For airside vehicle emissions, road vehicles and off-road vehicles give nearly equal contributions to the total, with rigid HGVs providing over a half of the road-vehicle contribution and the vehicles in the large-engine category (130-560 kW) accounting for over half of the off-road contribution. On the landside road network, HDV (HGV and buses) emit about the same amount of NO_x as LDV (cars and LGV), despite HDVs accounting for around 14 times fewer vehicle-km travelled on the designated network, reflecting the much larger NO_x emission factors (g/km) for HDV.

6.16 The total (LTO cycle) aircraft NO_x emissions at Heathrow (up to 1000 m) represent 35% of the total NO_x emission from UK aviation (Domestic and International LTO) and 0.3% of the total NO_x emissions from all UK sources, as given in the 2008 version of the National Atmospheric Emission Inventory.

6.17 The estimated average amount of NO_x per passenger emitted in the LTO cycle up to 1000 m height (including APU and engine testing emissions) increased by 2.0% between the 2002 PSDH and 2008/9 inventories. Excluding APU and engine testing emissions, the estimated increase is 4%. This increase in NO_x/passenger as the average size of aircraft in the fleet increases has been noted in studies at other airports, but is specific to the types of engines in current aircraft fleets and may not be a feature that persists indefinitely into the future.

6.18 For local air quality, ground-level emissions are much more important than elevated emissions. The estimate of ground-level aircraft NO_x emissions for 2008/9 is 2.6% lower than for 2002. Excluding APU and engine testing emissions, the change becomes an increase of 0.7%, showing the impact of the decrease in the estimated APU running times. This small change in total ground-level (aircraft) emissions is the net effect of larger changes for the individual modes (taxiing, roll etc), both negative and positive, typically of magnitude 10-20%. Some of the change for individual modes is the results of minor revisions to times-in-mode, with the remaining change chiefly reflecting the difference in fleet mix.

6.19 The estimate of the total emissions from aircraft taxiing for 2008/9 is significantly lower than for 2002, despite a greater number of movements in 2008/9, principally reflecting the significant decrease in taxiing times in 2008/9 compared to those used for the 2002 inventory. Taxi-out emissions are lower by 22% and taxi-in emissions lower by 11%. Similarly the estimate of the total emissions from APU running is 10% lower for 2008/9 than for 2002, reflecting the lower running times noted above.

6.20 In terms of the relative contribution from various aircraft types, Airbus A319/320/321 aircraft accounted for a significant fraction (21%) of the ground-level aircraft NO_x emissions in 2008/9 (excluding APU and engine testing), reflecting their dominant contribution (48%) to the total movements. However, the larger aircraft types, A340, B747 and B777, together contributed nearly 60% of the NO_x emissions, despite accounting for only 26% of the movements.

6.21 Aircraft emissions normalised by number of movements varied across aircraft types in 2008/9 by by nearly a factor of six. Even after allowing for different passenger capacities, the larger jets (such as the B777) have significantly higher emissions than the medium jets (such as the A320), which results from the way that the ICAO engine certification limits are currently framed. This indicates that the change in total airport NO_x emissions over time is sensitive to the details of the fleet composition, particularly in relation to large aircraft types.

6.22 The calculated value of total NO_x emissions from airside vehicles in the 2008/9 inventory is 10% higher than the equivalent value in the 2002 inventory, for an estimated 31% increase in the mass of fuel used airside (although the latter may not reflect a real increase in usage, given the major uncertainties in the fuel-accounting methodology). The effective NO_x emission factor in g/kg (defined as total emissions divided by total fuel mass irrespective of fuel type) for airside road vehicles decreased from 24.2 g/kg in 2002 to 18.9 g/kg in 2008/9. For airside off-road vehicles, the effective NO_x emission factor decreased from 49.4 g/kg for 2002 to 37.8 g/kg for 2008/9.

6.23 The estimate of the total NO_x emissions on the near-Heathrow road network for 2008/9 is 31% lower than the published PSDH value for 2002, with only a small component of the change attributable to a slightly smaller road network area for the 2008/9 calculation. The major component of the emissions reduction between the two periods is the penetration into the fleet of higher Euro-standard vehicles, but a component of the difference derives from the change in the national emission factor data base for road vehicles.

PM_{10} and $PM_{2.5}$

6.24 As for NO_x, ground-level PM (particulate matter, either PM_{10} or $PM_{2.5}$) aircraft emissions are likely to be much more significant than the emissions from airside vehicles, car parking and heating plant from a local air quality perspective, although the differential effect of plume rise may attenuate their relative importance for receptors close to the airport.

6.25 In contrast to the situation for NO_x, take-off roll is not a dominant contributor to the total ground-level aircraft exhaust PM emissions. In this case, the calculated emission rate at higher thrust does not compensate for the shorter time-in-mode. The contribution from APU running is comparable to that from taxiing (taxi-in and taxi-out). Estimated brake and tyre wear emissions are major contributors to total ground-level aircraft PM emissions, together accounting for 42% (27%) of the ground-level PM_{10} ($PM_{2.5}$) emissions, although the estimates are subject to large uncertainties.

6.26 For airside vehicles, the contribution from exhaust emissions is much higher than for fugitive emissions, although there are large uncertainties attached to the latter. For exhaust emissions, off-road vehicles are estimated to have contributed 69% (70%) of the total whereas for fugitive emissions off-road vehicles are estimated to have contributed only 19% of the total (for both PM_{10} and $PM_{2.5}$).

6.27 On the landside road network, estimated PM emission from fugitive sources (brake wear, tyre wear and re-suspension) are higher than from vehicle exhaust. This is increasingly the case over time as exhaust emissions fall in response to emissions control. For PM, HDVs give a smaller contribution to exhaust emissions than do LDV: for this pollutant the higher emission factors (g/km) for HDV are not enough to offset the lower vehicle-km travelled by HDV on the network.

6.28 The LTO cycle (exhaust) PM_{10} emissions at Heathrow (up to 1000 m) represent 37% of the total from UK aviation (Domestic and International LTO exhaust emissions), and 0.03% of the total PM_{10} emissions from all UK sources, as given in the 2008 version of the National Atmospheric Emission Inventory.

6.29 The estimated average amount of PM_{10} per passenger emitted in the LTO cycle up to 1000 m height (including APU, engine testing, brake wear and tyre wear emissions) increased by 1.5% between the 2002 PSDH and 2008/9 inventories.

6.30 The estimated value of total ground-level aircraft PM_{10} emissions for 2008/9 is 2.6% lower than the equivalent for 2002. This small change is the net effect of larger fractional changes (both positive and negative) in the contributions from components such as taxiing and APUs. As noted earlier, these changes reflect the combined influence of time-in-mode changes and aircraft movement/fleet mix changes. The 2008/9 estimates of taxiing and APU emissions are significantly lower than for 2002, reflecting the lower times-in-mode used for the inventory.

6.31 In terms of the relative contribution from various aircraft types, Airbus A319/320/321 aircraft accounted for a significant fraction (37%) of the ground-level aircraft PM_{10} emissions in 2008/9 (excluding APU, engine testing, brake wear and tyre wear), reflecting their dominant contribution (48%) to the total movements. However, the larger aircraft types, A340, B747 and B777, together contributed nearly 46% of the exhaust PM_{10} emissions, despite accounting for only 26% of the movements.

6.32 Modern jet engines usually have Smoke Numbers well below the CAEP limit, and thus there is no regulatory driver for continuous improvement. As a result, there can be large non-systematic variations (albeit below the limit) from engine to engine, so the variation in total airport PM emissions over time is sensitive to the specific engines fitted to the principal aircraft types in the fleet.

6.33 The increase in the estimated brake-wear emissions between 2002 and 2008/9 by 15% is a direct reflection of the larger average aircraft size in the 2008/9 fleet, given that brake wear is assumed to scale with MTOW (Maximum Take-Off Weight). The corresponding increase for tyre wear is 20%, reflecting a difference in the assumed dependence on MTOW.

6.34 The calculated value of total PM_{10} emissions from airside vehicles in the 2008/9 inventory is only 16% higher than the equivalent value in the 2002 inventory, despite the increase (31%) in the estimated total mass of fuel used airside for the 2008/9 inventory, reflecting the lower average emission factors in 2008/9. For airside road vehicles, the effective exhaust PM_{10} emission factor in g/kg (defined as total emissions divided by total fuel mass irrespective of fuel type) has decreased from 1.24 g/kg in 2002 to 0.74 g/kg in 2008/9. For off-road vehicles, the effective exhaust PM_{10} emission factor in g/kg has decreased from 4.04 g/kg for 2002 to 3.81 g/kg for 2008/9.

6.35 The estimate of the total exhaust PM_{10} emissions on the near-Heathrow road network for 2008/9 is 43% lower than the published PSDH value for 2002, with only a small component of the change attributable to the slightly smaller road network area for the 2008/9 calculation. The major component of the reduction in emissions between the two periods is the penetration into the fleet of higher Euro-standard vehicles, but a component of the difference derives from the change in the national emission factor data base for road vehicles.

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7.2 Key data sets used in the inventory were supplied by third parties, as follows:

- BAA supplied airport activity and operational data, principally for aircraft (BOSS movements, NTK data, APU running times engine test statistics), airside vehicles (fuel use and AVP database), car parking and heating plant;
- AECOM, acting for BAA, supplied road-network traffic data;
- NATS supplied ground-movement time-in-mode information from their APT system, via BAA;
- BA, via BAA, supplied data on BA energy usage on the airport;
- QinetiQ licensed AEA to use the forward-speed and ambient-effects tables compiled for the PSDH.

7.3 A number of data sources were classed as commercially confidential, so the data cannot be quoted in full here. This applied to the NATS data and to the QinetiQ data listed above.

7.4 QinetiQ gave permission for Figs 2.1–2.4, based on the data supplied under license, to be shown.

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8 References

[1] Underwood B Y, Walker C T and Peirce M J (2004) Heathrow emission inventory 2002: Part 1. AEAT/ENV/R/1657/Issue 5.

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

[3] Underwood B Y (2007) Revised emissions methodology for Heathrow: base year 2002. AEAT/ENV/R/2193 Final. http://webarchive.nationalarchives.gov.uk/+/http://www.dft.gov.uk/consultations/archive/2008/heathrowconsultation/technicalreports/emissionmethodology.pdf

[4] Underwood B Y (2007) Heathrow Airport Emission Summaries. AEAT/ENV/R/2521 Final.

[5] London Atmospheric Emissions Inventory (LAEI) www.london.gov.uk

[6] National Atmospheric Emissions Inventory (NAEI) www.naei.org.uk

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

[8] 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.

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

[10] DfT (2007) Adding Capacity at Heathrow.

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

[12] DfT (2008) Adding capacity at Heathrow Airport:Report on consultation responses.

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

[14] HMSO (2000) The Air Quality (England) Regulations. SI 0928; HMSO (2002) The Air Quality (England) (Amendment) Regulations. SI 3043.

[15] EU (2008) Directive 2008/50/EC.

[16] Underwood B Y, Walker CT and Peirce M J (2010) Air quality modelling for Heathrow Airport 2008/9. AEAT/ENV/R/2915 Issue 1.

[17] BUCHair (2007) JP Airline Fleets International. BUCHair UK Ltd

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

[19] FOI (2002) All TP Aircraft Engines FOI.xls. Available from the Swedish Defence Research Agency by request.

[20] QinetiQ (2005) Correction to engine emission data resulting from engine deterioration. QinetiQ/05/01725.

[21] CAEP (2007) Airport air quality guidance manual. First edition 2006. CAEP7-WP/28.

[22] IPCC(1999) Aviation and the Global Atmosphere.

[23] CAEP (2004) Guidance on the use of LTO emissions certification data for the assessment of operational impacts. CAEP/6-IP/5.

[24] Baughcum S L et al. (1996) Scheduled civil aircraft emission inventories for 1992: Database development and analysis. NASA CR4700, NASA, Langley Research Centre, Hampton, VA, USA.

[25] ICAO (1993) Environmental protection. Annex 16 Volume II Aircraft Engine Emissions.

[26] Horton G C (2006) The calculation of the effects of ambient conditions and forward speed on aircraft gas turbine emissions. QinetiQ/05/01805.

[27] UCAR (2007) The National Centre for Atmospheric Research (NCAR), operated by the University Corporation for Atmospheric Research (UCAR). http://dss.ucar.edu

[28] Morris K M (2002) Take-off at less than full power. ICAO/CAEP/Working Group 3 AEM Task Group, 27-28th June 2002, London, UK

[29] Middel J (2001) AEROCERT. 4^{th} EU Project AL-97-SC.242.

[30] Brooke A S, Caves R E and Jenkinson L R (1995) Methodology for assessing fuel use and emissions from aircraft ground operations. TT 95 R 05. Department of Aeronautical and Automotive Engineering and Transport Studies, the University of Technology, Loughborough

[31] QinetiQ (2006) Personal communication.

[32] Curran (2006) Method for estimating particulate emissions from aircraft brakes and tyres. QinetiQ/05/01827.

[33] UNECE (2003) Automobile brake and tyre wear. http://vergina.eng.auth.gr/mech0/lat/PM10

[34] Norris J, Pearson B and Shafik-Hooper L (2009) An airside vehicle strategy assessment for Heathrow. AEA/ED46237/Issue 1.

[35] EEA (2005) EMEP/CORINAIR Emission Inventory Guidebook – 2009.
Technical report No 6/2009. European Environment Agency.
www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009

[36] EU (2004) Directive 2004/26/EC.

[37] NAEI (2003) UK fleet composition projections v2. January 2003.

[38] BAA (2007) Project for the Sustainable Development of Heathrow: Surface Access Report. www.dft.gov.uk/consultations/archive/2008/heathrowconsultation/technicalreports/surfaceaccess.pdf

[39] AECOM (2009) Three runway Heathrow short-term models: NADM and RRTM.

[40] TRL (2009) Emission factors 2009: Report 3 – exhaust emission factors for road vehicles in the United Kingdom. PPR 356 April 2009.

[41] DfT (2009) www.dft.gov.uk/pgr/roads/environment/emissions

[42] NAEI (2009) rtp_fleet_projection_April09_FINAL (07-10-09).xls;
rtp_fleet_projection_April09_failed_catalysts (07-10-09).xls;

ao6472tm_rtp_Basic_fleet_split_for_London_&_Bus_fleet_London.xls (Tim Murrells, personal communication)

[43] Murrells T (2009) Personal communication.

[44] AQEG (2005) Particulate matter in the United Kingdom. Available from Defra publications and on the web at www.defra.gov.uk/environment/airquality/publications/particulate-matter/index.htm

[45] Underwood B Y (2007) Emissions methodology for future LHR scenarios. AEAT/ENV/R/2323 Issue 1. (one of the technical documents made publicly available in support of the 'Adding Capacity at Heathrow' Consultation).

[46] USEPA (1995) Compilation of air pollutant emission factors. Volume 1: stationary plant sources and area sources. AP-42 5th Edition.

[47] www.naei.org.uk

[48] USEPA (1995) Compilation of air pollutant emission factors. Volume 1: stationary point sources and area sources. AP-42 5th Edition.

[49] Underwood B Y, Walker C T and Peirce M J (2008) Gatwick emission inventory 2005/6. AEAT/ENV/R/2395 Issue 1.

[50] www.defra.gov.uk/evidence/statistics/environment/airqual/index.htm
http://cdr.eionet.europa.eu/gb/un/cols3f2jg/envs3f2vq

[51] CERC (2007) Air quality studies for Heathrow: base case, segregated mode, mixed mode and third runway scenarios modelled using ADMS-Airport. FM699/R23_Final/07

Table 1.1 Relevant Air Quality Strategy (AQS) 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).

Table 2.1 Aircraft movements in 2008/9 by aircraft type

Aircraft type	Fraction (%)		Most common engine	2002 (%)[1]
Airbus A320 series	48.5			35.5
A319		17.7	V2522-A5	10.3
A320		19.3	V2527-A5	15.7
A321		11.5	V2533-A5	9.5
Airbus A330	2.8		Trent 772	1.1
Airbus A340 series	5.2			2.0
A343		1.8	CFM56-5C4	1.9
A346		3.1	Trent 556-61	0.1
A340 other		0.2	CFM56-5C3	0.0
Airbus A380	0.3		Trent 970-84	0.0
Boeing 737 series	6.0			18.2
Boeing 737-200, 300, 400, 500		4.2	CFM56-3C-1	16.5
Boeing 737-600, 700, 800, 900		1.8	CFM56-7B26	1.7
Boeing 747[2]	9.5			10.8
Boeing 757[3]	4.0		RB211-535E4	6.9
Boeing 767[4]	6.0		RB211-524H	5.8
Boeing 777	11.4			7.5
B772		1.0	GE90-76B	1.9
B777-200ER		8.2	Trent 892	5.4
B773		0.3	Trent 892	0.2
B777-300ER		1.9	GE90-115B	0.0
MD80	1.9		JT8D-217C	4.4
Other	4.5			7.8
Total %	100.0			100.0
Total movements	470,029			466,554

[1] This column includes subtotals so does not simply sum to 100%
[2] Almost entirely B747-400 in 2008/9 fleet
[3] Almost entirely B757-200 in 2008/9 fleet
[4] Almost entirely B767-200 in 2008/9 fleet

Table 2.2 Mean and final NO_x factors during take-off, for a range of engine types

Engine	OPR[1]	Mean factor[2]	Final factor[2]
CFM56-3C-1	25.5	1.0251	1.0645
V2527-A5	27.2	1.0272	1.0700
CFM56-5B3/P	32.8	1.0367	1.0950
Trent 772	35.8	1.0505	1.1314
Trent 892	41.4	1.0590	1.1542

[1] OPR – overall pressure ratio
[2] 'Factor' is the ratio of NO_x emission rate accounting for aircraft speed to that for aircraft stationary

Table 2.3 Thrust settings used in early emission inventories[1]

Mode	Thrust %
Taxi-out	7
Holding at runway head	7
Take-off roll	100
Initial climb	100
Climb-out	85
Approach	30
Landing roll	7[2]
Taxi-in	7

[1] These values have now been superseded by more detailed methodologies
[2] Periods of reverse thrust above idle were recognised even in early emission inventories.

Table 2.4 Average take-off thrust by aircraft type

Aircraft type	Percentage at full thrust (%)	Average take-off thrust* (%)
A319	6.3	82.3
A320	7.5	77.5
A321	7.5	76.0
A330	5.4	80.6
A340	1.0	86.1
A380	2.0	87.0
B737	6.8	78.2
B747	8.1	82.8
B757	6.3	76.4
B767	3.2	72.3
B777	3.6	79.3
MD80	6.0	78.0

*This is the average thrust when aircraft not departing at full thrust, given as fraction of engine rating

Table 2.5 Fractional use and duration of reverse thrust above idle

Aircraft type	% using reverse thrust > idle	Duration (s)
A310	100	27
A319	30	14
A320	63	18
A321	35	21
A330	67	19
A340	50	32
B737	93	19
B747 ‘Classics’	100	33
B747-400	33	27
B757	8	2
B767	100	16
B777	57	19
EMB 145	100	13
F70/100	0	-
MD11	100	24
MD80/90	25	16

Table 2.6 Initial-climb and climb-out times[a]

	Initial climb time (s)				Cimb-out time (s)			
	1000 ft		1500 ft		1000 ft		1500 ft	
A/C type	Mean	SE[b]	Mean	SE[b]	Mean	SE[b]	Mean	SE[b]
300	26.0	1.2	-	-	60.9	2.0	-	-
319	25.7	1.5	37.7	1.9	63.7	3.1	51.8	2.5
320	24.1	1.3	36.6	2.6	65.1	4.5	52.6	3.9
321	24.9	1.4	35.9	1.7	62.1	3.3	51.2	3.0
330	31.5	1.8	-	-	78.8	5.1	-	-
343	52.6	3.9	-	-	107.8	8.6	-	-
346	50.7	3.1	-	-	101.6	2.8	-	-
380	52.8	2.0	-	-	98.4	3.1	-	-
737	26.1	1.7	38.3	2.3	59.6	3.6	47.5	3.0
747	44.3	2.8	-	-	76.6	6.0	-	-
757	23.8	0.9	35.2	1.2	62.5	2.8	51.1	2.6
767	31.0	1.5	-	-	70.9	2.5	-	-
772	34.4	2.0	-	-	76.5	3.2	-	-
777-ER	35.6	2.2	-	-	67.7	3.0	-	-
MD80	-	-	32.8	2.1	-	-	48.9	4.8
MD90	-	-	33.5	2.4	-	-	34.7	1.9
Reg Jets	23.6	2.0	33.1	2.4	51.8	4.2	42.3	3.9

[a] Times to 1000 ft and 1500 ft are given for aircraft types where either is used depending on operator – see text in Section 2
[b] SE – standard error on the mean

Table 2.7 Comparison of initial-climb and climb-out times for 2008/9 and 2002

	Initial-climb time(s)		Climb-out time (s)	
NATS Group	2008/9	2002	2008/9	2002
1	40.6	35.6	81.3	89.3
2	29.4	28.5	67.8	70.7
4	25.9	24.0	60.4	57.8
5	29.6	29.9	58.5	63.1
All	32.9	32.3	65.2	70.9

Table 2.8 NATS Groups and Wake Vortex categories

NATS Group	Wake Vortex category	Example A/C types
1	Heavy	A330; A340; A380; B747; B777
2	Heavy	A300; A310; B767,
3	Heavy	(Concorde) - no longer used
4	Upper	B757
5	Medium	A319/320/321; B737 (all series); F100; BAe146 (at LHR)
6	Medium	Avro RJ100
7	Small	Embraer RJ135; Canadair Regional Jet 100,700; Fokker F70
8	Small	ATR-42; ATR-72; De Havilland Dash 8; Fokker F50
8A	Small	Embraer 145
9-12	Light	Fairchild Dornier D328

Table 2.9 Approach time as a function of WV category

Category	Approach time (s)	
	2008/9	PSDH
Heavy	225	236
Medium	231	246
Small	233	258
Light	243	258

Table 2.10 APU NO_x emission rates and class assignments

NO_x class	NO_x emission rate (kg/hour)			Aircraft types in class
	No load	ECS	MES	
a	0.274	0.452	0.530	B727-100/200; BAe 146; A318; ERJ 135/145; F100, Tu 154M; Business Jets (with an APU)
b	0.364	0.805	1.016	B737-NG; CRJ; CRJ700; MD90
c	0.565	1.064	1.354	B737-CB757-2; A319/320/321; MD80; B767-2; B767-3
d	0.798	1.756	2.091	A300; A310; MD11; DC10; L1011-1/5/50/100
e	1.137	2.071	2.645	A330; B747-4; B747-SP; A340-3; B747-1; B747-2; B747-3
f	1.210	2.892	4.048	B777-2; B777-3; A340-6; A380

Table 2.11 APU PM_{10} emission rates

PM_{10} class	PM_{10} emission rate (kg/hour) as function of NO_x emission rate (kg/hour)	Aircraft types in class
A	$PM_{10}=0.0233 \times (NO_x)^{0.0934}$	All types (with an APU) except those below
B	$PM_{10}=0.379 \times (NO_x)^{2.642}$	Business jets (with an APU); BAe146; ERJ 135/145; CRJ; CRJ700
C	$PM_{10}=0.0630 \times (NO_x)^{0.173}$	B757-2; B767-2; B767-3; A300; A310

Table 2.12 APU running time per LTO cycle

	APU running time /LTO (min)	
	2008/9	2002 PSDH
Narrow-bodied	32.9	55.8
Wide-bodied	88.0	101.5

Table 2.13 Volume of fuel supplied for (potential) airside use

	Annual volume (m^3)	
	2008/9	2002/3
Gasoil/diesel	11207	9117
Petrol	165	503
LPG	7	48

Table 2.14 Estimated mass of fuel consumed airside

Vehicle type	Inventory	Mass of fuel (tonne) Gasoil	Diesel	Petrol	LPG	Total
Road vehicles	2008/9	6055	1163	109	2	7329
	2002	4400	1669	342	16	6426
Off-road vehicle/plant	2008/9	2698	518	12	2	3230
	2002	1163	441	29	12	1645
Total	2008/9	8753	1681	122	4	10560
	2002	5563	2110	371	28	8072

Table 2.15 Breakdown of fuel used airside by vehicle category in 2008/9

	Category	Fuel (tonne)
Road vehicles	Car	1377
	LGV	2517
	Rigid HGV	2401
	Artic HGV	594
	Bus/coach	439
Off-road vehicles/plant	37-75 kW	1134
	75-130 kW	263
	130-560 kW	1834
Total		10560

Table 2.16 Characteristics of airside operations

Vehicle category	Fraction of time idling (%)	Average speed when moving (kph)
Baggage tug	64	12.6
Cargo lorry	75	38.2
Catering vehicle	55	21.7
Coach	45	17.9
ITO*	74	14.7
Pushback tug	39	3.7

* ITO – inter-terminal baggage operation

Table 2.17 Effective (exhaust) emission factors for airside road vehicles (g/kg)

Vehicle type	Category	Emission factor (g/kg)	
		NO_x	PM*
Diesel Car	Pre-Euro 1	14.51	3.77
	Euro 1	19.86	1.44
	Euro 2	18.25	0.65
	Euro 3	9.80	0.64
	Euro 4	8.36	0.44
Diesel LGV	Pre-Euro 1	26.79	5.34
	Euro 1	22.96	1.23
	Euro 2	17.02	0.80
	Euro 3	7.23	0.81
	Euro 4	5.56	0.54
Rigid HGV	Pre-Euro I	35.64	3.23
	Euro I	30.91	1.92
	Euro II	35.69	0.68
	Euro III	30.88	0.83
	Euro IV	17.86	0.20
	Euro V	10.94	0.20
Artic HGV	Pre-Euro I	35.64	1.89
	Euro I	29.24	1.83
	Euro II	32.60	0.61
	Euro III	29.80	0.78
	Euro IV	18.40	0.18
	Euro V	11.15	0.18
Bus	Pre-Euro I	37.84	2.28
	Euro I	30.48	1.44
	Euro II	36.44	0.63
	Euro III	30.76	0.50
	Euro IV	18.53	0.19
	Euro V	11.59	0.18
Coach	Pre-1988	36.54	1.94
	Pre-Euro I	36.54	1.94
	Euro I	32.98	1.68
	Euro II	37.85	0.68
	Euro III	34.89	0.79
	Euro IV	19.90	0.21
	Euro V	12.37	0.21
Petrol car	Pre-Euro 1	15.58	0.05
	Euro 2	9.24	0.04
	Euro 3	3.95	0.04
	Euro 4	3.03	0.04
	Euro 5	2.34	0.04
Petrol LGV	Pre-Euro 1	19.61	0.06
	Euro 2	7.44	0.04
	Euro 3	4.44	0.02
	Euro 4	2.97	0.02
	Euro 5	1.54	0.02

* PM – Particulate Matter; PM_{10}=0.98*PM; $PM_{2.5}$=0.95*PM_{10}

Table 2.18 Emission factors (g/kg) for diesel and petrol off-road vehicles

Fuel	Category		Emission factor (g/kg)		
			NO_x	PM_{10}	$PM_{2.5}$
Diesel	37-75 kW	Uncontrolled	48.22	6.84	6.56
		Stage I	32.19	3.60	3.46
		Stage II	29.66	1.53	1.48
		Stage IIIA	15.06	1.49	1.44
Diesel	75-130 kW	Uncontrolled	46.74	6.08	5.85
		Stage I	33.01	2.99	2.88
		Stage II	25.93	1.21	1.16
		Stage IIIA	13.36	1.15	1.09
Diesel	130-560 kW	Uncontrolled	49.01	5.39	5.15
		Stage I	33.39	2.41	2.32
		Stage II	26.33	0.84	0.81
		Stage IIIA	13.56	0.80	0.77
Petrol	37-75 kW	Uncontrolled	11.34	*	*
		Controlled	11.59	*	*
Petrol	75-130 kW	Uncontrolled	11.96	*	*
		Controlled	11.96	*	*
Petrol	130-300 kW	Uncontrolled	13.16	*	*
		Controlled	12.79	*	*

[a] No PM values given – taken to be insignificant

Table 2.19 NO_x emission factors for airside LPG-fuelled vehicles

Vehicle type	Category	Emission factor (g/kg)	
		NO_x	PM
Car	Pre Euro 1	22.84	0.069
	Euro 1	29.77	0.047
	Euro 2	6.49	0.030
	Euro 3	5.91	0.029
	Euro 4	4.38	0.026
LGV	Pre Euro 1	28.74	0.087
	Euro 1	32.83	0.051
	Euro 2	7.50	0.034
	Euro 3	6.45	0.031
	Euro 4	4.29	0.026
HGV and specialist		28.57	

Table 2.20 Fraction by Euro standard

(a) Petrol car and LGV

Category	Fraction (%)	
	Car	LGV
Pre-Euro 1	1.0	4.2
Euro 1 OK	4.8	3.4
Euro 1 fail	1.0	0.7
Euro 2 OK	16.4	15.1
Euro 2 fail	3.4	3.1
Euro 3 OK	16.8	28.8
Euro 3 fail	2.2	4.3
Euro 4 OK	50.9	38.2
Euro 4 fail	3.6	2.3
Total	100.0	100.0

(b) Diesel car and LGV

Category	Fraction (%)	
	Car	LGV
Pre-Euro 1	0.2	1.4
Euro 1	3.4	4.2
Euro 2	8.3	18.7
Euro 3 no DPF	34.4	34.0
Euro 3 with DPF	6.4	-
Euro 4 no DPF	37.8	41.7
Euro 4 with DPF	9.4	-
Total	100.0	100.0

(c) HGV

Category	Fraction (%)			
	London		Outside London	
	Rigid	Artic	Rigid	Artic
Pre Euro I	0.0	0.0	0.0	0.0
Euro I	0.6	0.1	2.5	0.8
Euro II	5.4	1.0	23.4	15.0
Euro III	58.4	62.4	46.0	53.0
Euro IV	28.3	29.6	22.3	25.1
Euro V	7.3	6.9	5.8	6.0
Total	100.0	100.0	100.0	100.0

(d) Bus

Category	Fraction (%)
Pre Euro I	0.7
Euro I	1.0
Euro II	9.1
Euro III	54.9
Euro IV	27.5
Euro V	6.7
Total	100.0

Table 2.21 Traffic composition (vehicle-km by vehicle category), for sub-categories recognised in TRL2009, for 2008/9

	Fraction (%)					
	London			Outside London		
Category	Urban	Rural	M'way	Urban	Rural	M'way
Petrol car	73.0	60.2	51.5	73.0	60.2	51.5
Diesel car	27.0	39.8	48.5	27.0	39.8	48.5
Total	100.0	100.0	100.0	100.0	100.0	100.0
Petrol LGV	10.6	10.6	10.6	10.6	10.6	10.6
Diesel LGV	89.4	89.4	89.4	89.4	89.4	89.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Rigid HGV	74.8	60.7	36.0	83.5	60.7	36.0
Artic HGV	25.2	39.3	64.0	16.5	39.3	64.0
Total	100.0	100.0	100.0	100.0	100.0	100.0
Black cab	11.5[a]					
Other diesel car	88.5[a]					
Total	100.0					

[a] The urban proportions have been used throughout the Heathrow road network area

Table 2.22 Traffic composition (vehicle-km by vehicle category), for sub-categories recognised in TRL2009

(a) Breakdown by car engine size

Engine size	Fraction (%)	
(cc)	Petrol car	Diesel car
<1400	38.3	5.2
1400-2000	47.7	63.6
>2000	14.1	31.1
Total	100.0	100.0

(b) Breakdown by LGV weight category

Weight	Fraction (%)	
category	Petrol LGV	Diesel LGV
N1(I)	6.2	6.2
N1(II)	25.7	25.7
N1(III)	68.1	68.1
Total	100.0	100.0

(c) Breakdown by rigid-HGV weight category

Weight	Fraction (%)			
category	Urban	Rural	Motorway	Average
3.5-7.5 t	47.1	45.5	47.8	46.6
7.5-12 t	3.3	3.2	3.4	3.3
12-14 t	2.9	2.8	2.9	2.8
14-20 t	22.7	21.9	23.0	22.4
20-26 t	6.7	7.6	7.0	7.2
26-28 t	4.8	5.5	5.1	5.2
28-32 t	11.2	12.1	9.7	11.1
>32 t	1.4	1.5	1.2	1.4
Total	100.0	100.0	100.0	100.0

(d) Breakdown by articulated-HGV weight categories

Weight category	Fraction (%)			
	Urban	Rural	Motorway	Average
14-20 t	0.7	0.5	0.4	0.4
20-28 t	9.8	7.6	5.9	6.7
28-34 t	5.1	3.9	3.0	3.5
34-40 t	76.9	80.2	83.8	82.1
40-50 t	7.6	7.8	7.0	7.3
Total	100.0	100.0	100.0	100.0

(e) Bus/coach split by road type

	Fraction (%)	
	Urban/rural	Motorway
Bus	72.0	0.0
Coach	28.0	100.0
Total	100.0	100.0

(f) Breakdown by bus/coach weight category

Weight category	Fraction (%)	
	Bus	Coach
<15 t	31.4	50.0
15-18 t	68.6	50.0
Total	100.0	100.0

Table 2.23 Fugitive PM emission factors for brake and tyre wear

Vehicle category	Emission factor (10^{-3} g/km)			
	Brake wear[1]		Tyre wear[2]	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Car	7.31	2.91	6.43	4.50
LGV	11.41	4.54	10.15	7.10
Rigid HGV / buses (motorway)[3]	31.93	12.71	15.81	11.07
Rigid HGV / buses (urban)[3]	31.93	12.71	16.00	11.20
Rigid HGV / buses (rural)[3]	31.93	12.71	16.25	11.37
Artic HGV (motorway)[3]	31.93	12.71	35.65	24.95
Artic HGV (urban)[3]	31.93	12.71	35.36	24.75
Artic HGV (rural)[3]	31.93	12.71	35.74	25.02

[1] Speed dependent (see text); values shown for 65 kph
[2] Speed dependent (see text); values shown for 80 kph
[3] Value are given for 50% load.

Table 2.24 Car park and car rental transactions in 2008/9

		Annual thro'put (thousands)	Distance travelled (m)
Public	Business T1,T2,T3	168	1214
	Business T4	50	493
	Business T4 Park Plus	59	493
	Long Stay	155	973
	Park 1	37	579
	T5 Business Park	89	220
	T5 Fast Track	100	477
	T5 Overheight	78	477
	T5 Short Stay	2027	2387
	T5 Long Stay	142	629
	T1 Short Stay	673	1075
	T1A Short Stay	751	1243
	T2 Short Stay	842	903
	T3 Short Stay	2505	1075
	T4 Short Stay	919	679
	Car rental	434	362/629[a]
Staff	N4	440	466
	Eastside	586	421
	PEX	446	973
	Flightpath	405	973
	Southside	294	399
	P5	162	287
	P4	287	726
	P2	22	78
	NT5	999	406/666[a]
	N2	284	348

[a] Values for two separate parts of rental pound or car park

Table 2.25 Fleet-averaged cold start emission factors for 2008/9 (g/trip)

Category	Emission factor (g/trip)		
	NO_x	PM_{10}	$PM_{2.5}$
Car (average)	0.816	0.024	0.022
Taxi (diesel car)	0.143	0.091	0.081

Table 2.26 Fleet-averaged road vehicle exhaust emission factors at 16 kph for 2008/9 (g/km)

Category	Emission factor (g/km)		
	NO_x	PM_{10}	$PM_{2.5}$
Cars	0.371	0.011	0.010
Black cabs	0.786	0.084	0.075

Table 2.27 Queuing emission rates for black cabs for 2008/9 (g/s)

Emission rate (10^{-3} g/s)		
NO_x	PM_{10}	$PM_{2.5}$
2.70	0.34	0.31

Table 2.28 Heating plant: fuel energy input in 2008/9 (MJ)

Fuel	Plant	Annual fuel energy input (10^6 MJ)
Gas (BAA)	CHP	1335.37
	448	373.16
	T4	64.56
	T5	18.97
Gas (BA)	BA Cargo	253.44
	BA Maint 1	535.27
	BA Maint 2	103.52
	Compass Centre*	14.77
	T4 Early Baggage Store*	1.03
	Museum	0.40
	Northside House	10.78
Gasoil	CHP	0.19
	British Midland	11.02
	Viscount	5.27
	450 Old Fire Station	6.11
	895	0.81
	679	6.49
	1092	5.16
	1157 ASU	0.54
	Control tower	0.85
	Metro	1.62
Total		2749.32

* These were handed over to BAA during 2008. Only the BA usage is given here, with the BAA usage counted elsewhere

Table 2.29 Emission factors for heating plant

(a) plant-specific emission factors (gas firing)

Plant	Emission factor (10^{-3} g/MJ)	
	NO_x	PM_{10}
CHP	97.0	18.02
448 summer	41.4	0.42
448 winter	41.5	0.42
T4	38.9	0.26
T5	25.8	

(b) default emission factors

Plant	Emission factor (10^{-3} g/MJ)	
	NO_x	PM_{10}
Boilers (NAEI)		
gas	143.1	1.62
gasoil	104.2	6.03
Turbines (AP-42)		
Gasoil	300.0	26.19

Table 2.30 Emission factors for LPG combustion in the Fire Training Ground

Pollutant	Emission factor (g/litre)
NO_x	1.80
PM_{10}	0.06

Table 3.1 Initial climb angle up to 1000 ft (305 m)

Aircraft Group	Angle (º)
300	13.2
319	13.8
320	14.6
321	14.0
330	11.4
343	7.3
346	7.0
380	6.6
737	13.4
747	7.7
757	14.2
767	10.9
772	9.6
777-ER	9.3
MD80	15.9
MD90	14.2
Reg Jets	15.5

Table 5.1 NO_x emissions for 2008/9 by source category; fractional change from equivalent 2002 values

Source category			Emissions (tonnes/year)[1]			FD[2] %
Airport						
Aircraft			4424.84			6.8
	Ground level			1618.67		-2.6
		Taxi-out			212.78	-22.0
		Hold			166.21	11.7
		Take-off roll			717.51	9.9
		Landing roll			40.37	4.5
		Taxi-in			132.39	-10.5
		APU			346.06	-10.2
		Engine testing			3.34	-78.6
	Elevated			2806.17		13.0
		Initial climb			869.62	32.0
		Climb out			1398.22	6.1
		Approach			538.33	6.3
Airside vehicles/plant			260.49			10.0
	Road vehicles			138.41		-11.0
	Off-road vehicles			122.09		50.1
Car parks etc			18.27			-31.1
	Public car parks[3]			11.62		-30.1
	Staff car parks			5.07		-27.7
	Taxis (TFP and forecourts)			1.58		-45.1
Stationary sources			283.74			58.5
	Heating plant			283.60		58.6
	Fire Training Ground			0.14		0.0
Road network			2463.59			-31.0
	LDVs			1170.49		N/A
	HDVs			1293.11		N/A

[1] Values quoted to 0.01 tonne for convenience in taking ratios etc. and should not be taken as indicative of the precision of the estimates
[2] Fractional Difference=100*(2008/9 value-2002 value)÷2002 value
[3] Includes car rental

Table 5.2 Breakdown of airside-vehicle NO_x emissions for 2008/9 by vehicle category

Vehicle type	Category	NO_x (tonne/year)	% of total
Road vehicles	Car	14.22	5.46
	LGV	23.88	9.17
	Rigid HGV	73.35	28.16
	Artic HGV	16.30	6.26
	Bus/coach	10.65	4.09
Off-road vehicles	37-75 kW	43.17	16.57
	75-130 kW	8.48	3.26
	130-560 kW	70.43	27.04
Total		260.49	100.00

Table 5.3 Traffic-average NO_x emission factor on the road network (g/km)

Quantity	Units	2008/9
LDV		
NO_x	tonne/year	1170.49
Vehicle-km	10^6 /year	2696.28
Ratio	g/km	0.43
HDV		
NO_x	tonne/year	1293.11
Vehicle-km	10^6 /year	197.20
Ratio	g/km	6.56
Total		
NO_x	tonne/year	2463.59
Vehicle-km	10^6 /year	2893.47
Ratio	g/km	0.85

Table 5.4 Ground-level aircraft NO_x emissions[1] by aircraft type

	2008/9			2002		
Aircraft type	NO_x[1] (tonne/year)	%	NO_x/mvt (kg/mvt)	NO_x[1] (tonne/year)	%	NO_x/mvt (kg/mvt)
Airbus A300/310	8.83	0.70	2.43	30.71	2.44	2.69
Airbus A319	90.82	7.16	1.10	59.99	4.76	1.25
Airbus A321	99.64	7.85	1.10	90.51	7.18	1.23
Airbus A320	80.77	6.36	1.49	73.70	5.85	1.67
Airbus A330	59.28	4.67	4.44	23.95	1.90	4.55
Airbus A340	159.54	12.57	6.55	49.71	3.94	5.28
Airbus A380	12.14	0.96	8.03	-	-	-
Boeing 737	29.98	2.36	1.07	98.84	7.84	1.17
Boeing 747	291.15	22.94	6.55	435.70	34.56	8.63
Boeing 757	37.13	2.93	1.99	50.31	3.99	1.57
Boeing 767	84.18	6.63	2.98	86.47	6.86	3.19
Boeing 777	297.94	23.47	5.58	206.80	16.40	5.93
MD80/90	10.36	0.82	1.09	26.47	2.10	1.28
Other	7.49	0.59	0.44	27.68	2.20	1.11
Total	1,269.27	100.00	2.70	1,260.82	100.00	2.70

[1] LTO ground–level emissions from main engines only (omitting APU and engine testing)

Table 5.5 PM$_{10}$ emissions for 2008/9 by source category; fractional change from equivalent 2002 values

Source category			Emissions (tonnes/year)[1]			FD[2] %
Airport						
Aircraft			50.57			6.2
	Ground level			35.88		-2.6
		Taxi-out			4.38	-22.7
		Hold			3.35	9.5
		Take-off roll			3.39	33.8
		Landing roll			0.55	14.3
		Tyre wear			5.98	20.0
		Brake wear			9.07	15.1
		Taxi-in			2.78	-13.6
		APU			6.31	-27.1
		Engine testing			0.07	-82.1
	Elevated			14.69		36.4
		Initial climb			3.35	51.2
		Climb out			6.15	31.8
		Approach			5.19	33.3
Airside vehicles/plant			21.43			16.0
	Exhaust			17.75		21.6
		Road			5.44	-31.6
		Off-road			12.31	85.2
	Fugitives			3.68		-5.3
		Road			2.97	-23.4
		Off-road			0.70	N/A
Car parks etc			1.64			-0.3
	Exhaust			0.75		-17.7
		Public car parks[2]			0.35	-10.6
		Staff car parks			0.15	-8.7
		Taxis			0.26	-29.3
	Fugitives			0.88		21.5
		Public car parks[2]			0.70	42.6
		Staff car parks			0.17	-19.9
		Taxis			0.01	-50.4
Stationary sources			26.08			14.6
	Heating plant			26.08		14.6
	Fire Training Ground			<0.01		0.0
Road network			239.34			84.0[4]
	Exhaust			74.78		-42.5
		LDV			52.14	N/A
		HDV			22.64	N/A
	Fugitives			164.56		N/A

[1] Values quoted to 0.01 tonne for convenience in taking ratios etc. and should not be taken as indicative of the precision of the estimates
[2] Fractional Difference=100*(2008/9 value-2002 value)÷2002 value
[3] Includes car rental
[4] 2002 value did not include fugitives
N/A – not available for 2002

Table 5.6 $PM_{2.5}$ emissions for 2008/9 by source category

Source category	Emissions (tonnes/year)[1]		
Airport			
Aircraft	43.31		
Ground level		28.63	
Taxi-out			4.38
Hold			3.35
Take-off roll			3.39
Landing roll			0.55
Tyre wear			4.19
Brake wear			3.61
Taxi-in			2.78
APU			6.31
Engine testing			0.07
Elevated		14.69	
Initial climb			3.35
Climb out			6.15
Approach			5.19
Airside vehicles/plant	18.84		
Exhaust		16.97	
Road			5.17
Off-road			11.80
Fugitives		1.87	
Road			1.50
Off-road			0.36
Car parks etc	1.12		
Exhaust		0.67	
Public car parks[2]			0.31
Staff car parks			0.13
Taxis			0.23
Fugitives		0.45	
Public car parks[2]			0.36
Staff car parks			0.09
Taxis			0.01
Stationary sources	26.08		
Heating plant		26.08	
Fire Training Ground		<0.01	
Road network	156.06		
Exhaust		71.04	
LDVs			49.53
HDVs			21.51
Fugitives		85.02	

[1] Values quoted to 0.01 tonne for convenience in taking ratios etc. and should not be taken as indicative of the precision of the estimates
[2] Includes car rental

Table 5.7 Breakdown of airside-vehicle PM emissions for 2008/9 by vehicle category

(a) PM_{10}

Vehicle type	Category	Exhaust (tonne/year)	% of total	Fugitive (tonne/year)	% of total
Road vehicles	Car	0.79	4.43	0.84	22.70
	LGV	2.00	11.29	1.20	32.72
	Rigid HGV	2.05	11.56	0.74	20.00
	Artic HGV	0.45	2.53	0.12	3.17
	Bus/coach	0.15	0.84	0.08	2.27
Off-road vehicles	37-75 kW	4.90	27.62	0.46	12.44
	75-130 kW	0.78	4.40	0.08	2.09
	130-560 kW	6.63	37.33	0.17	4.61
Total		17.75	100.00	3.68	100.00

(b) $PM_{2.5}$

Vehicle type	Category	Exhaust (tonne/year)	% of total	Fugitive (tonne/year)	% of total
Road vehicles	Car	0.75	4.40	0.42	22.78
	LGV	1.90	11.21	0.62	33.03
	Rigid HGV	1.95	11.49	0.36	19.32
	Artic HGV	0.43	2.51	0.06	3.32
	Bus/coach	0.14	0.84	0.04	2.17
Off-road vehicles	37-75 kW	4.71	27.76	0.23	12.56
	75-130 kW	0.75	4.42	0.04	2.02
	130-560 kW	6.34	37.37	0.09	4.82
Total		16.97	100.00	1.87	100.00

Table 5.8 Traffic-average exhaust PM emission factor on the road network (g/km)

Quantity	Units	PM_{10}	$PM_{2.5}$
LDV			
Emissions	tonne/year	52.14	49.53
Vehicle-km	10^6 /year	2696.28	2696.28
Ratio	g/km	0.0193	0.0184
HDV			
Emissions	tonne/year	22.64	21.51
Vehicle-km	10^6 /year	197.20	197.20
Ratio	g/km	0.1148	0.1091
Total			
Emissions	tonne/year	74.78	71.04
Vehicle-km	10^6 /year	2893.47	2893.47
Ratio	g/km	0.0258	0.0246

Table 5.9 Ground-level aircraft PM[a] emissions[b] by aircraft type

Aircraft type	2008/9 PM (tonne/year)	2008/9 %	2008/9 PM/mvt (kg/mvt)	2002 PM (tonne/year)	2002 %	2002 PM/mvt (kg/mvt)
Airbus A300/310	0.13	0.92	0.036	0.31	2.05	0.027
Airbus A319	2.18	15.10	0.026	0.65	4.34	0.014
Airbus A320	2.00	13.87	0.022	1.08	7.24	0.015
Airbus A321	1.20	8.29	0.022	0.71	4.77	0.016
Airbus A330	0.40	2.77	0.030	0.17	1.11	0.032
Airbus A340	1.39	9.64	0.057	0.53	3.54	0.056
Airbus A380	0.07	0.52	0.049	-	-	-
Boeing 737	0.40	2.74	0.014	1.32	8.79	0.016
Boeing 747	3.11	21.51	0.070	5.29	35.33	0.105
Boeing 757	0.30	2.09	0.016	1.01	6.78	0.032
Boeing 767	0.80	5.56	0.028	0.93	6.21	0.034
Boeing 777	2.11	14.58	0.039	1.35	9.05	0.039
MD80/90	0.22	1.50	0.023	0.47	3.15	0.023
Other	0.13	0.92	0.008	1.14	7.63	0.046
Total	14.45	100.00	0.031	14.97	100.00	0.032

[a] For main engine exhaust $PM_{2.5}$ and PM_{10} have been taken to be the same
[b] LTO ground–level emissions from main engines only (omitting APU, engine testing, brake wear and tyre wear)

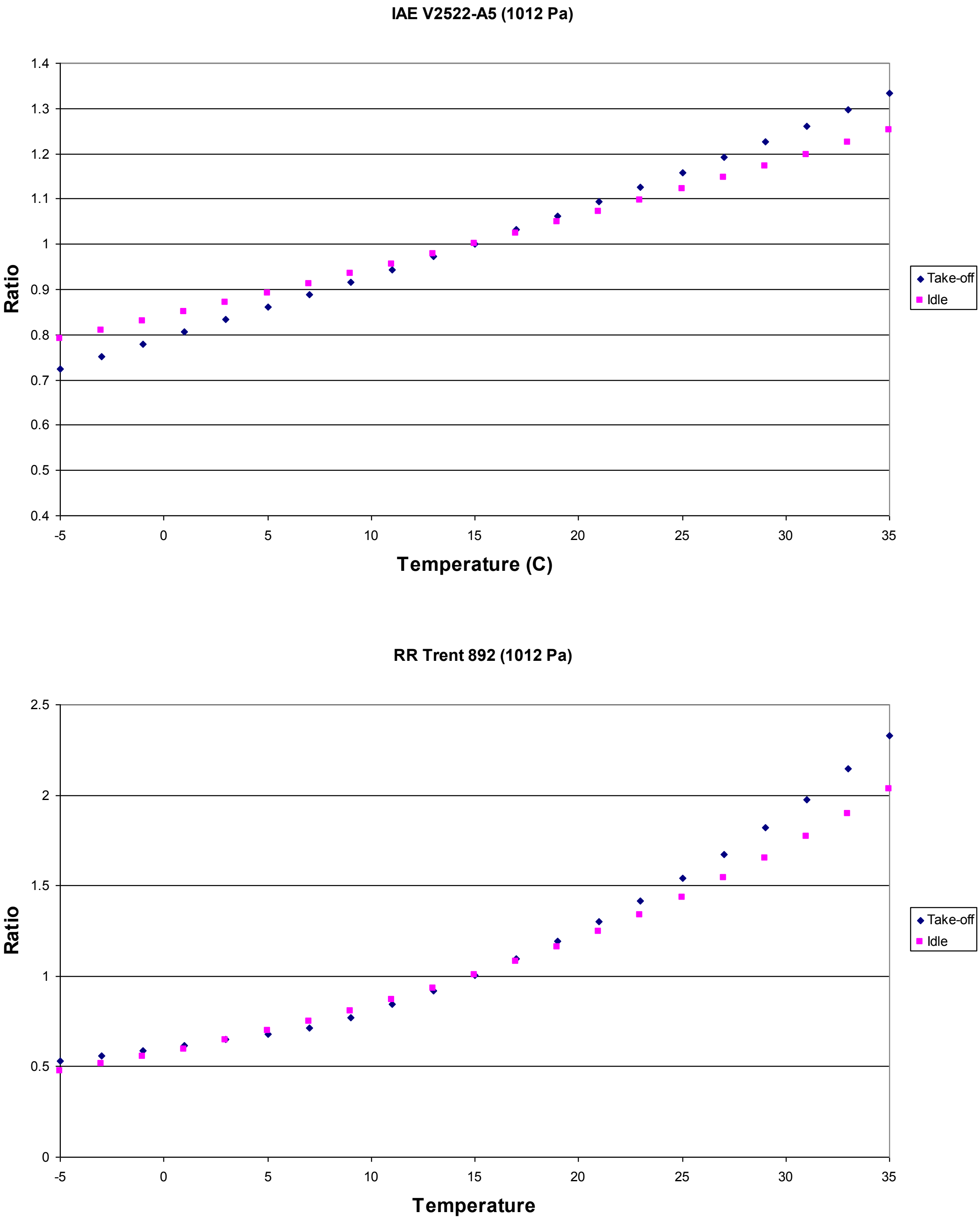
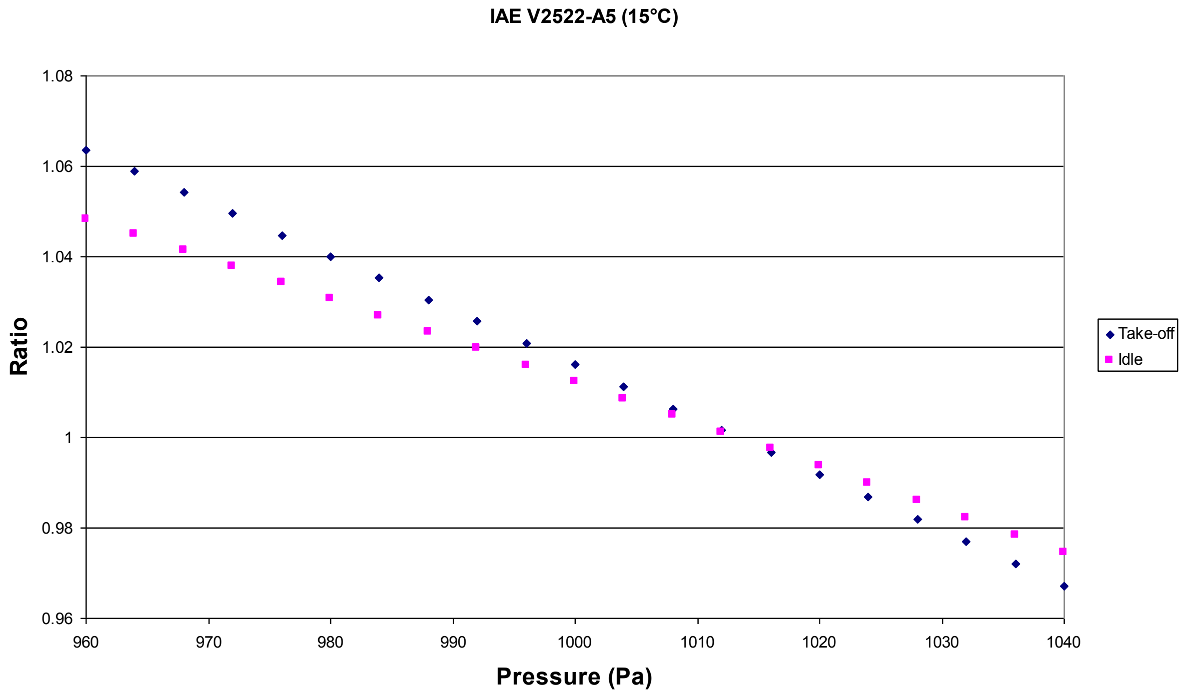


Fig 2.1 Example of temperature variation of NO_x emission rate for two selected engines. Ratio is referenced to value at 15°C



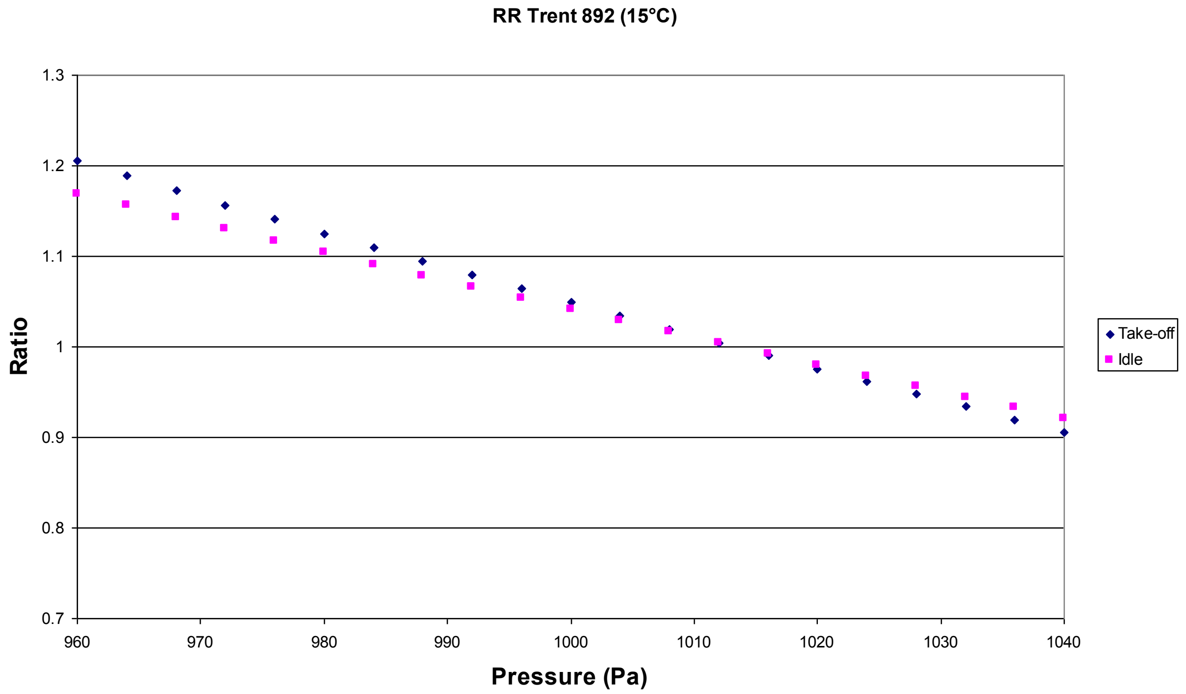


Fig 2.2 Example of pressure variation of NO_x emission rate for two selected engines. Ratio is referenced to value at 1013 Pa

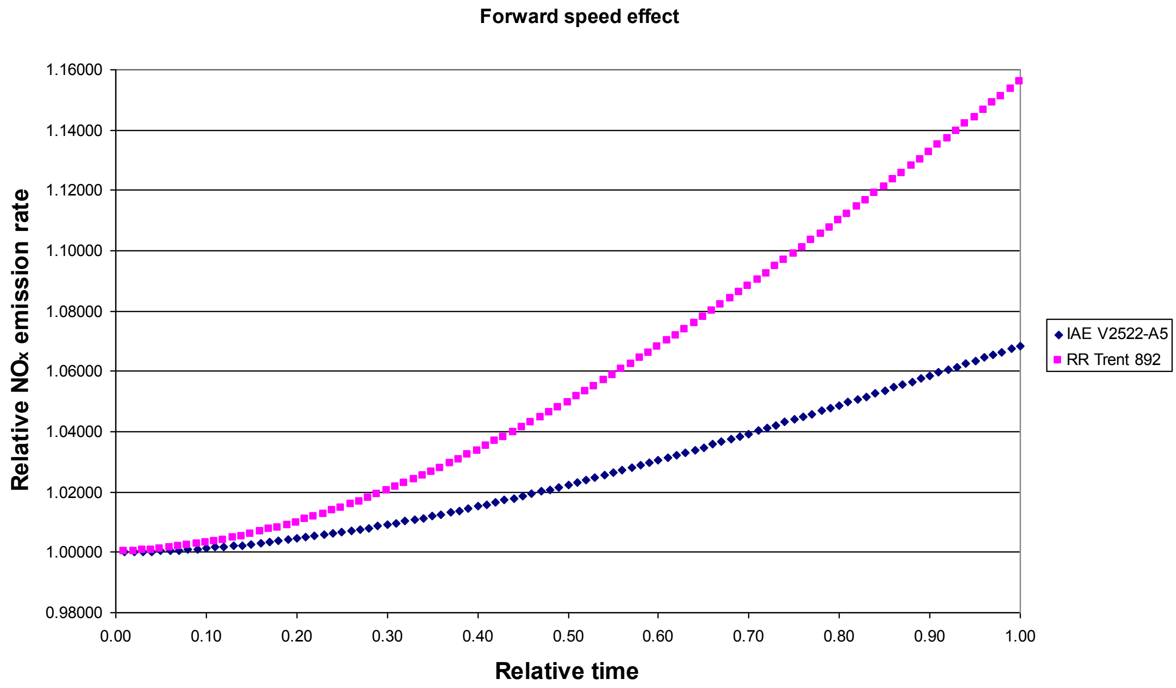


Fig 2.3 Example of forward speed effect for NO_x emissions during the take-off roll. NO_x emission rate is reference to the value for a stationary aircraft; time is expressed as a fraction of the total roll time. (NB: emission rates here do not include the effect of engine spool-up)

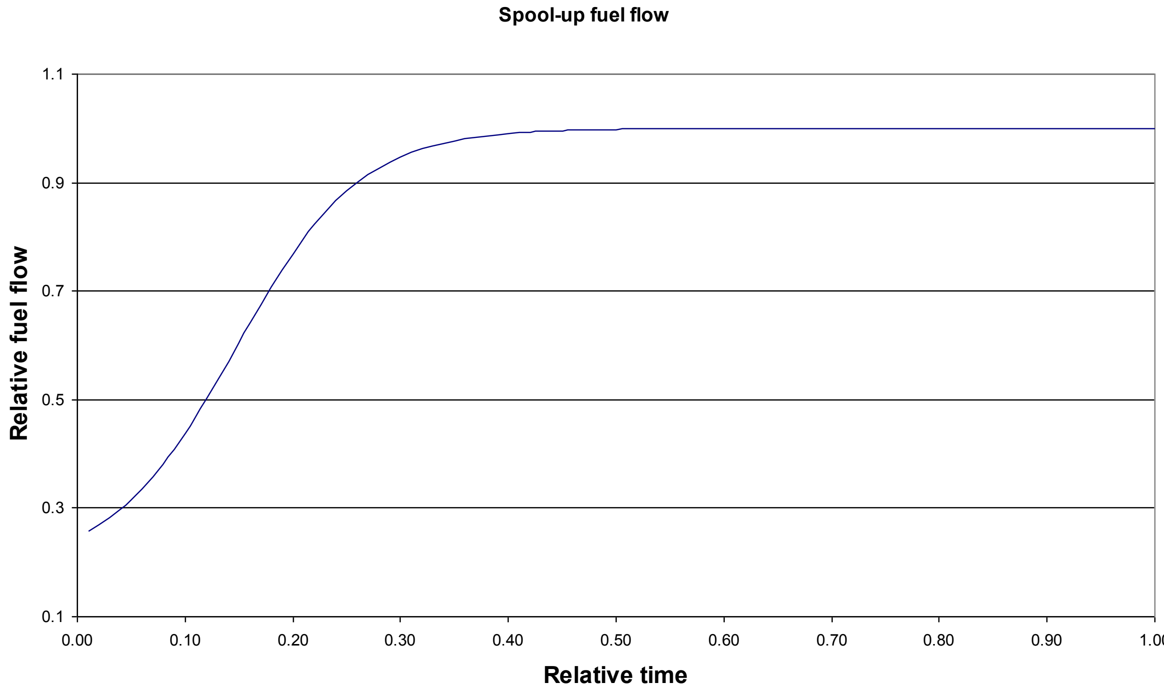


Fig 2.4 Fuel flow variation due to engine spool-up during take-off roll. Time is expressed as a fraction of total roll time; fuel flow is expressed relative to fuel flow when the engine has stabilised at take-off thrust.

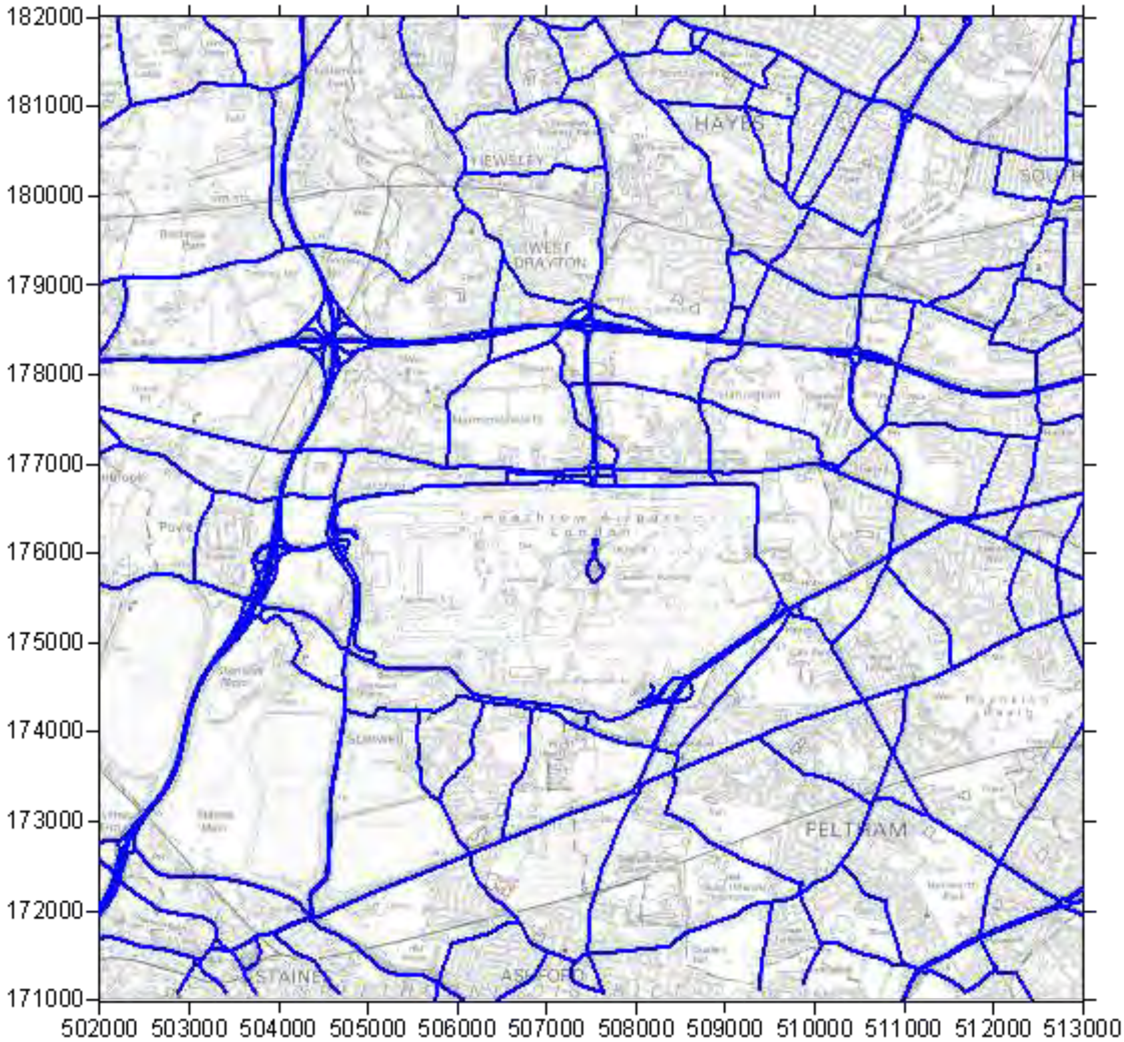


Fig 2.5 (a) Road network for which emissions calculated for the 2008/9 emission inventory

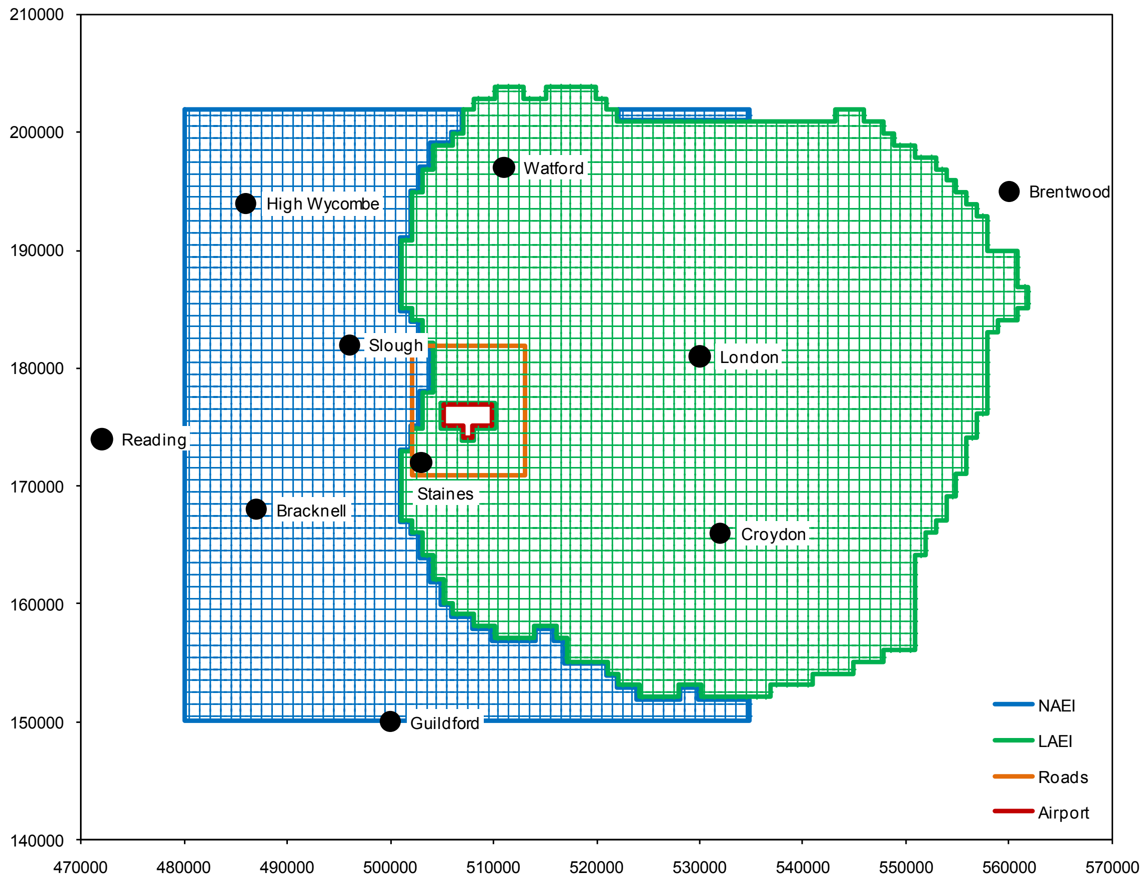


Fig 2.5 (b) Inventory areas used in the 2008/9 air quality modelling

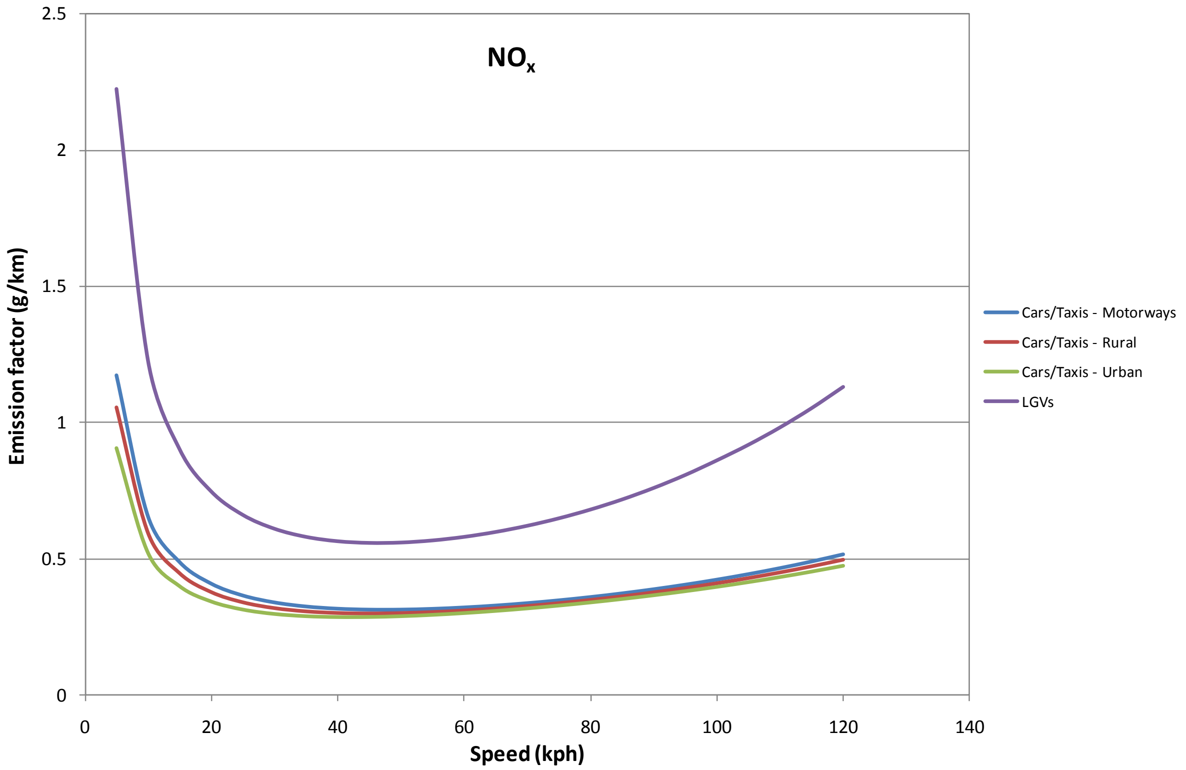


Fig 2.6 (a) NO_x speed-emission curves for LDV traffic categories for 2008/9

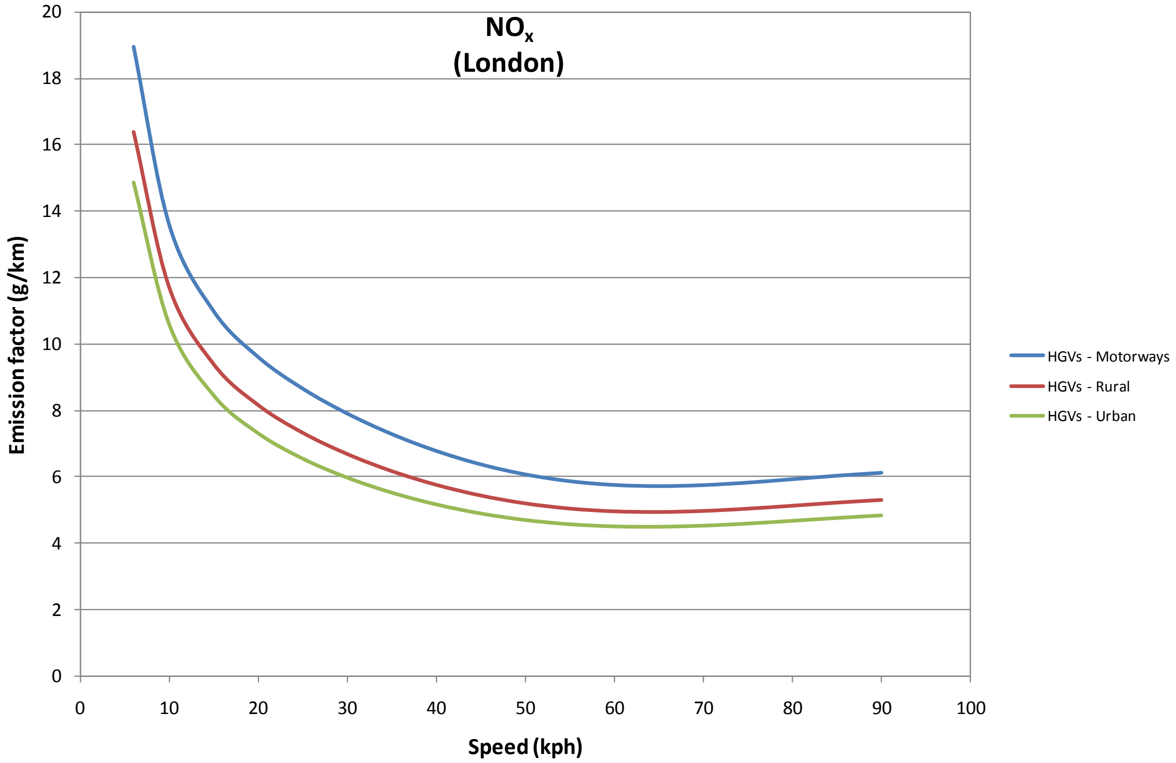


Fig 2.6 (b) NO_x speed-emission curves for the HGV traffic category for 2008/9, within London

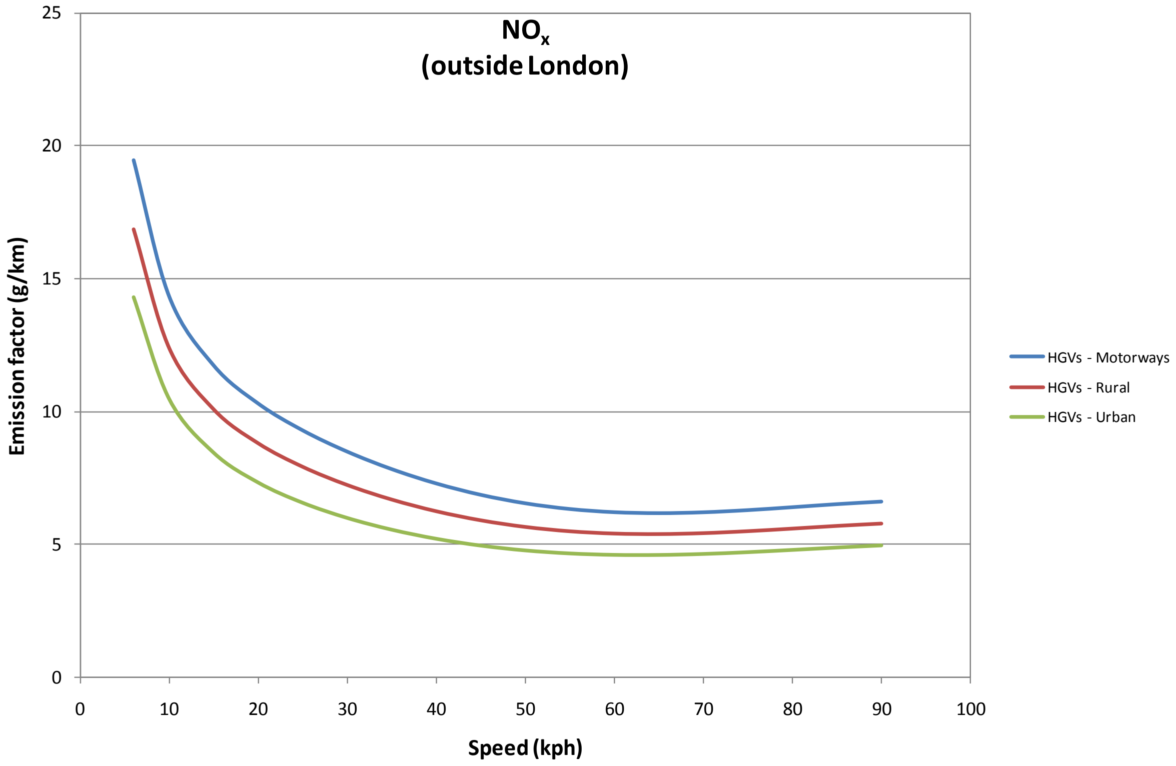


Fig 2.6 (c) NO_x speed-emission curves for the HGV traffic category for 2008/9, outside London

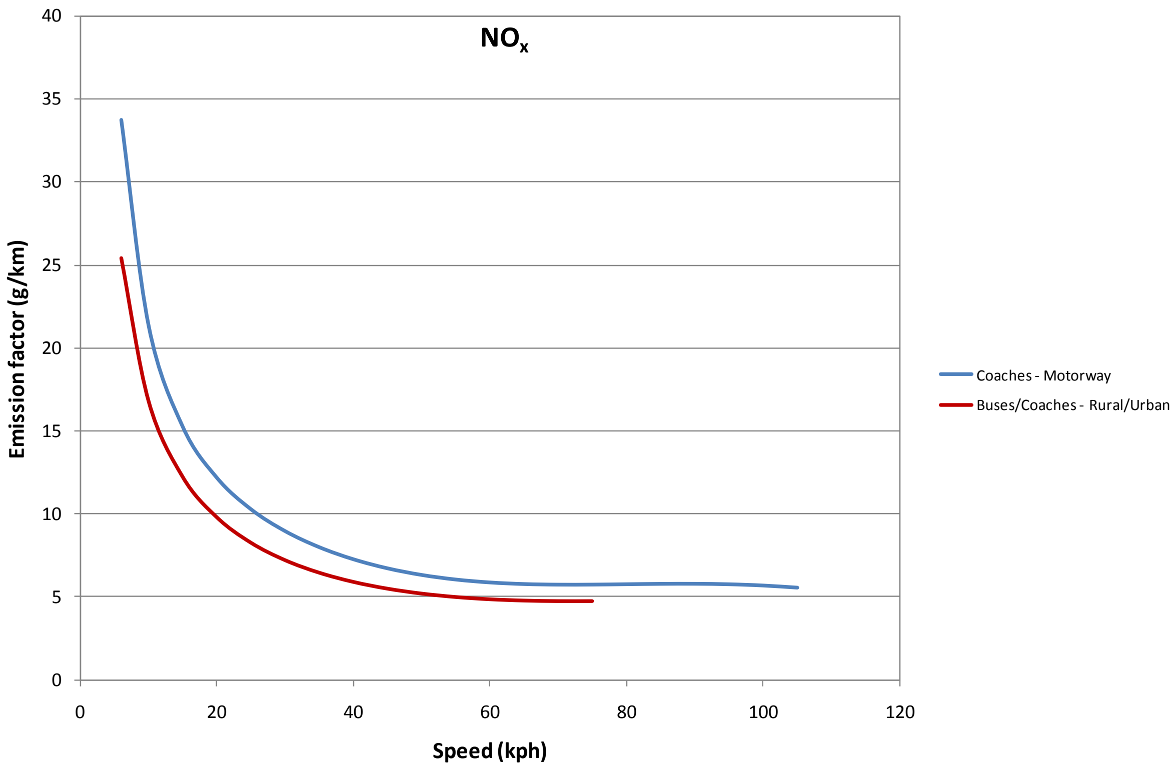


Fig 2.6 (d) NO_x speed-emission curves for the bus/coach traffic category for 2008/9

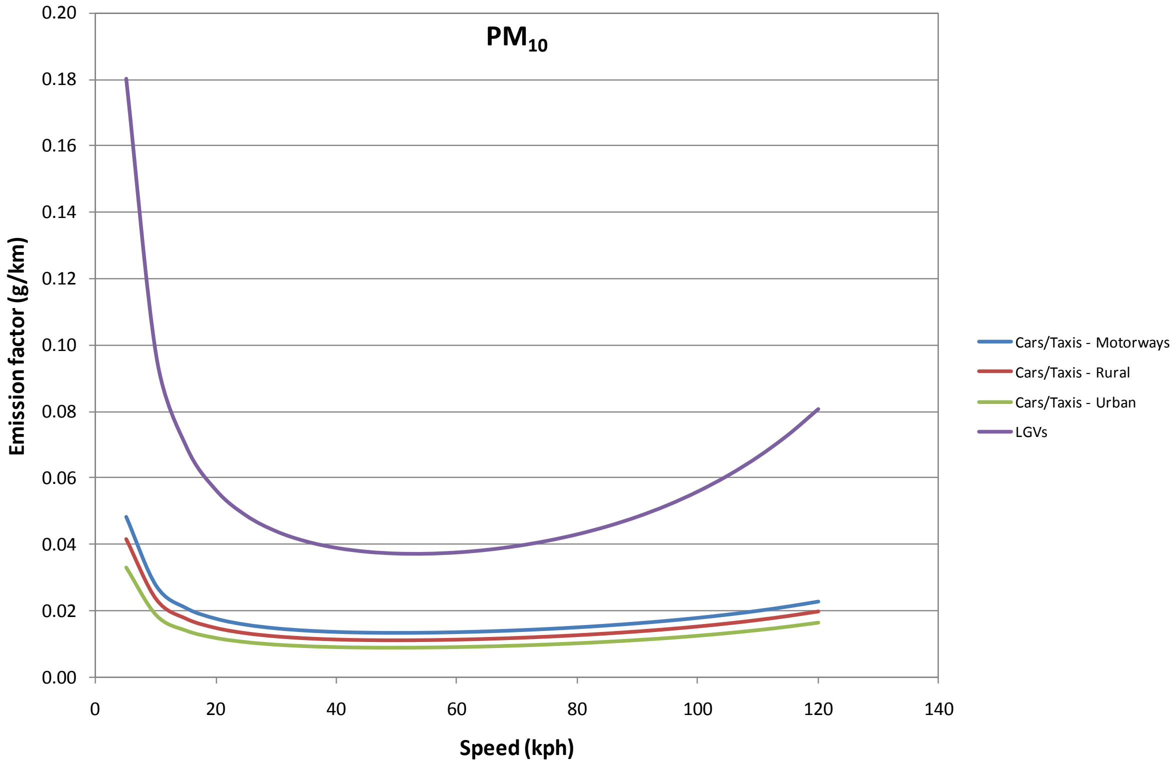


Fig 2.6 (e) PM_{10} speed-emission curves for LDV traffic categories for 2008/9

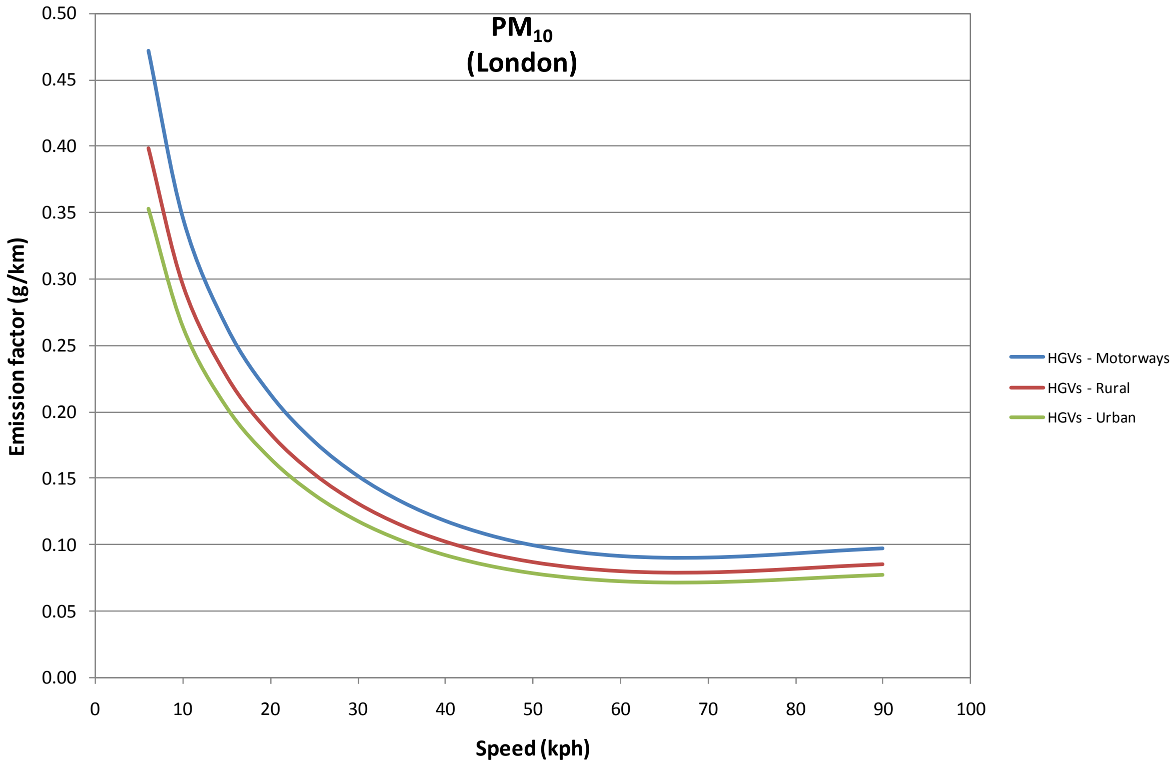


Fig 2.6 (f) PM_{10} speed-emission curves for the HGV traffic category for 2008/9, within London

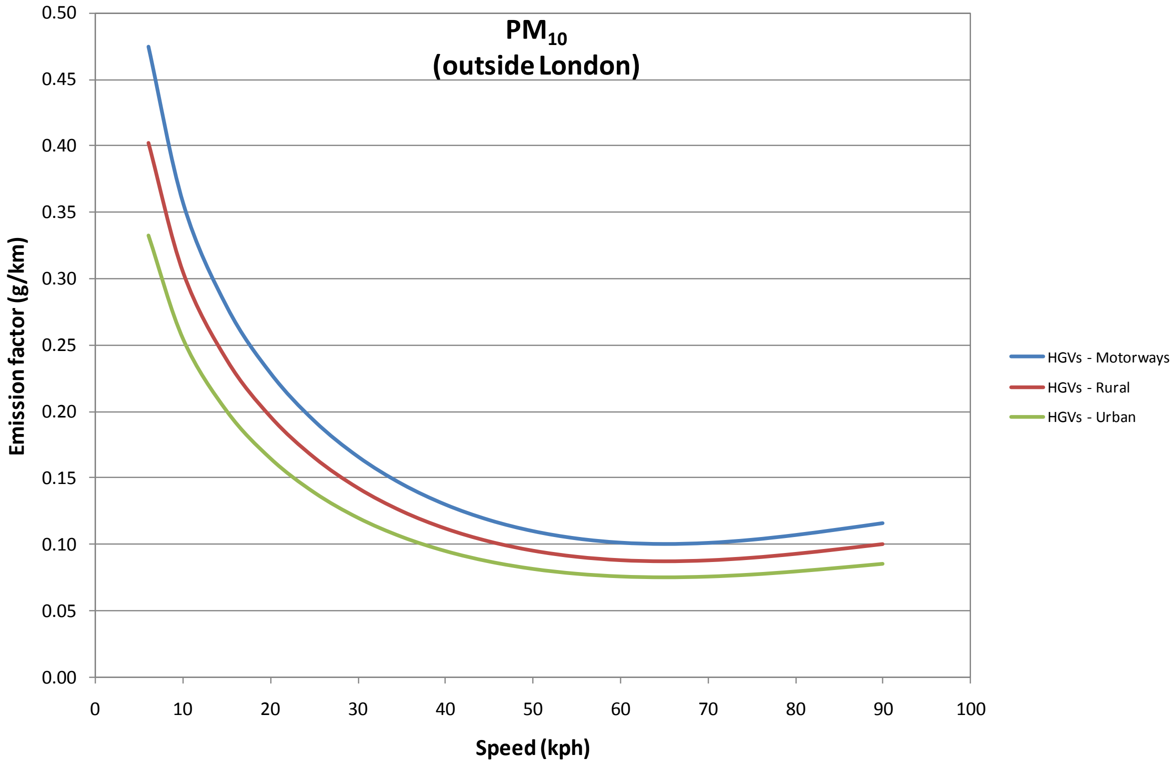


Fig 2.6 (g) PM_{10} speed-emission curves for the HGV traffic category for 2008/9, outside London

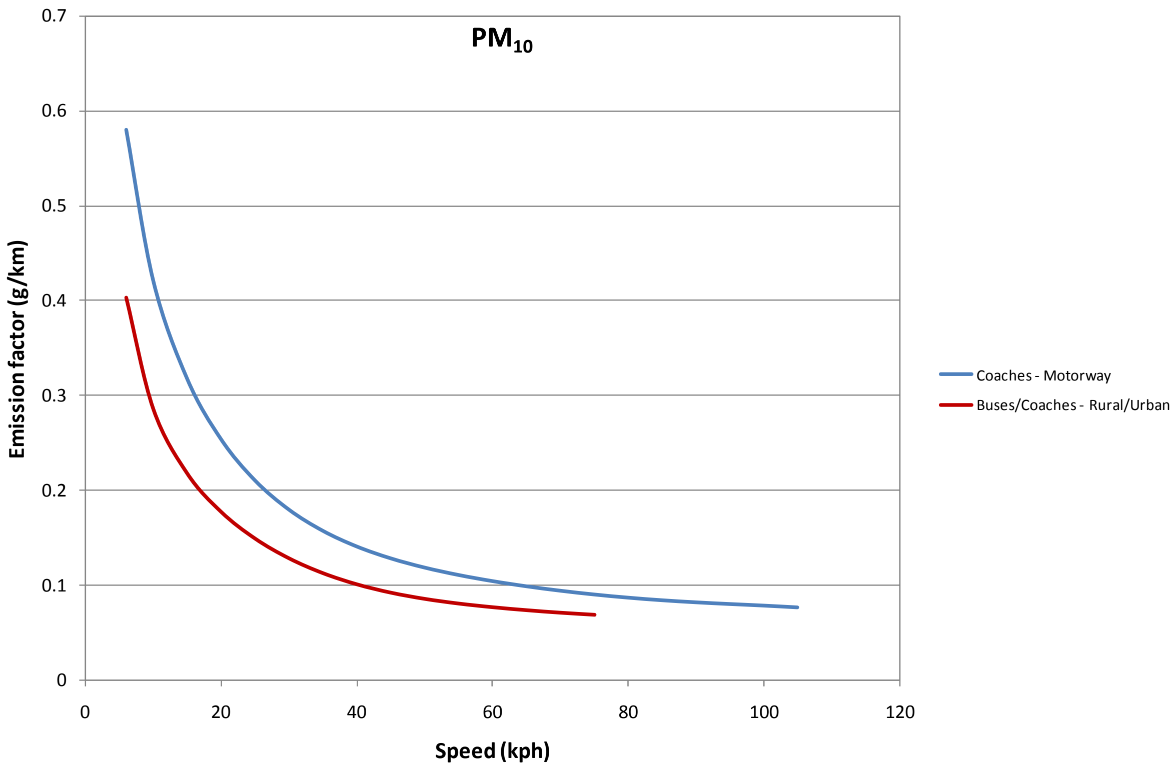


Fig 2.6 (h) PM_{10} speed-emission curves for the bus/coach traffic category for 2008/9

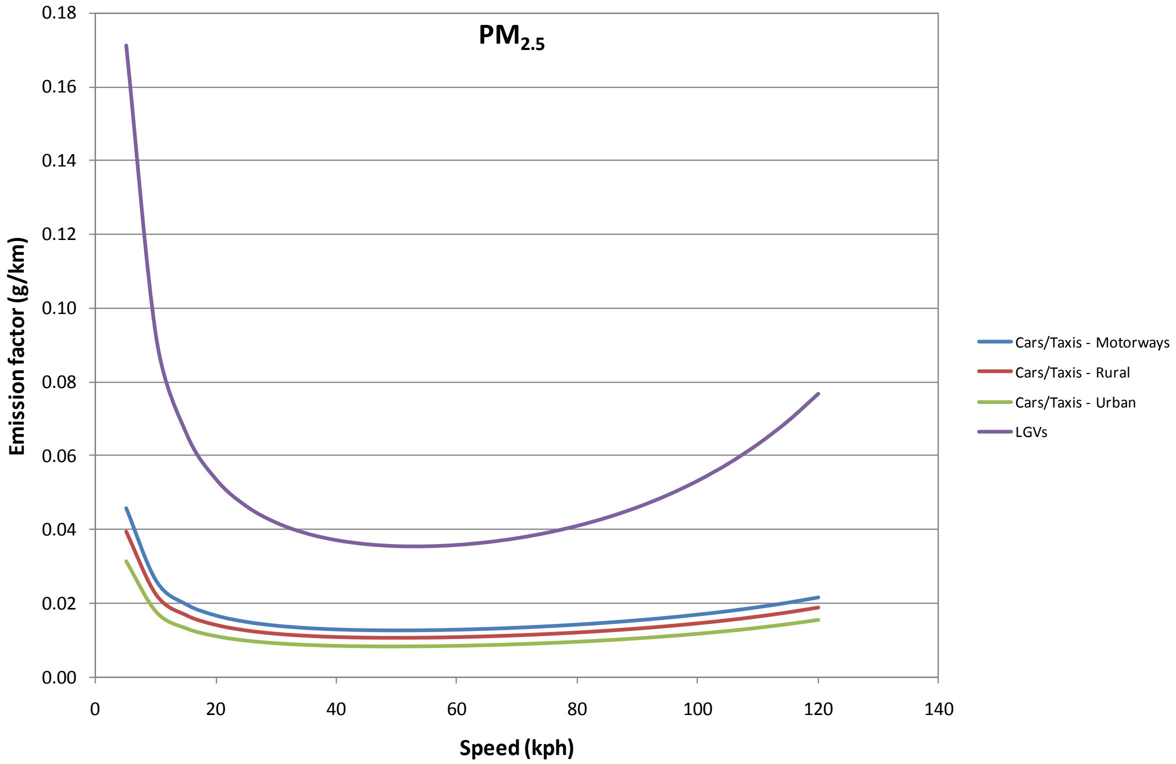


Fig 2.6 (i) $PM_{2.5}$ speed-emission curves for LDV traffic categories for 2008/9

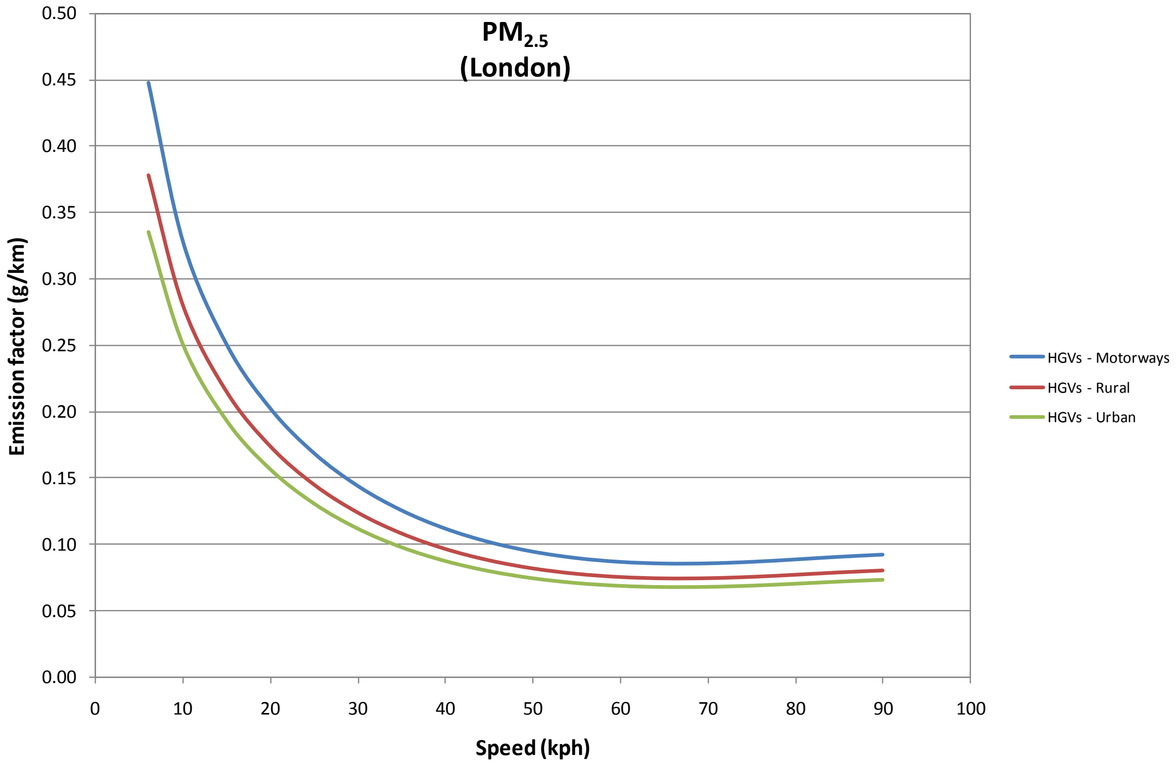


Fig 2.6 (j) $PM_{2.5}$ speed-emission curves for the HGV traffic category for 2008/9, within London

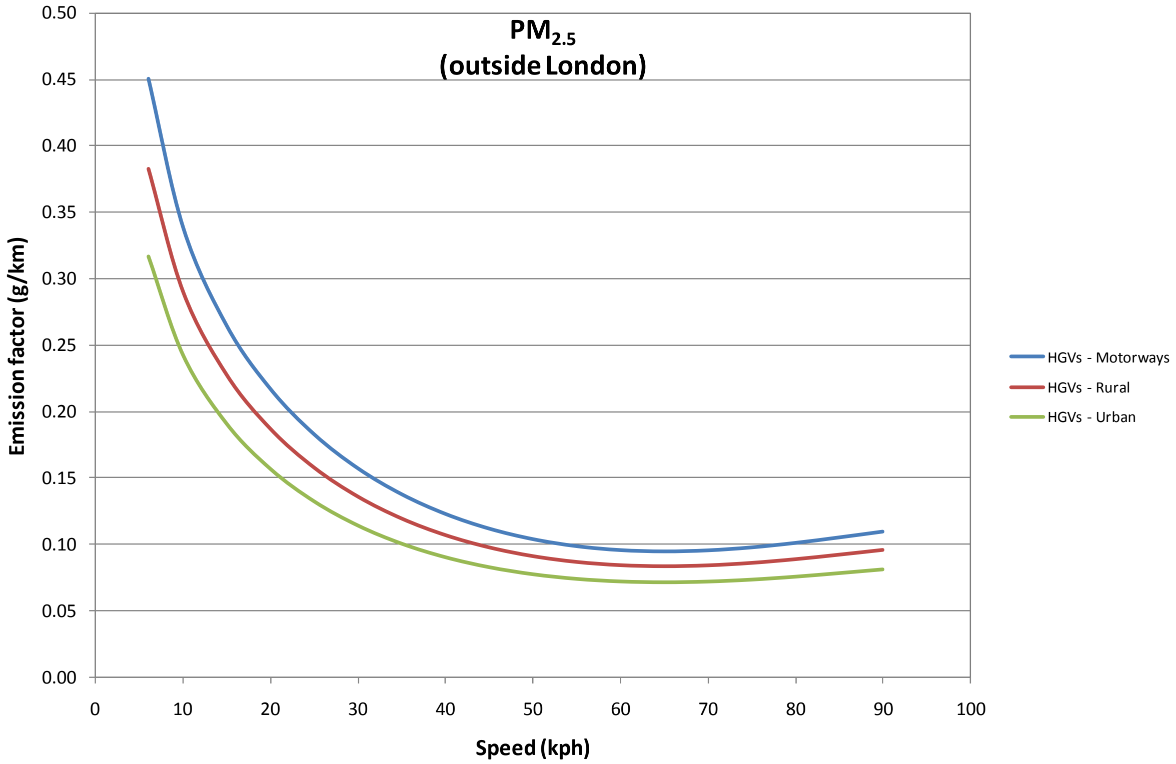


Fig 2.6 (k) $PM_{2.5}$ speed-emission curves for the HGV traffic category for 2008/9, outside London

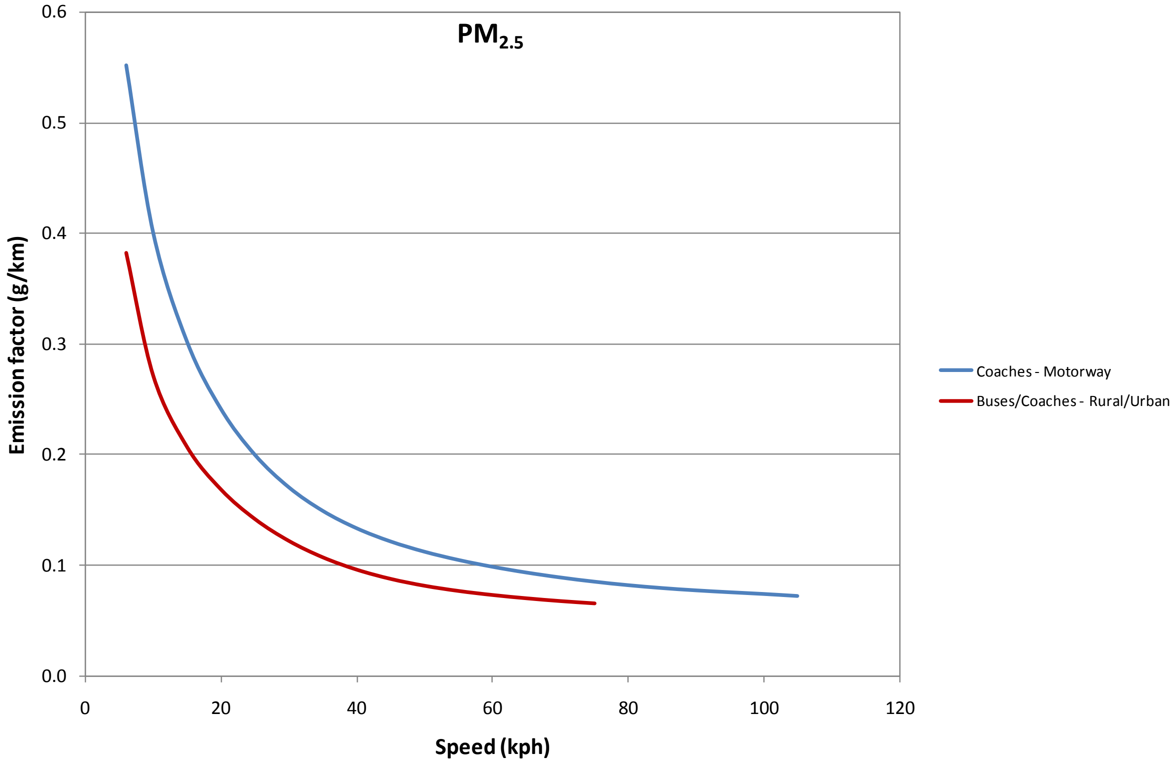


Fig 2.6 (l) $PM_{2.5}$ speed-emission curves for the bus/coach traffic category for 2008/9

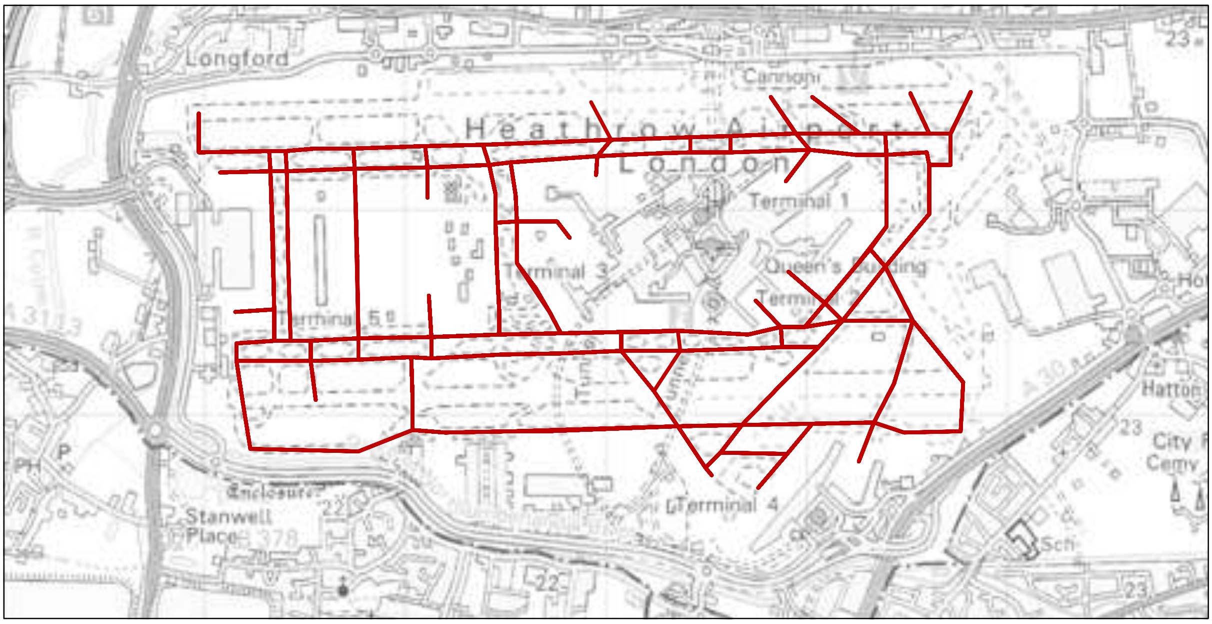


Fig 3.1(a) Taxiway network for taxi-out

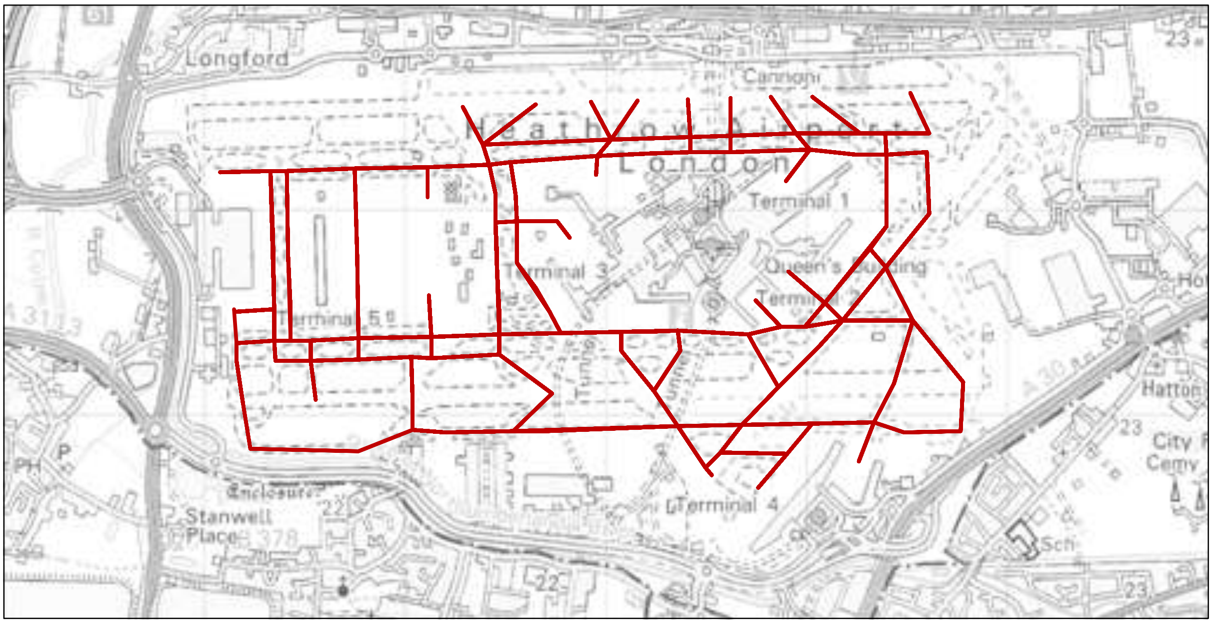


Fig 3.1(b) Taxiway network for taxi-in

Fig 3.2 Spatial representation of hold emissions; location of start-of-roll points

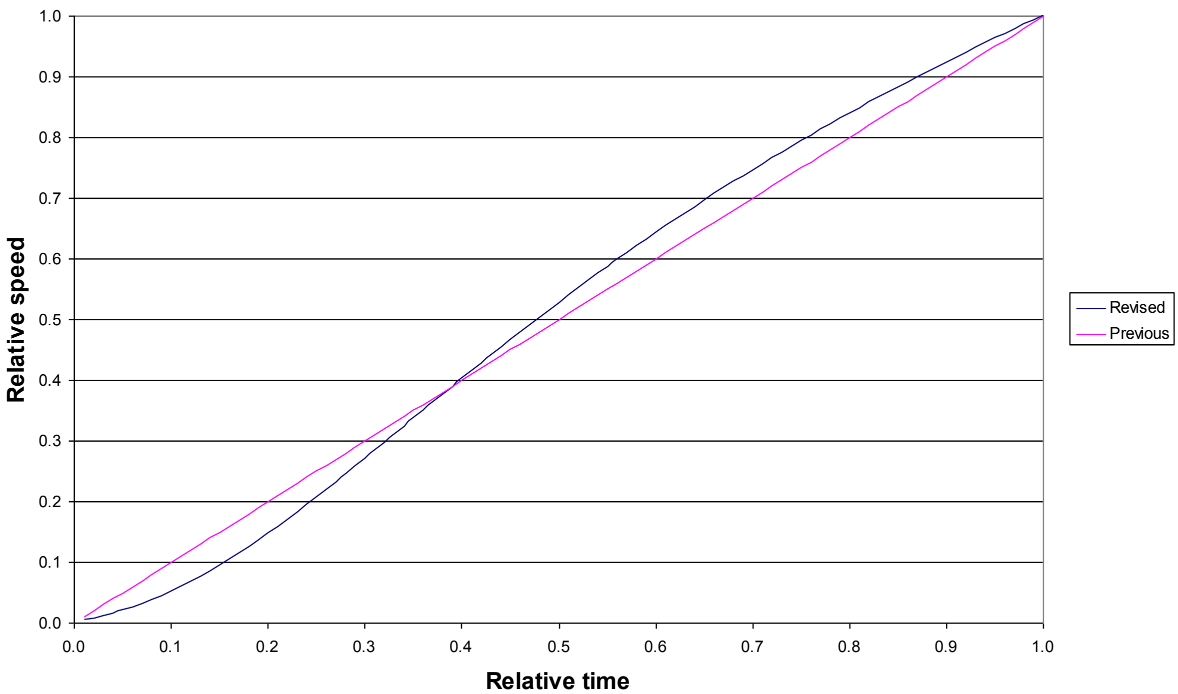


Fig 3.3 Universal speed curve compared to assumption of uniform acceleration

Fig 3.4 Stands and stand groups

Fig 3.5 Areas over which engine testing emissions distributed

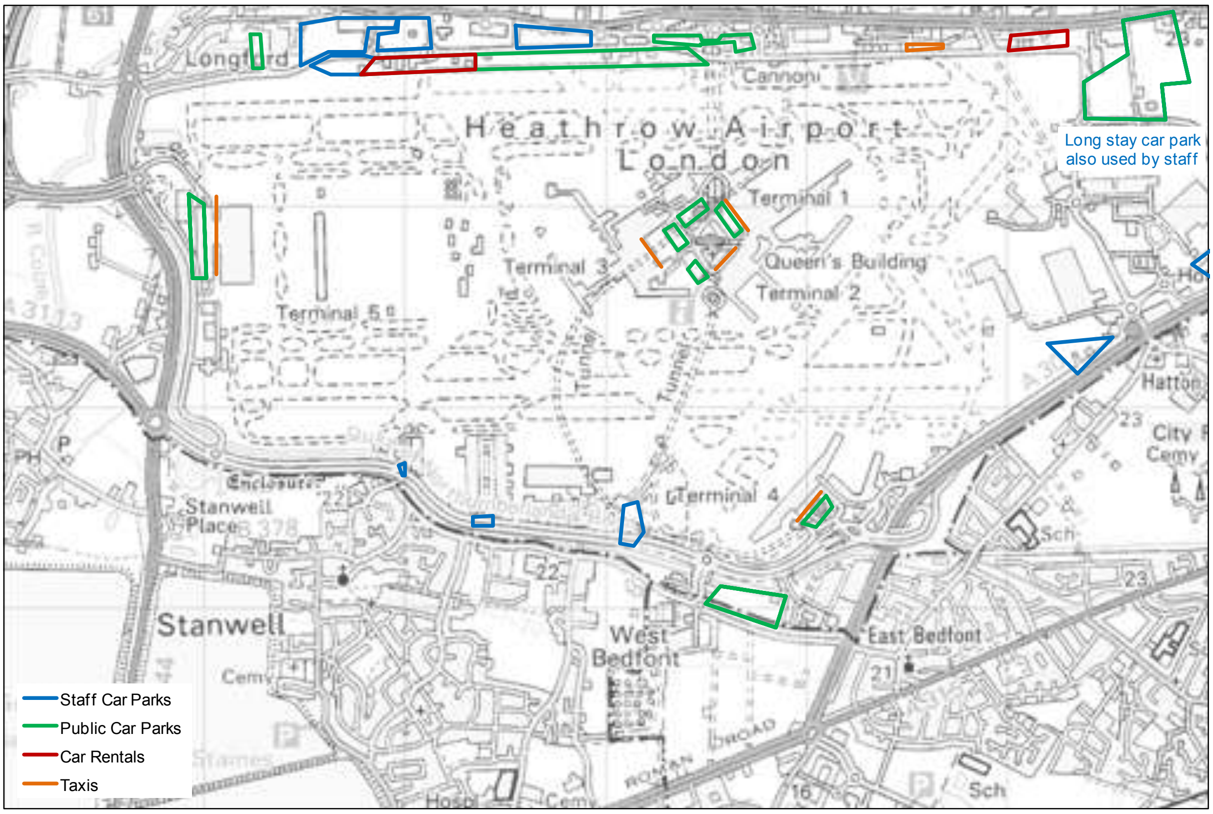


Fig 3.6 Location of car parks (staff and public), car rental pounds, Taxi Feeder Park and queuing emissions on the terminal forecourts

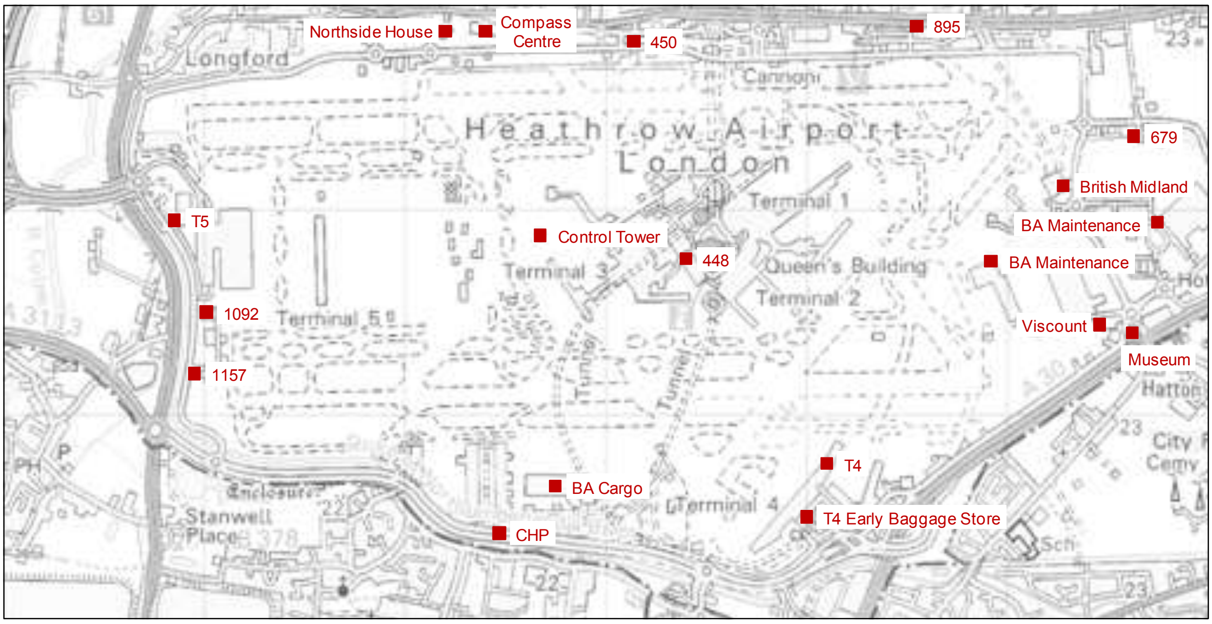


Fig 3.7 Location of heating plant

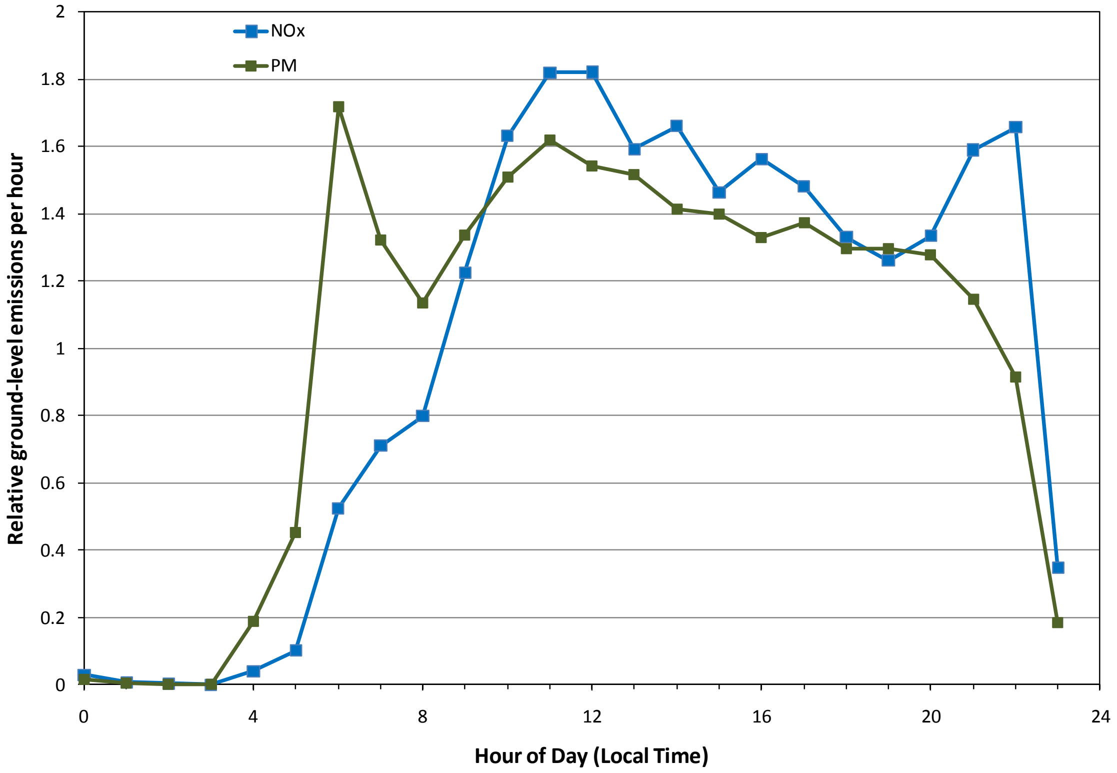


Fig 4.1 Relative ground-level aircraft emissions as a function of hour of day (PM emissions include brake and tyre wear)

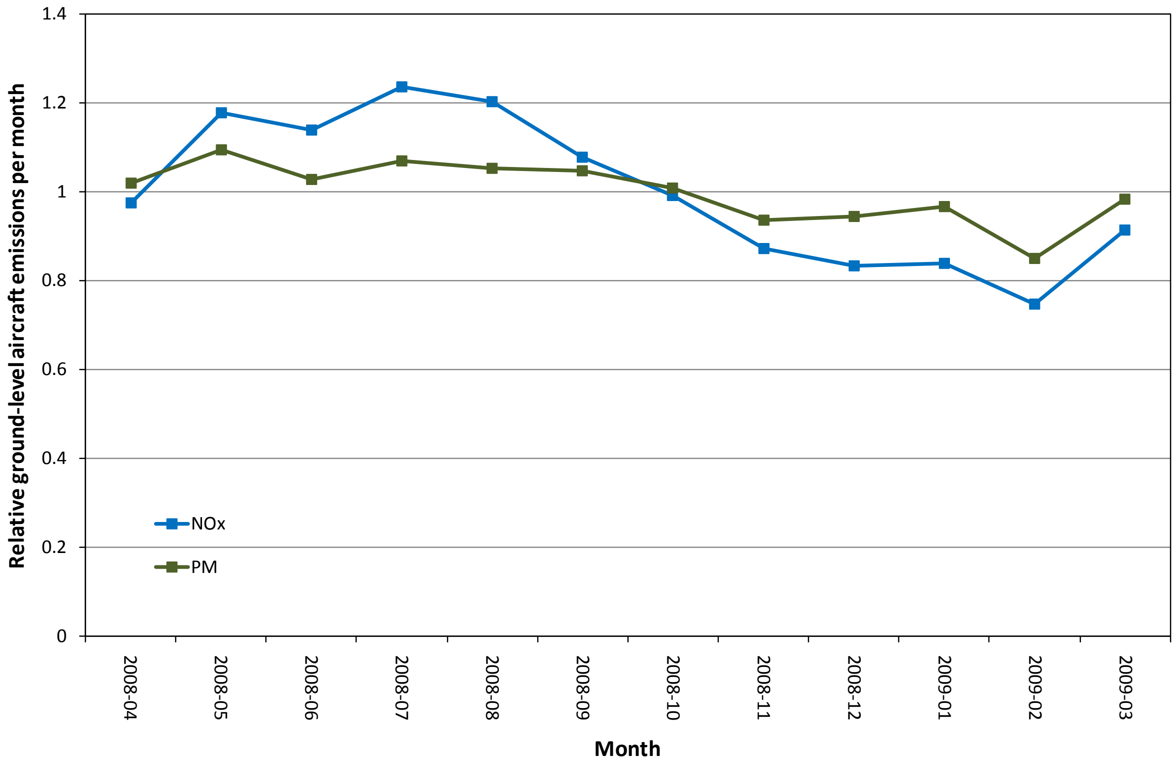


Fig 4.2 Relative ground-level aircraft emissions as a function of month of year (PM emissions include brake and tyre wear)

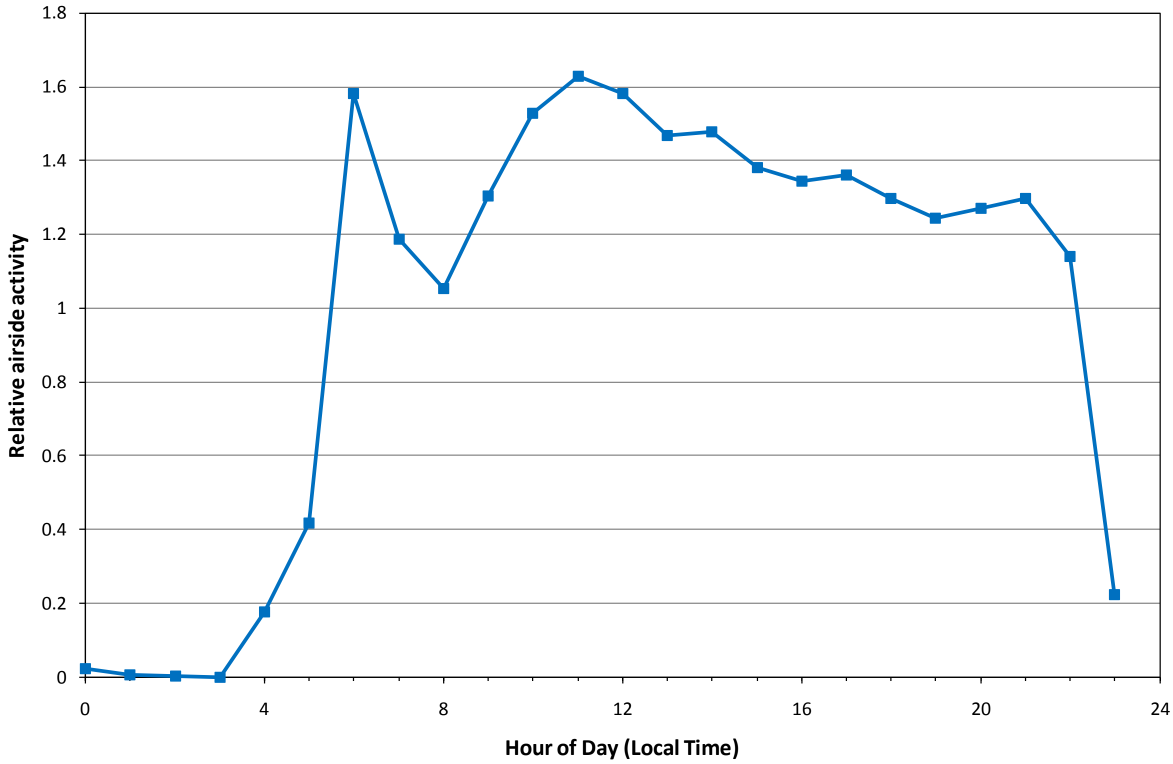


Fig 4.3 Relative airside 'activity' (movements * MTOW) as a function of hour of day

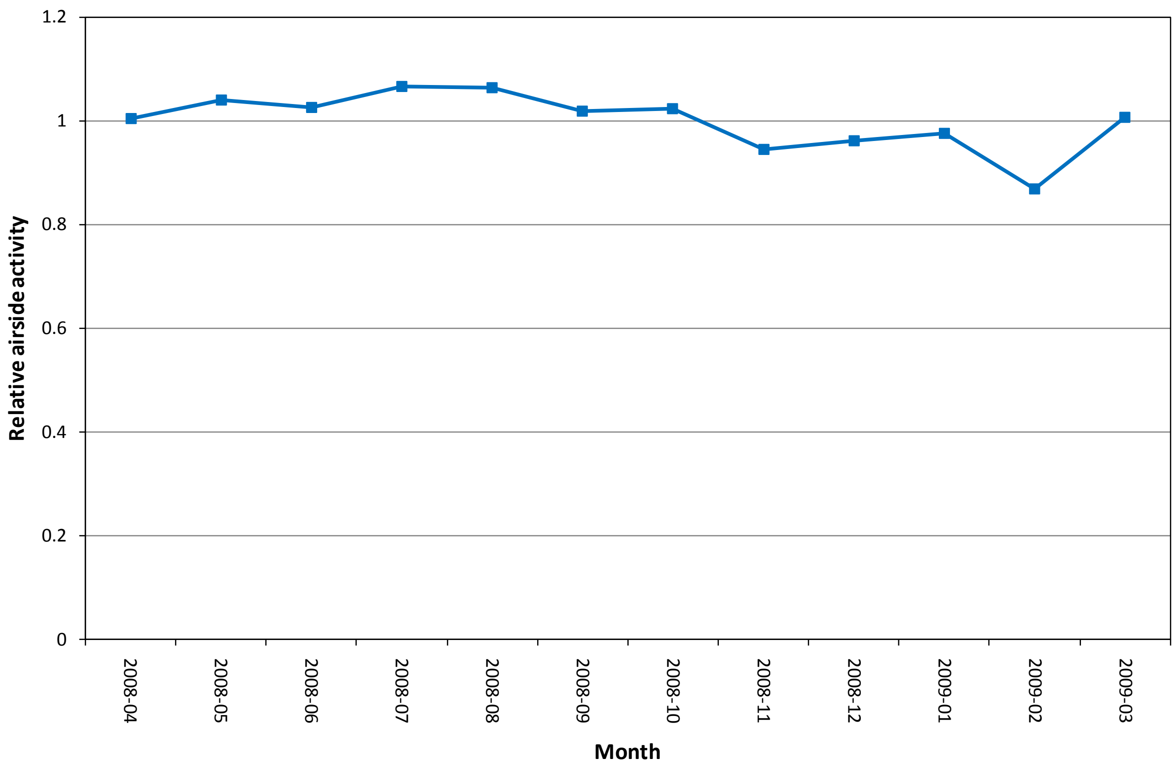


Fig 4.4 Relative airside 'activity' (movements * MTOW) as a function of month

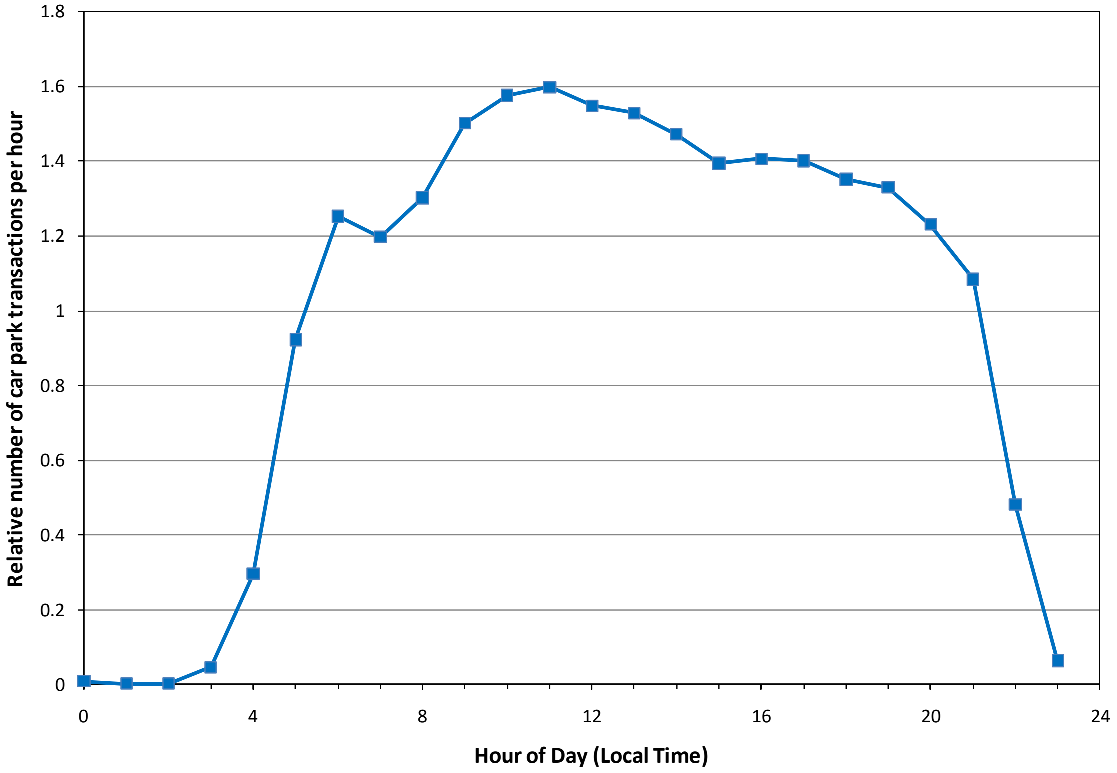


Fig 4.5 Hourly profile of car park transactions

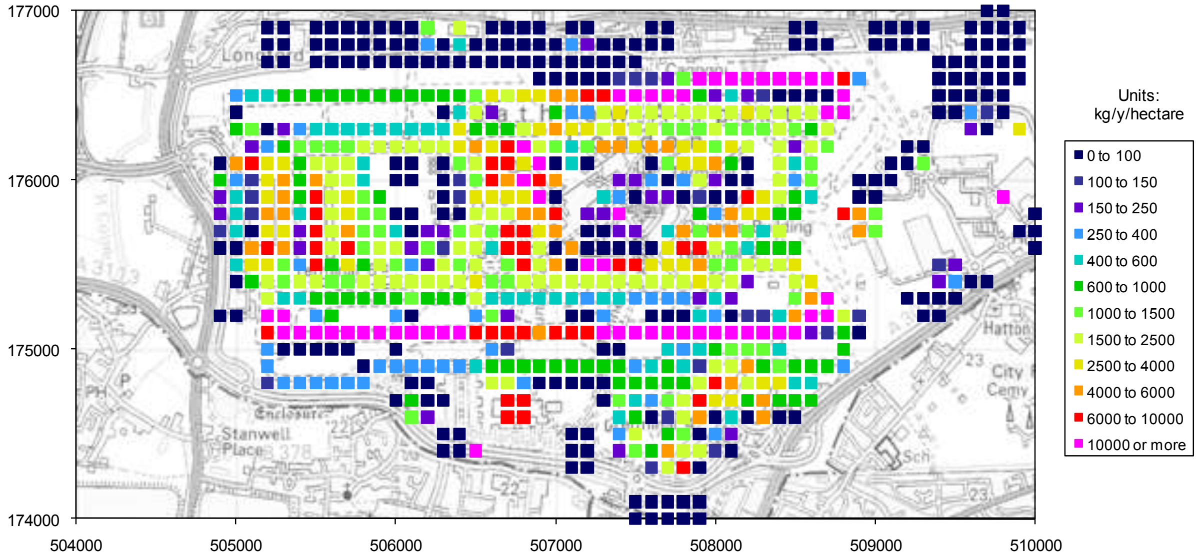


Fig 5.1 Spatial density of ground-level NO_x emissions (excluding elevated aircraft emissions and heating plant emissions)

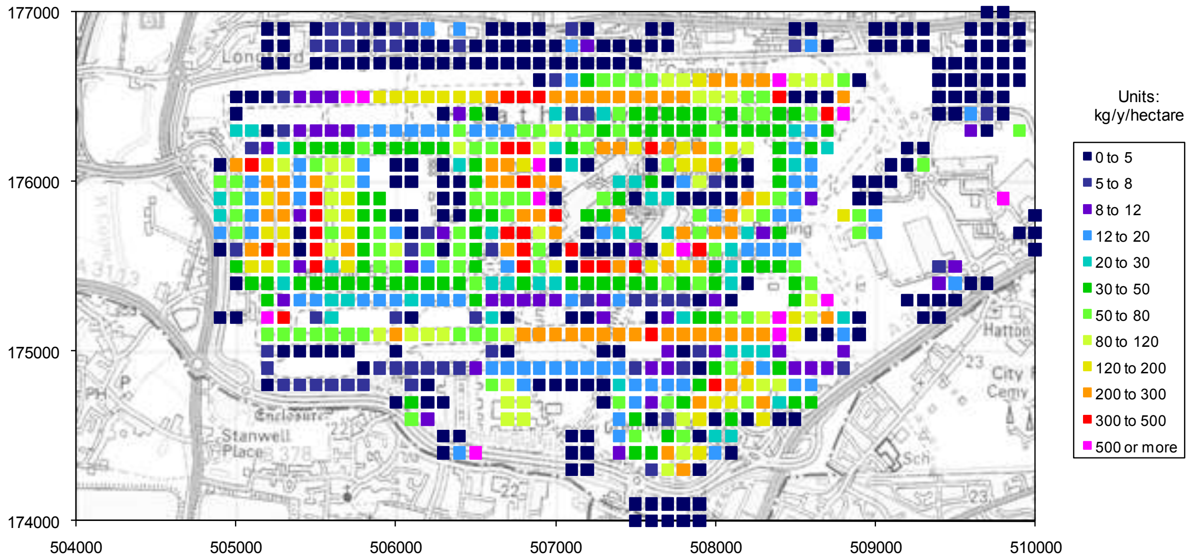


Fig 5.2 Spatial density of ground-level PM_{10} emissions (excluding elevated aircraft emissions and heating plant emissions)

Appendices

Appendix 1: Aircraft PM_{10} Exhaust Emissions Methodology
Appendix 2: Ground-Movement Times-in-Mode

Appendix 1

Aircraft PM_{10} Exhaust Emissions Methodology

A1.1 When LHR emission inventories were compiled in support of the T5 Public Inquiry, there was no readily available method for estimating PM_{10} emissions from aircraft engines. An approximate approach was devised by AEA based on the Smoke Number (SN) data reported in the ICAO databank. The derivation of an emission index for PM_{10} had two steps: first, data from Champagne (1971)[A1.1] was used to relate SN to a gravimetric particle measure (g of particulate matter per unit volume of exhaust gas at standard temperature and pressure (STP)); secondly, a simplified equation for the combustion of aviation fuel was used to derive the volume of exhaust (at STP) per unit mass of fuel burned, using representative air-to-fuel ratios (AFRs) for each of the ICAO thrust points. In its first version, the method used a single representative SN value for each of the four ICAO thrust settings, with the value based on databank values for engines in common use at the time.

A1.2 A number of major uncertainties in this methodology were recognised at the time, a principal one being whether or not the relationship derived by Champagne using an older type of combustor is still applicable to modern combustors. In addition, the measurements related to the primary carbonaceous particulate matter generated in the combustion process whereas there may be additional particle loading of the exhaust stream as gases cool and semi-volatile components condense out.

A1.3 Furthermore, the figure presenting the Champagne results displayed two lines, one for particles smaller than about 1 mm (although the exact size cut-off was not known) and one for all particles. The latter was used by AEA, although the work noted some uncertainty over the origin of the larger particles. The ‘all particle’ curve is a factor of two higher than the ‘small particle’ curve. Generally, particles from the combustor of a jet engine are expected to be smaller (considerably smaller) than 1 mm in diameter; the larger particles were postulated to have arisen from the intermittent breaking away of deposits within the combustor, but it could not be ruled out that they were artefacts of the experimental system.

A1.4 A few refinements were made to the basic methodology in the subsequent years. First, engine-specific SN numbers were used rather than a single representative value for each thrust. It was noted that the ICAO databank had more missing data for SN, with only a maximum value quoted for many engines rather than values for each ICAO thrust point. In such cases, the maximum SN value was applied to all thrust settings, leading to a conservative estimate of PM_{10} emissions.

A1.5 The method was subsequently, based on the work of Döpelheuer and Lecht[A1.2], who reviewed the Champagne data alongside similar data from other sources. The additional data were more consistent with the ‘small particle’ Champagne data than with the ‘all particle’ data, so AEA adopted the fit to the ‘small particle’ data given by Döpelheuer and Lecht, namely

$$c(mg/Nm^3) = 3.25\,10^{-6}SN^4 - 1.27\,10^{-4}SN^3 + 3.22\,10^{-3}SN^2 + 8.76\,10^{-2}SN + 0.14$$

where c is the soot loading in the exhaust stream. Despite these refinements, the principal uncertainties relating to volatile components and gaps in the SN data set remained.

A1.6 In 2005, WG3 (Working Group 3) of CAEP asked the FAA (US Federal Aviation Administration) and QinetiQ to work together to derive an improved PM_{10} methodology. Although the work is still ongoing, QinetiQ judged the work to be sufficiently well advanced to recommend an interim method to the PSDH[A1.3], which was adopted for subsequent PSDH work. The key features of the revised method (termed FOA-Heathrow2006 by QinetiQ) are summarised below:

A1.7 The soot loading in the exhaust stream is given by a power law (albeit with different coefficients from those in the original proposed FOA), namely

$$\ln(c) = 1.23357\ln(SN) - 2.6697$$

where *c* is the exhaust stream PM_{10} loading in mg/m^3 at STP. To derive the volume of exhaust gases per kg of fuel burned, the FOA-Heathrow2006 methodology uses a method closely similar to that in the original AEA methodology, resulting in the expression

$$V = 0.776AFR + 0.877 \qquad \text{m}^3\text{/kg at STP}$$

where V is the volume in m^3/kg at standard temperature and pressure. The representative AFR values have been revised for the FOA-Heathrow2006 methodology, namely 45 (50) for take-off, 51 (60) for climb out, 83 (100) for approach and 106 (120) for idle (with the previous AEA values in parentheses). The above expression is appropriate for turbofan (TF) engines in the ICAO databank. For mixed turbofan (MTF) engines, the measurement is made after mixing with by-pass air, so *AFR* in the above has to be replaced by *AFR(1+BPR)*, where *BPR* is the by-pass ratio of the engine.

A1.8 A sulphate contribution is derived by assuming 3% of the fuel sulphur content converts to SO_3. However, in the presence of water vapour SO_3 will rapidly convert to sulphuric acid (H_2SO_4), which will attract further water vapour; the aqueous sulphuric acid is more likely to form on existing particulate matter than to create separate droplets, and further aqueous phase reactions are possible. This leaves it unclear what to take as the additional PM_{10} mass (which will vary with substrate, atmospheric humidity and the type of instrument use to measure the mass). In the interim, only the mass of sulphate ion is counted as contributing extra PM_{10} mass, giving a contribution to EI(PM_{10}) of 0.043 g/kg (assuming a mean fuel sulphur content of 0.048%).

A1.9 A contribution from the condensation of volatile organic compounds has been derived from the results of a limited number of tests in the US. A simplified methodology based on this work assumes that the fraction of total hydrocarbon emission mass that converts to aerosol at a given thrust setting is the same for all engines. Although the tests conducted so far showed some dependence of the fraction on thrust setting, it was judged that the sparse data set available does not warrant a methodology more complex than taking an average factor over all thrust settings. Thus, the contribution to PM_{10} mass from organic aerosol, $EI(PM_{10})_{vorg}$, is given by

$$EI(PM_{10})_{vorg} = \alpha\, EI(HC)$$

where α is thrust- and engine-independent, and EI(HC) is the emission index for total hydrocarbons, as given in the ICAO databank. The recommended value for α at the time of the PSDH was 1%.

A1.10 For many engines in the ICAO databank, only a maximum SN is given rather than a specific value for each of the 4 standard thrust settings. QinetiQ has also devised a basis for filling these gaps in the SN data, based on the observed trends in the data for those engines with

SN values for the standard thrust settings. Although the data display considerable scatter (particularly at low SN, where measurement uncertainties are more significant), the following five categories of engine were identified in terms of the ratios amongst the SN values for the 4 ICAO thrust settings:

· most non-DAC (Dual Annular Combustor) engines;
· Aviadgatel engines;
· GE CF34 engines;
· Textron Lycoming engines;
· DAC engines.

A1.11 The recommended ratios are shown in Table A1.1. Most engines with high utilisation at LHR fall into the first category. Gaps in the SN data are not common for the Aviadgatel, GE CF34 and Textron Lycoming series of engines, so the tabulated ratios are rarely needed for these engine types. There is more scatter in the data for the DAC engines, and the recommended ratios are based on the GE90 data.

A1.12 The performance of the recommendations was checked by comparing predicted versus actual SN for engines with thrust-specific values in the databank, showing that the predicted SN value is generally within ±2 of the actual value (for SN values greater than 6) - with a slight positive bias (ie tendency to over-prediction) - and nearly always within ±4. These uncertainties are relatively more significant for the low-thrust modes, but, typically, these contribute only a small fraction of the total LTO exhaust PM10 (except for DAC engines).

Table A1.1 Recommended ratios of SN/SN(max) for engines with only SN(max) quoted

Category	Ratio SN[1]/SN(max)			
	Take-off	Climb-out	Approach	Idle
Most non-DAC[2]	1.0	0.9	0.3	0.3
Aviadgatel	1.0	1.0	0.8	0.3
GE CF34	1.0	0.4	0.3	0.3
Textron Lycoming	1.0	1.0	0.6	0.3
DAC	0.3	0.3	0.3	1.0

[1] SN – Smoke Number
[2] DAC – Dual-Annular Combustor

References

[A1.1] Champagne D L (1971) Standard measurement of aircraft gas turbine engine exhaust smoke. ASME 71-GT-88.

[A1.2] Döpelheuer A and Lecht M (1999) Influence of engine performance on emission characteristics. RTO Meeting Proceedings 14 Gas Turbine Engine Combustion, Emissions and Alternative Fuels. RTO-MP-14 AC/323(AVT)TP/10. NATO Research and Technology Organization.

[A1.3] Hurley C D, Eyers C J and Calvert W J (2006) Estimation of total particulate emissions from civil aero engines at London Heathrow. QinetiQ/06/00472.

Appendix 2

Ground-Movement Times-in-Mode

A2.1 BAA supplied an extract from their BOSS database for the period of interest (April 2008 to March 2009), which gives a flight-by-flight record of key parameters used in compiling the emission inventory, such as aircraft registration number (used to assign engines), flight date/time, runway identifier (and whether arrival or departure) and stand used. Although it contains some time information, it does not give the duration of each of the ground-movement flight phases treated separately from an emissions perspective.

A2.2 A key additional data set, supplied by NATS via BAA, was taken from the archive of data from the APT (Airport Playback Tool) system at LHR, which extracts information from ground-radar signals. This gives, on a flight-by-flight basis, the times (to the nearest second) of a number of key 'events'; for example, for arrivals it gives the time the aircraft crosses the runway threshold, the time it turns off the runway and the time it reaches the stand; for departing aircraft, it gives the time of pushback, the time of joining the holding queue, the time to turn on the runway etc. The APT data set has records for around 65% of the movements in the relevant period.

A2.3 The strategy for using the APT data was to match as many flights in BOSS as possible with individual flights in the APT data, thereby providing flight-by-flight times-in-mode for these 'reconciled' flights. The data for reconciled flights was then used to generate statistical information to enable appropriate times-in-mode to be assigned where data gaps exist. To assist in the reconciliation process, the APT data set gives the aircraft registration (tail) number, which is also given in BOSS. Since a given tail number may appear several times in a single day, the association by tail number was supplemented by a check on flight date/time, to ensure that the correct individual flight had been identified. After this process, around 50% of the total number of movements in the BOSS database for the period had been reconciled with an APT record.

A2.4 For the reconciled flights, the following times can be calculated:

- taxi-out time – from leaving the stand to joining the hold queue at runway head;
- hold time – from joining the hold queue to wheels roll for take-off;
- take-off roll – from wheels roll to airborne;
- landing roll – from threshold to runway exit;
- taxi-in – from runway exit to stand.

Not all these times are available for each reconciled flight. For hold, take-off roll and landing roll, the data capture is good (around 80%) whereas for taxiing times the data capture is only around 50%. Nevertheless, the data set for each of the above time parameters is extensive and the missing entries appear to be randomly distributed, so the data provide a good basis for filling data gaps.

A2.5 In fact, the APT data allow the total hold time to be broken down into three separate components: time between joining the hold queue and turning onto the runway (queuing time); time between joining the runway and being fully lined up (line-up time); and time between being fully lined up and wheels roll (runway wait time). Queuing times are typically of order several minutes, line up times are typically of order 10-20 seconds and runway wait times are on average around 20-30 seconds. The distinction between these three phases of holding will not be retained in quoting emissions, but is retained in the discussion below because the procedures for filling data gaps are somewhat different for line-up and reaction time compared to those for queuing time.

A2.6 The statistical analysis of the data for reconciled flights, for use in assigning times to non-reconciled flights, is discussed separately below for each ground-movement flight phase.

Taxi-Out

A2.7 Specific taxi-out times were available for 71,613 departures (out of a total of 235,131 in the period). In order to assign taxi-out times to all other departures, average taxi-out time was calculated as a function of those parameters judged to be the key sources of variability. Clearly distance travelled is a key determinant of taxiing time, so taxi-out times were worked out separately for each departure runway, given that the distance from a particular stand to a given runway end varies significantly from one departure runway to another. For the few departures on 09L (for which there are no examples in the APT data), an average time for each terminal was used.

A2.8 In relation to variation with stand location, 21 'stand groups' were defined to provide an appropriate level of spatial partitioning of the stands on the airport, with each group including of order ten stands, but with group boundaries chosen to accommodate the complex stand layout at Heathrow. In the spatial assignment of taxiing emissions, all taxiing routes to a given stand group are assumed to terminate at a representative spatial location within the group. The assignment of stands to groups is shown in Table A2.1 and the groups are marked on Fig 3.4. Taxiing times vary from stand group to stand group not only because distances along preferred taxiing routes vary from group to group but also because taxiway congestion and taxiway crossing delays may vary.

A2.9 Past work has shown that taxiing times have a systematic dependence on aircraft size, although the variation is not strong. This was taken into account in the present work by deriving mean values separately for each NATS Group, where the latter is a grouping of aircraft types devised for the purposes of runway occupancy studies but providing an adequate surrogate for aircraft size. The NATS grouping for Heathrow is shown in Table 2.8 of the main text.

A2.10 Taxi-out time also varies with the hold point at which the aircraft queues to join the runway, given that different hold points correspond to different distances of travel from the same stand group. The hold point identifier is given in the APT data set but not in BOSS, so hold point is not known for non-reconciled flights. Thus mean taxi-out times for a given runway, stand group and NATS Group were calculated as weighted averages over the mean times calculated separately for each hold point, with weighting factors given by the observed frequencies of hold point usage (for the particular runway, stand group and NATS Group), as given by the reconciled flights[*]. For the purpose of calculating total emissions, therefore, non-reconciled flights in the BOSS database were assigned the mean time for the appropriate runway direction, stand group and NATS Group. However, for working out the spatial distribution of taxi-out emissions (Section 3), the emissions for a given runway, stand group and NATS Group were shared amongst the routes to all the relevant hold points, with the share for a given hold point proportional to the product of the hold point probability and the mean taxi-out time for the hold point (for the particular runway, stand group and NATS Group)[†].

A2.11 Where there are no examples of a particular departure runway/stand group/NATS Group in the reconciled departures, the corresponding data for NATS Groups for the given runway/stand group were pooled to give a mean value independent of aircraft type, with the corresponding non-reconciled flights then allocated this mean time. By definition, this fallback procedure was needed only for aircraft type/runway direction/stand group combinations that appear rarely in the BOSS database for the 12-month inventory period, so any additional approximation involved has little impact. Similarly, if no reconciled departures

[*] This procedure is equivalent to pooling all the data for different hold points when forming the average taxi-out time for a given runway and stand group.
[†] This procedure is equivalent to generating a set of pseudo-departures for each non-reconciled departures, one for each pertinent hold point, with each pseudo-departure assigned a weight (that is used to scale its contribution to emissions) given by the appropriate hold point probability.

exist for the given stand group arising for non-reconciled flights, data for all stand groups at a given terminal were pooled to form an average.

A2.12 The potential variation of taxi-out times (for a given runway, stand group and NATS Group) with hour-of-day was investigated but found not to be statistically significant, so data for all hours of the day were pooled in forming averages. Of course, for the reconciled flights any (even minor) systematic variation with hour of day will be automatically represented. In summary, therefore, for application to non-reconciled departures, taxi-out times were assumed to depend on departure runway, hold point, stand group and NATS Group.

A2.13 For the PSDH revision of the 2002 LHR inventory, taxi-out times were derived from a sample of radar-based ground-movement times from around 2005, although the data were not provided on a flight-by-flight basis but already averaged to some extent. Table A2.2 compares the mean values derived here for the 2008/9 inventory with the values derived for PSDH 2002 inventory. Average times for T1-T4 are around 30% lower for 2008/9 than for 2002, with the average times for T5 lower than for the other terminals because of shorter taxiing routes. The opening of T5, with increased stand availability, improved the general distribution of aircraft across the terminals, which led to lower taxiing times. Some of the improvement may have been related to the transient situation immediately following the opening. In addition, there has been a drive to reduce taxi-out times via improved management of when aircraft leave the stand.

Hold

A2.14 It is observed that average queuing times for hold points further down the runway are systematically shorter on average, so for assigning times to non-reconciled departures a dependence of queuing time on hold point was included. As noted above in the description of taxi-out times, hold point is not known for non-reconciled flights, and the same procedure is used for holding times as for taxi-out, namely to use times averaged over hold point when calculating total emissions from non-reconciled flights but to share the emissions amongst hold points when assigning emissions spatially[*].

A2.15 Hold times (averaged over all hours of the day) by runway are shown in Table A2.3, which compares the 2008/9 values with those for 2002. The average times derived for the two inventory periods are nearly the same, with the 2008/9 averages 2-11% shorter.

A2.16 Similarly, a dependence of queuing time on hour of day was included because there was clear evidence of longer queuing times in the middle of the day. For illustration, the hourly profile of mean queuing time taken over all hold points for both runway directions is shown in Fig A2.1. No significant systematic variation of line-up time or runway-wait time with hour of day was observed, so these time components were assumed to depend on runway and hold point only. Where there were no instances of reconciled flights for a given hour of the day, the queuing time averaged over all hours of the day was used. A month-of year dependence was also retained for queuing time, as shown in Fig A2.2, although the variation is not large.

A2.17 In principle, queuing times may depend on aircraft size as a result of hold queue management, but the dependence was found not to be major for the principal aircraft types, so data for all aircraft types were pooled. For the reconciled flights, of course, any (even minor) systematic variation with aircraft size will be automatically represented. For line-up time and runway-wait time, a dependence on NATS Group was retained, although the evidence for this dependence was not strong.

[*] Although queuing time is taken not to depend on aircraft type nor stand group , the hold point probabilities do depend on these variables but, on the other hand, are assumed not to depend on hour of day.

Take-Off Roll

A2.18 For reconciled departures, the APT data set gives the time of wheels roll and the airborne time, thereby enabling roll time to be extracted. There is some uncertainty over whether the algorithm deriving airborne time from the radar signal (which detects a sudden change in horizontal aircraft speed) yields a value closer to aircraft rotation or to aircraft lift-off: most likely the time lies somewhere between the two. Typically, for large jets the interval between visually- (or radar-) detected rotation and actual lift-off is only a few seconds, so this uncertainty is likely to be at most of order 10% of the total roll time.

A2.19 Inspection of the data for reconciled flights reveals that roll times have some systematic variation with hold point for the same aircraft type, with times shorter on average for aircraft starting further down the runway, which is not surprising given the implied difference in length of available runway. As noted earlier, hold point is not identified for non-reconciled flights, so a procedure similar to that described above for taxi-out time was used: when calculating total emissions for non-reconciled flights a weighted-average roll time over all hold points was used but when calculating spatial distributions the emissions were shared amongst hold points (ie start-of-roll blocks), with the share for a given hold point proportional to the product of the hold point probability and the mean roll time.

A2.20 For assigning times to non-reconciled flights, roll time was thus assumed to depend first on departure runway/hold point (ie start-of-roll block). For a given runway/hold point combination, average roll times were then calculated for each aircraft registration (tail) number, on the understanding that the best predictor of roll time for a particular non-reconciled flight is the average roll time observed for the same individual aircraft for its reconciled flights (if there are any). Where there were no reconciled departures for a given tail number, an average roll time taken over all tail numbers of the same aircraft type (at the level of 3-letter IATA code) was used. Where there were no reconciled departures even for the aircraft type, an average roll time taken over all reconciled departures with the same NATS Group was used. By definition, these coarser level of aircraft characterisation were needed only for tail numbers or aircraft types that appear rarely in the BOSS database for the 12-month inventory period, so any additional approximation involved has little impact.

A2.21 Prior to the 2008/9 inventory, the last comprehensive data set for take-off roll times was derived from a sample of 20,000 departures in 2000, analysed in terms of aircraft type. For comparison purposes, Table A2.4 gives average take-off roll time as a function of aircraft type for the major aircraft types operating at Heathrow in 2008/9, with the values for 2008/9 compared to those from the previous data set used for the 2002 inventory. For the Medium jets (such as the A319 and B737) the differences are small, but on average 2008/9 times are shorter for some Heavy larger aircraft types (13% shorter for A340 and 9% shorter for B747), although with little difference for the B777. It should be borne in mind that there is significant flight-to-flight variation in roll times for a given aircraft type depending on aircraft load and ambient conditions, with standard deviations typically around 10-15% of the mean.

Landing Roll

A2.22 Inspection of the data for reconciled arrivals showed that landing roll time depends on exit block for a given aircraft type, as expected from the variation of distance travelled. Exit block is not recorded in BOSS so, for the non-reconciled arrivals, exit block is not known. This data gap is handled in a similar way to that devised for missing hold point identifier for departures: when calculating total emissions for non-reconciled flights a weighted-average roll time over all exits was used but when calculating the spatial distributions the emissions were shared amongst exit points, with the share for a given exit proportional to the product of the exit probability and the mean landing roll time for the exit*.

A2.23 Thus, for assigning times to non-reconciled arrivals, landing roll time is assumed to depend first on runway/exit combination, which defines the length of roll. For a given runway/exit, average roll times were then calculated for each aircraft registration (tail) number, using the same rationale as for take-off roll, namely that the best predictor of landing roll time for a particular non-reconciled arrival is the average roll time observed for the same individual aircraft for its reconciled arrivals (if there are any). Where there were no reconciled arrivals for a given tail number, an average roll time taken over all tail numbers of the same aircraft type (at the level of 3-letter IATA code) was used. Where there were no reconciled arrivals even for the aircraft type, an average roll time taken over all reconciled arrivals for the same NATS Group was used. By definition, these coarser level of aircraft characterisation were needed only for tail numbers or aircraft types that appear rarely in the BOSS database for the 12-month inventory period, so any additional approximation involved has little impact.

A2.24 For the PSDH revision of the 2002 inventory, landing roll times were calculated from a sample of 68,593 arrivals in 2004/5. Table A2.5 compares the mean values over all exit points and aircraft types as a function of runway obtained from that data set with the equivalent values from the current data set. There are no major systematic differences in the averages.

Taxi-In

A2.25 Specific taxi-in times were available for 46,465 arrivals (out of a total of 234,898 in the period). For reconciled arrivals, flight-specific taxi-in times were used, and for the remainder averages derived from the reconciled flights were developed.

A2.26 Clearly, as with taxi-out, distance travelled is a key determinant of taxiing time, so taxi-in times were worked out separately for each arrival runway and stand group. As noted earlier, past work has shown that taxiing times have a systematic dependence on aircraft size, although the variation is not strong. As with taxi-out, therefore, this was taken into account by deriving mean values separately for each NATS Group.

A2.27 Taxi-in time also varies with the runway exit for a given arrivals runway, given that different hold points correspond to different distances of travel to the same stand group. The exit block is identified in the APT data set but not in BOSS, so exit is not known for non-reconciled flights. Thus mean taxi-in times for a given runway, stand group and NATS Group were calculated as weighted averages over the mean times calculated separately for each exit, with weighting factors given by the observed frequencies of exit usage (for the particular runway, stand group and NATS Group), as given by the reconciled flights†. For the purpose of calculating total emissions, therefore, non-reconciled flights in the BOSS database were assigned the mean time for the appropriate runway direction, stand group and NATS Group. However, for working out the spatial distribution of taxi-in emissions (Section 3), the emissions for a given runway, stand group and NATS Group were shared amongst the routes from all the relevant exits, with the share for a given exit proportional to the product of the exit probability and the mean taxi-in time for the exit (for the particular runway, stand group and NATS Group).

A2.28 Where there are no examples of a particular arrival runway/stand group/NATS Group in the reconciled arrivals, the corresponding data for all NATS Groups for the given runway/stand group were pooled to give a mean value independent of aircraft type, with the corresponding non-reconciled flights then allocated this mean time. By definition, this fallback procedure was needed only for runway/stand group/NATS Group combinations that appear rarely in the

* This procedure is equivalent to generating a set of pseudo-arrivals for each non-reconciled arrival, one for each pertinent runway exit, with each pseudo-movement assigned a weight (that is used to scale its contribution to emissions) given by the appropriate runway exit probability.
† This procedure is equivalent to pooling all the data for different exits points when forming the average taxi-in time for a given runway and stand group.

BOSS database for the 12-month inventory period, so any additional approximation involved has little impact. Similarly, if no reconciled arrivals exist for the given stand group arising for non-reconciled flights, data for all stand groups at a given terminal were pooled to form an average. As for taxi-out, no significant dependence of taxi-in time on hour-of-day was noted.

A2.29 For the PSDH revision of the 2002 LHR inventory, taxi-in times were derived from a sample of radar-based ground-movement times from 2005, although the data were not provided on a flight-by-flight basis but already averaged to some extent. Table A2.6 compares the mean values by runway and NATS Group (averaged over exits and stand groups) derived here for the 2008/9 inventory with the corresponding values derived for PSDH 2002 inventory. The 2008/9 times are on average around 15% shorter than those for 2002, reflecting an improvement in ground movement efficiency following the opening of T5.

Table A2.1 Stand Groups

Stand Group	Stands included
A (T5)	506, 507, 508, 509, 511, 512, 513, 514, 515, 516, 517, 518
B (Europier)	124, 145, 146, 147, 148, 149, 150, 152, 153, 154, 155, 170, 171, 242, 256, 257, 258, 701, BB, BBW, BMA
B (Pier 4A)	101, 103, 105, 109, 174, 176, 178, 180, 182, 184, 186, 188, 190, 192, 192L, 192R
B (South)	212, 212L, 212R, 214, 301, 303, 303L, 303R, 305, 305L, 305R, 307, 309, 311, 313
B (T5)	531, 532, 533, 534, 535, 536, 537, 538, 539
C	541, 542, 543, 544, 544L, 544R, 545, 545L, 545R, 546, 546L, 546R, 547, 547L, 547R, 548, 548L, 548R, 551, 552, 553, 554, 555, 556
Cargo	601, 602, 603, 604, 605, 606, 607, 608, 609, 611, 614, 615, 616
D (North)	561, 562
D (South)	162, 565, 566, 567, 568, 575, 576, 581, 582, 583
E	590, 591, 592, 594, 595, 596
F	316, 317, 319, 321, 363, 365
G	318, 320, 322, 323, 325, 327, 329, 331, 335, 340, 342, 364
H	326, 328, 330, 332, 334, 336, 338, 350, 351, 352, 353, 354, 355, NO1
J	102, 104, 106, 108, 110, 112, 117, 119, 121, 123, 125, 125L, 125R, 127, 127L, 127R, 129
Link 56	501, 502, 503, 505
P	203, 205, 207, 209, 209L, 209R, 236, 238
Q	202, 204, 206, 208, 210, 211, 213, 215
T	401, 402, 403, 404, 405, 406, 408, 409, 410, 411, 412, 440, 441, 461, 463
V	414, 415, 416, 417, 419, 420, 421, 422, 423, 424, 425, 429, 430, 431, 432
W	451, 452, 453, 454, 455, 456, RB1, RS1, RS2
Y	519, 520, 521, 522, 523, 524, 525, 526, 527

Table A2.2 Mean taxi-out times by NATS Group and terminal: 2008/9 compared to 2002

NATS		Taxi-out time (s)						
Group[a]	Period	T1	T2	T3	T4	T5	Cargo	All
1	2008/9	602	609	733	742	494	895	670
	2002	863	889	1103	902	-	880	1013
2	2008/9	607	608	761	613	445	653	562
	2002	733	762	969	836	-	894	852
4	2008/9	617	531	745	630	488	605	616
	2002	777	747	900	740	-	928	769
5	2008/9	587	527	590	524	472	-	522
	2002	772	763	845	748	-	807	773
All	2008/9	587	530	703	686	476	753	572
	2002	773	765	1027	835	-	865	834

[a] Only the dominant NATS Groups shown separately, but 'All' includes all aircraft types

Table A2.3 Hold time[1] as a function of hold point

	Hold time (s)	
Runway	2008/9	2002
09L	473	529
09R	540	562
27L	476	483
27R	420	428

[1] Total hold time, including queuing, line-up and runway wait, averaged over all hours of the day and aircraft types

Table A2.4 Take-off roll time by aircraft type

Runway	Mean roll time (s)	
	2008/9	2002
Airbus A300/310	35.1	34.2
Airbus A319	33.2	33.0
Airbus A320	30.8	32.4
Airbus A321	30.2	32.5
Airbus A330	38.9	41.5
Airbus A340	42.2	48.7
Airbus A380	39.4	-
Boeing 737	31.6	30.4
Boeing 747	40.6	44.6
Boeing 757	30.4	28.8
Boeing 767	37.0	33.2
Boeing 777	37.2	37.8
MD80/90	31.0	31.1
Other	27.7	28.0

Table A2.5 Landing roll time by runway

Runway	Landing roll time (s)	
	2008/9	2002
09L	62.6	61.1
09R	76.3	69.0
27L	57.7	52.8
27R	56.3	54.1
All	58.8	56.0[a]

[a] Includes the (few) arrivals on runway 230 in the data set for the 2002 inventory

Table A2.6 Mean taxi-in times by NATS Group and terminal: 2008/9 compared to 2002

NATS Group[a]	Period	Taxi-in time (s)						
		T1	T2	T3	T4	T5	Cargo	All
1	2008/9	493	401	370	540	378	404	415
	2002	557	538	486	727	-	604	583
2	2008/9	295	393	350	577	392	459	393
	2002	400	393	469	734	-	629	492
4	2008/9	225	379	313	545	326	451	253
	2002	350	408	462	676	-	563	435
5	2008/9	283	350	284	516	371	-	343
	2002	314	400	416	637	-	562	365
All	2008/9	298	353	350	534	373	432	362
	2002	326	396	468	697	-	579	433

[a] Only the dominant NATS Groups shown separately, but 'All' includes all aircraft types

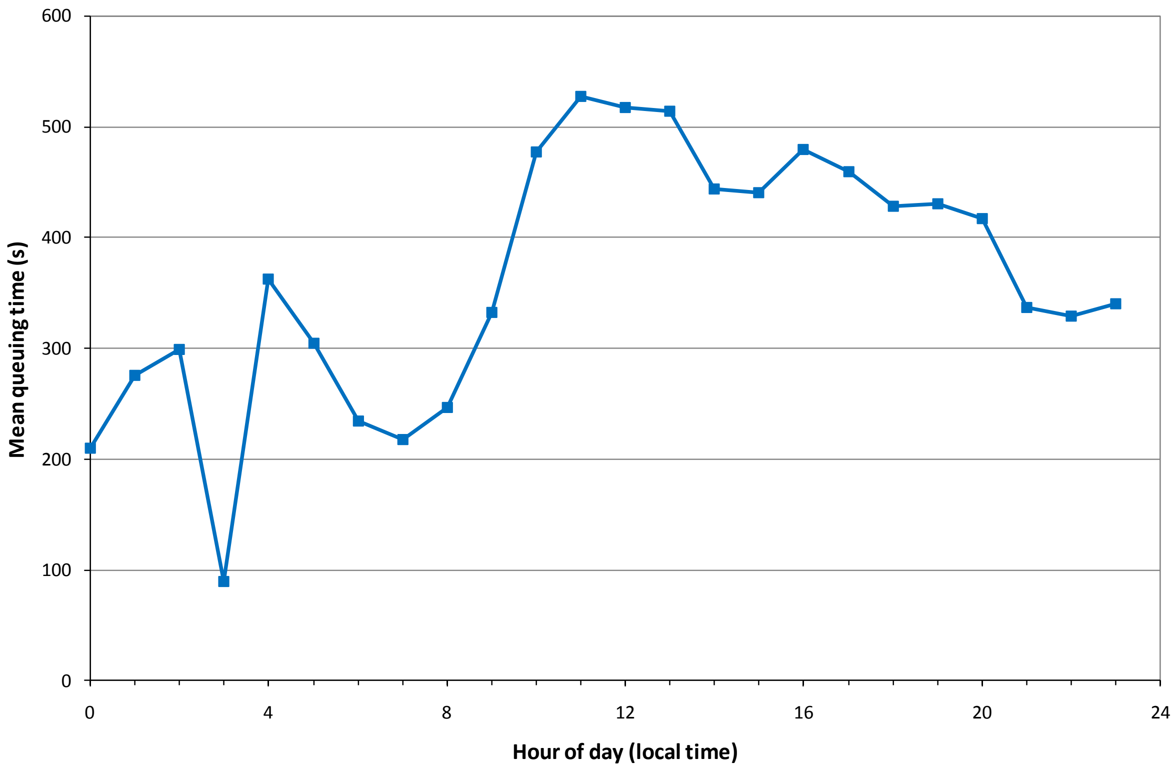


Fig A2.1 Mean queuing time as a function of hour of day

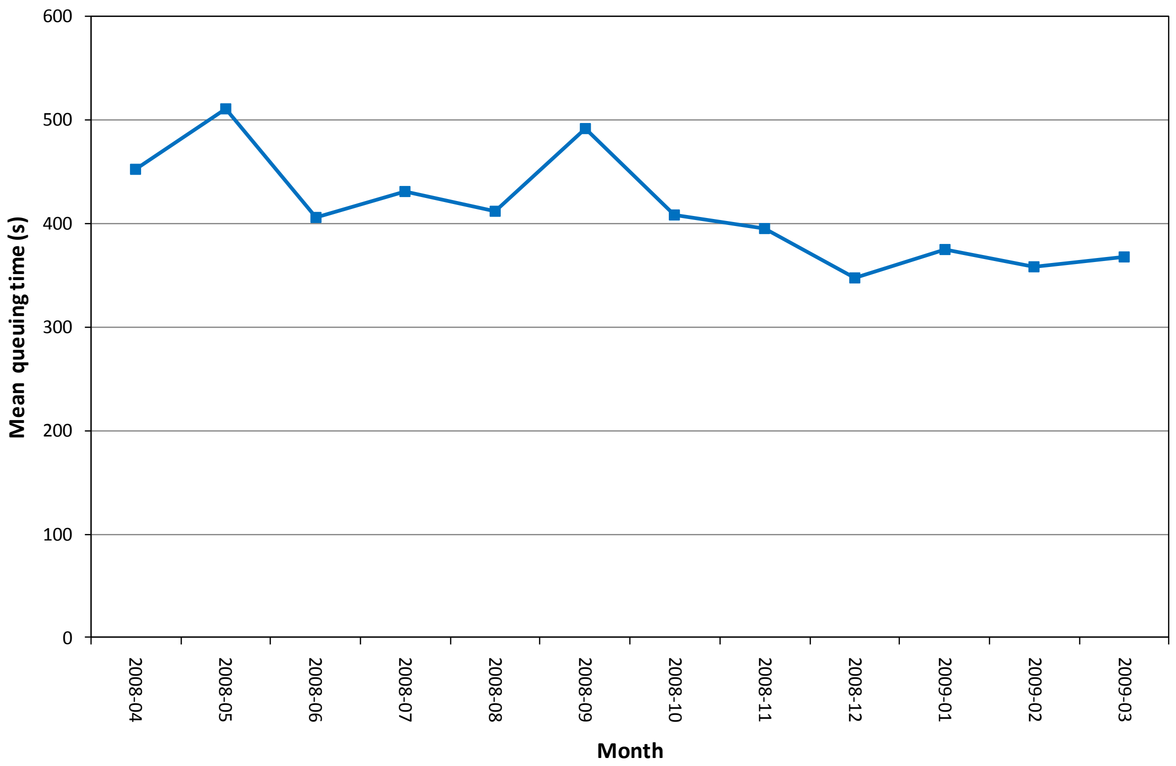


Fig A2.2 Mean queuing time as a function of month of year

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