APPENDIX AVAILABLE ON THE HEI WEB SITE

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The London Low Emission Zone Baseline Study

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Appendix B. Spatial Analysis of Modeled Air Pollution Data

Note: Appendices Available on the Web may appear in a different order than in the original Investigators' Report. HEI has not changed these documents. This appendix was relettered as follows:

Appendix B was originally Appendix A

Correspondence may be addressed to Dr. Frank J. Kelly, Environmental Health Environmental Research Group, School of Biomedical & Health Sciences, King's College London,
150 Stamford Street, London SE1 9NH, UK *frank.kelly@kcl.ac.uk*

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The London Low Emission Zone Baseline Study

APPENDIX A

SPATIAL ANALYSIS OF MODELLED AIR POLLUTION DATA

The King’s College London Emissions Toolkit for road traffic

The King’s College London Emissions Toolkit (ET) was used to provide detailed 2002, 2005, 2008 and 2010 traffic emission scenarios for 6344 roads and for the following vehicle types: cars, motorcycles, taxis, light goods vehicles (LGVs) buses - London Transport [LT] and non-LT and rigid and articulated heavy goods vehicles HGVs). Emissions included oxides if nitrogen (NO_x), nitrogen dioxide (NO_2), particles with an aerodynamic diameter of 10 μm or smaller (PM_{10}) exhaust and PM_{10} tyre and brake wear. PM_{10} resuspension was not included because of the uncertainty associated with emission factors for this source and also as recent studies have found it to contribute a very small proportion of primary PM_{10} emissions in London (Harrison 2004). The model simulates exhaust emissions based upon hourly traffic flows and speeds, along each of the road links using vehicle stock (based upon Euro classification) from the National Atmospheric Emissions Inventory (NAEI) (Baggott et al 2007). London specific vehicle stock was used for LT buses and taxis (black cabs). Exhaust emissions were based upon speed related emissions curves as described by Barlow et al (2001), and tyre and brake wear emissions (Ntziachristos and Boulter 2003). A number of assumptions were used to simulate the fitting of after treatment exhaust devices. For example, fitting particle traps to large diesel vehicles reduced NO_x and PM_{10} by 5% and 95%, respectively but increased carbon dioxide (CO_2) by 0.8% whilst fitting Selective Catalytic Reduction (SCR, a urea based NO_x emissions control system) to large diesel vehicles resulted in a 50% reduction in NO_x. Exhaust emissions from hydrogen fuel cell vehicles were assumed to be zero, although there was no reduction of PM_{10} tyre and brake wear emissions for these vehicles.

Recent evidence has pointed to the importance of primary NO_2 ‘(NO_2 (p))’ emissions in urban areas, and particularly those changes associated with new vehicles and those using after treatment devices such as particle traps (Carslaw and Beevers 2004, 2005, Carslaw et al 2007). Incorporation of NO_2 (p) into the air pollution model was therefore important in predicting annual mean NO_2 concentrations and in this study was based upon results from the NO_2 emissions inventory. The estimates of NO_2 emissions were calculated as a proportion of NO_X emissions and varied by vehicle type, vehicle age, after treatment technology and in the case of new diesel cars (Euro3+) and LGVs, by vehicle speed. The NO_2 to NO_X emissions ratios were taken from a combination of published data (Latham et al 2001; Richards et al 2002) and emissions tests made by Transport for London (TfL) and the Department for Transport (DfT). The NO_2 to NO_X emissions ratios estimated from the emissions inventory were tested against measurements using a multiple regression approach (Carslaw et al 2007) and showed good agreement for LGVs, HGVs and buses.

The King's College London Air Pollution Toolkit

Air pollution predictions were made using the King's College London Air Pollution Toolkit (APT). The toolkit is capable of modelling more than one million individual sources with different source characteristics, and has a typical output grid resolution of 20 x 20 metres. Emission sources, other than that of road transport, were taken from both the 2002 and 2003 London Atmospheric Emissions Inventory (LAEI) and included: Part A Processes (large regulated industrial processes); Part B Processes (smaller regulated industrial processes); Boilers (large boiler plants); Gas/Oil/Coal (domestic and commercial combustion); Agriculture and Nature; Rail; Ships and Airports.

London's air pollution was predicted using a combined modelling-measurement approach and a kernel modelling technique to describe the initial dispersion. The kernel model used a set of model concentration fields that were produced with an emissions source of unity:1 g s^{-1} (point sources), 1 g m^{-3} s^{-1} (volume sources) or 1 g km^{-1} s^{-1} (road sources). The assumption being, that one can calculate the contribution of any source to total air pollution concentrations by applying the model concentration field, and adjusting for the source strength, so long as each source exhibits similar emissions characteristics. The model assumed 2 principal source types: the road network close to the receptor location and the combined emissions from all sources, including road traffic, from more distant locations. The road network around each receptor location in London was modelled by splitting each road link into 10 metre lengths based on geographically accurate Ordnance Survey (OS) road centreline data. Roads were modelled in this way up to 500 metres from each receptor location using the ADMS roads model (CERC 2003) in combination with street canyon model OSPM v5.0.64 (Berkowicz 2000). The modeling approach combines the use of a next generation gaussian model (ADMS-roads) using Monin-Obukov similarity theory to assess atmospheric turbulence. The model has been used widely in the UK to make assessments of this kind. The choice of a UK model also means that associated data, for example, meteorological measurements are available and compatible with the models requirements. The use of OSPM where street canyons exist is also based around the need for a widely used and validated model which is practical enough to be employed over large urban areas, whilst representing the main features of dispersion within street canyons, for example, the recirculation eddy during cross flow winds. Other sources and road emissions, further than 500 metres from each location, were modelled as shallow volume sources using the ADMS 3 (CERC 2004) model. Volume sources are represented as a box into which the emissions are released and have a length and width of 1 x 1 kilometres and a height that is dependent upon the source characteristics. It was assumed that road transport emissions were released into a volume 2 metres deep and all other sources are released into a 50 metre deep volume, apart from the emissions from large industrial processes, for which specific emissions data were available.

A list of the major non-vehicle related emissions sources in London are given below:

- Part A Processes (i.e., large regulated industrial processes)
- Part B Processes (i.e., smaller regulated industrial processes)
- Boilers (i.e., large boiler plants)
- Gas (domestic, industrial-commercial and gas leakage)
- Oil (domestic and commercial oil fuel combustion)
- Coal (domestic and commercial combustion)
- Agriculture-Nature (agricultural and natural)
- Rail
- Ships (marine vessels)
- Airports

As an initial 'calibration' step, the model was used to predict NO_x concentrations at 31 monitoring sites throughout the London area. The results of this were used to undertake a multiple regression analysis in the form:

$$C_M = a.E_{ROAD} + b.E_{OTHER} + c$$

Where a, b and c are constants, E_{ROAD} is the contribution made from the nearby road network, E_{OTHER} the contribution from other sources plus road emissions further than 500 metres from each site and C_M the annual mean NO_X concentration at a monitoring site. Once the analysis was completed, predictions can be made for any receptor location using the values E_{ROAD} and E_{OTHER} taken from the traffic emissions model and the LAEI. Subsequently a further test of model performance was undertaken giving some confidence that the model worked well at all sites in London and not just at those that were part of its development.

Conversion from NO_X to NO_2

The toolkit model uses specially derived relationships for the conversion of annual average NO_X to NO_2 (Carslaw et al 2001). These curves were created by combining the NO_X frequency distribution and the relationship between hourly average NO_2 and NO_X for a measurement site and for any year. The method used all the hourly measurements of NO_X and NO_2 for each curve and hence reflected the different regimes in which nitric oxide is converted to NO_2. For the contribution close to roads, a new method was implemented which used the roadside increment of NO_X and NO_2 (including NO_2 (p)) above background concentrations. Initial tests of the method used, estimated that NO_2 (p) (% volume) (Carslaw and Beevers 2005) varied by site across the range 3.2 % (Hillingdon, HI0) to 23.5 % (Redbridge, RB2). The relationship between measured and predicted NO_2 concentrations gave an R^2 value of 0.98. We therefore concluded that this approach produced a good annual mean NO_2 concentration prediction at roadside locations if the model produced good estimates of annual mean NO_X concentrations, and there was an accurate estimate of NO_2 (p).

Finally, in addition to changes in NO_2 (p) from road vehicles, there was also a regional contribution to ambient oxidants (OX) (NO_2 plus ozone [O_3]) via regional O_3. This regional O_3 has the potential to change through time and as such was incorporated into the predictions of NO_2. A detailed description of the partitioning between regional OX (O_3) and locally generated OX (NO_2 (p)) is given in a number of publications (Clapp and Jenkin 2001; Carslaw and Beevers 2004, 2005; Jenkin 2004). Of note, Jenkin (2004) provided a method by which changes in regional OX can be applied to empirical modelling techniques and this method has been adapted for use in the King's College London model. The assumption for future increases of regional O_3 was based upon the analysis of O_3 trends at Mace Head in Ireland (Carslaw 2005). The results showed that the increase in O_3 concentration between 1990 and 2004 was 0.18 ± 0.04 ppb yr^{-1} and hence a O_3 increase of 0.18 ppb yr^{-1} was assumed to occur for recent years.

Predictions of annual average PM_{10}

Primary PM_{10} concentrations were predicted in the same regression coefficients as for NO_X concentrations, without additional model calibration. Annual mean PM_{10} predictions used a combination of emissions from the detailed road network as well as other PM_{10} sources, represented as volume sources of varying dimension. PM_{10} from outside London was taken from the analysis of measurements and is split into primary, secondary and natural particles. This was based upon use of the comprehensive PM_{10}, particles with an aerodynamic diameter of 2.5 µm or smaller ($PM_{2.5}$) and NO_X measurements in London (Fuller et al 2002, 2006).

Meteorological measurements

All model runs were based upon the year 2002, and used hourly average meteorological data (8760 hours), which is summarised into 10^o wind sectors and recorded at a height of 10 metres at the UK Meteorological Office's, Heathrow Airport site. The parameters measured included temperature, wind speed, wind direction, precipitation, relative humidity and cloud cover. The assumptions used in the kernel model included a surface roughness of one metre, a minimum Monin-Obukov length of 100 metres and weekday/weekend hourly emissions variations.

Emission assumptions for the air pollution model

The LAEI 2002 and 2003 summarises emissions from non-vehicle related sources for the base year and 2010 only. The time trend in emissions from non-vehicle sources in London was predicted to be small compared with road traffic but for future years, 2008 and 2010 emissions changes were made by interpolating between LAEI predictions for 2002/3 and 2010. The gradual change in vehicle technology has led to improvements in predicted emissions from vehicles between 2002 and 2010. The emissions estimates for each year were created using detailed changes in vehicle stock (summarised into Euro class categories), vehicle km changes and changes to vehicle speed, road link by road link.

For all but LT buses and taxis, the estimates of vehicle stock were made using the UK National Stock model (Tim Murrells, personal communication), for the remaining 2 vehicle categories stock details were provided by LT buses (Anna Rickard, personal communication) and the Greater London Authority (GLA) (Sarah Legge, personal communication). Vehicle kilometre changes between years were small, however changes were applied across London using estimates provided by TfL (Charles Buckingham, personal communication). Finally, vehicle speed estimates used average link speed data from the “floating car”, a continuously circulating vehicle in London.

The specific scenario, number 6, required that all LEZ ‘in-scope’ vehicles meet the E4 emissions standard for PM_{10} and NO_X. More details of the vehicle stock assumptions (both LEZ and Non-LEZ vehicles) are included, as well as the assumptions made when fitting exhaust after treatment to LEZ vehicles (see Table A1 and Table A2). In addition the transport related emissions changes associated with the LEZ are summarized in Table A3.

Table A1. The assumptions for vehicle stock (LEZ and non-LEZ vehicles) for 2010 base case and scenario 6.

Vehicle type	Vehicle/fuel technology	2010	Scenario 6	Difference Scenario 6- 2010
Petrol Cars				
preEuroI		0.8	0.8	0.0
EuroI		1.7	1.7	0.0
EuroII		12.5	12.5	0.0
EuroIII		18.7	18.7	0.0
EuroIV		66.3	66.3	0.0
EuroV		0.0	0.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Black Taxis				
preEuroI		0.0	0.0	0.0
EuroI		0.0	0.0	0.0
EuroII		0.0	0.0	0.0
EuroIII		78.3	78.3	0.0
EuroIV		21.3	21.3	0.0
EuroV		0.4	0.4	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Diesel Cars				
preEuroI		0.0	0.0	0.0
EuroI		0.9	0.9	0.0
EuroII		4.5	4.5	0.0
EuroIII		23.2	23.2	0.0
EuroIII	Particle Trap	5.4	5.4	0.0
EuroIV		53.6	53.6	0.0
EuroIV	Particle Trap	12.4	12.4	0.0
EuroV		0.0	0.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Small Petrol Light Goods Vehicles				
preEuroI		0.5	0.5	0.0
EuroI		1.4	1.4	0.0
EuroII		7.7	7.7	0.0
EuroIII		31.9	31.9	0.0
EuroIV		58.4	58.4	0.0
EuroV		0.0	0.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Large Petrol Light Goods Vehicles				
preEuroI		0.5	0.5	0.0
EuroI		1.4	1.4	0.0

EuroII		7.7	7.7	0.0
EuroIII		31.9	31.9	0.0
EuroIV		58.4	58.4	0.0
EuroV		0.0	0.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Small Diesel Light Goods Vehicles				
preEuroI		0.3	0.3	0.0
EuroI		1.4	1.4	0.0
EuroII		12.1	12.1	0.0
EuroIII		27.5	27.5	0.0
EuroIII	Particle Trap	0.0	0.0	0.0
EuroIV		58.6	58.6	0.0
EuroIV	Particle Trap	0.0	0.0	0.0
EuroV		0.0	0.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Large Diesel Light Goods Vehicles				
preEuroI		0.3	0.3	0.0
EuroI		1.4	1.4	0.0
EuroII		12.1	12.1	0.0
EuroIII		27.5	27.5	0.0
EuroIII	Particle Trap	0.0	0.0	0.0
EuroIV		58.6	58.6	0.0
EuroIV	Particle Trap	0.0	0.0	0.0
EuroV		0.0	0.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.0	0.0	0.0
Rigid Heavy Goods Vehicles				
old		0.0	0.0	0.0
preEuroI		0.0	0.0	0.0
EuroI		0.6	0.1	-0.5
EuroII		13.8	1.6	-12.2
EuroII	Particle Trap	0.0	0.8	0.8
EuroIII		39.2	5.0	-34.2
EuroIII	Particle Trap	0.0	0.0	0.0
EuroIV		20.7	35.3	14.6
EuroV		25.7	25.7	0.0
EuroVI		0.0	0.0	0.0
EuroIII	Particle Trap + Selective Catalytic Reduction	0.0	30.1	30.1
EuroII	Particle Trap + Selective Catalytic Reduction	0.0	1.4	1.4
Articulated Heavy Goods Vehicles				
old		0.0	0.0	0.0
preEuroI		0.0	0.0	0.0

EuroI		0.3	0.0	-0.2
EuroII		6.9	0.8	-6.1
EuroII	Particle Trap	0.0	0.4	0.4
EuroIII		36.0	4.4	-31.5
EuroIII	Particle Trap	0.0	0.0	0.0
EuroIV		25.3	36.6	11.4
EuroV		31.6	31.6	0.0
EuroVI		0.0	0.0	0.0
EuroIII	Particle Trap + Selective Catalytic Reduction	0.0	25.4	25.4
EuroII	Particle Trap + Selective Catalytic Reduction	0.0	0.7	0.7
Bus				
preEuroI	Particle Trap	0.0	0.2	0.2
preEuroI		2.0	0.3	-1.7
EuroI		5.0	0.7	-4.3
EuroII		16.3	2.2	-14.1
EuroII	Particle Trap + Selective Catalytic Reduction	0.0	2.3	2.3
EuroII	Particle Trap	0.0	1.2	1.2
EuroIII		36.9	10.4	-26.5
EuroIII	Particle Trap	0.0	0.0	0.0
EuroIV		17.5	30.9	13.3
EuroV		22.3	22.3	0.0
EuroI	Particle Trap	0.0	0.7	0.7
EuroIII	Particle Trap + Selective Catalytic Reduction	0.0	28.9	28.9
London Transport Bus				
old		0.0	0.0	0.0
preEuroI		0.0	0.0	0.0
preEuroI	Oxidation catalyst	0.0	0.0	0.0
preEuroI	Particle Trap	0.0	0.0	0.0
EuroI		0.0	0.0	0.0
EuroI	Oxidation catalyst	0.0	0.0	0.0
EuroI	Particle Trap	0.0	0.0	0.0
EuroII		0.0	0.0	0.0
EuroII	Oxidation catalyst	11.9	11.9	0.0
EuroII	Particle Trap	3.4	3.4	0.0
EuroIII		0.0	0.0	0.0
EuroIII	Particle Trap	51.0	51.0	0.0
EuroIV		21.4	21.4	0.0
EuroV		12.0	12.0	0.0
EuroVI		0.0	0.0	0.0
LPG	alternative fuel	0.3	0.3	0.0

Within the LEZ scenarios vehicles that fit particle traps are commonplace. The assumptions used to factor vehicle emissions to simulate the introduction of such traps are given in Table A2. With the addition of NO_X abatement for buses, using a combination of Exhaust Gas Recirculation (EGR) and Selective catalytic reduction (SCR), a 50% reduction in NO_X has also been assumed.

Table A2. The factors applied to each vehicle to simulate the fitting of a particle trap.

NO_X	PM_{10}	CO	HC	SO_2	CO_2
0.95	0.05	0.1	0.1	1.008	1.008

Table A3. Road traffic emissions (tonnes/annum) across the LAEI area, for 2010 base case and LEZ scenario 6.

Scenario	NO_X	Total PM_{10}	CO_2	PM_{10} Tyre and Brake wear
2010 Base Case	27561	2128	11770096	1084
2010 Scenario 6	24284	1954	11775128	1084

Across the whole of the LAEI area the reduction in emissions of NO_X was 3277 tonnes or 12% of 2010 base case emissions. The equivalent figure for the emissions of PM_{10} was 174 tonnes or 8% of 2010 base case emissions. Finally an insignificant increase was calculated for CO_2 of around 0.04%.

Air Pollution model performance

As part of the model development a recalibration and evaluation exercise are undertaken. For a complete description of this process see (HEI,CCS report). Approximately 30 monitoring sites throughout London were used to recalibrate the model to fit the data and subsequently a further model evaluation was undertaken using approximately 50 - 60 NO_X sites and 40 PM_{10} sites. This gives some confidence that the model works well at all sites in London and not just at those that were part of its development.

Results from before and after recalibration are presented along with those sites not used in the recalibration exercise. The ‘before correction’ results can be seen on the graph in the right hand column of Figure A1, which shows that the model performs reasonably well at background locations but that at roadside there is a large under prediction. Roadside locations are difficult to predict for many reasons, given the complexity of the monitoring locations, the steep concentration gradients and emissions inventory limitations.

Measured vs predicted scatter plots are provided for all sites in 2002 (see Figure A2) and for each pollutant. Alongside each of the scatter plots is the associated residual plot. Whilst all model predictions show some scatter due to model uncertainty the residual (predicted – measured) frequencies should be normally distributed (or near normal). It is unlikely that with 40 – 60 points that a normal distribution is possible, however the model results do show that the majority of residuals occur at or very close to zero and that the frequency of these drop away quickly. Overall therefore the toolkit model performance for 2002 show good agreement with the measurements from the LAQN.

Finally, the non-calibration site evaluation is also shown in Figure A1 (left hand column). This shows that there is little difference between the model performance at these sites compared with all sites from the LAQN.

Model v measured NO_X concentrations for non-calibration sites

Model v measured NO_X concentrations without model correction

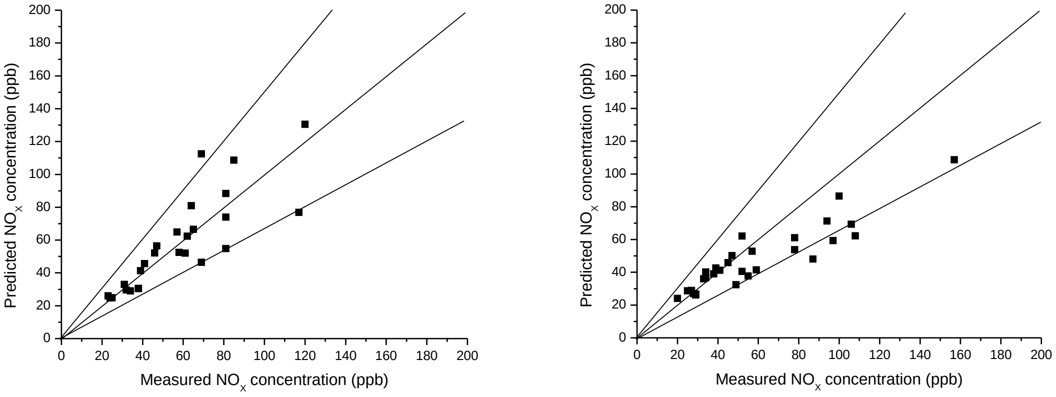
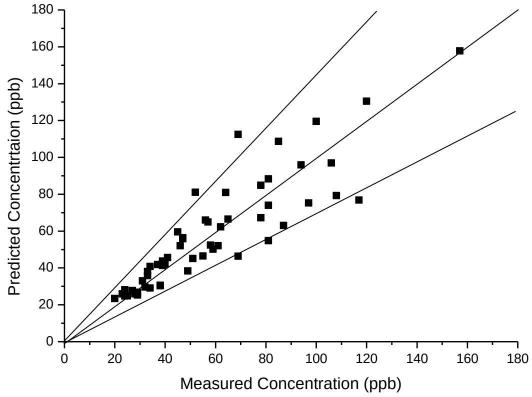
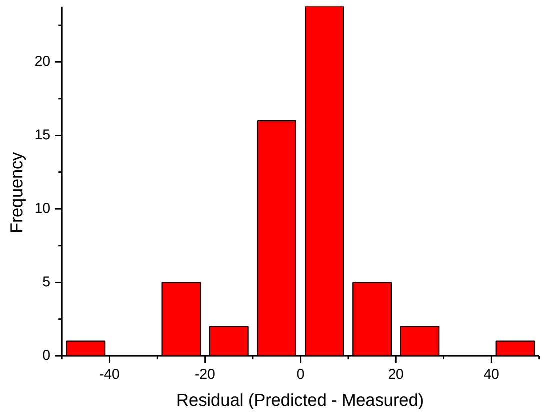


Figure A1. Model evaluation results for non-calibration sites (left hand column) and prior to re-calibration (right hand column).

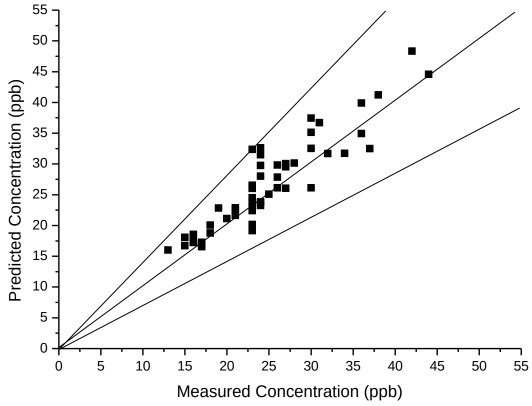
Nitrogen Oxides (NO_X) 2002 (ppb)



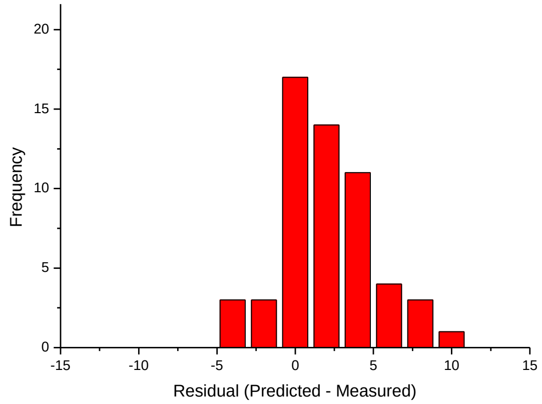
NO_X residuals (predicted-measured) (ppb)



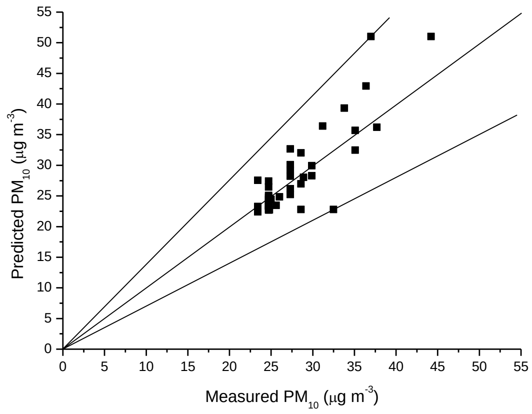
Nitrogen Dioxide (NO_2) 2002 (ppb)



NO_2 residuals (predicted-measured) (ppb)



Annual Mean PM_{10} 2002 ($\mu g\ m^{-3}$)



PM_{10} residuals (predicted-measured) ($\mu g\ m^{-3}$)

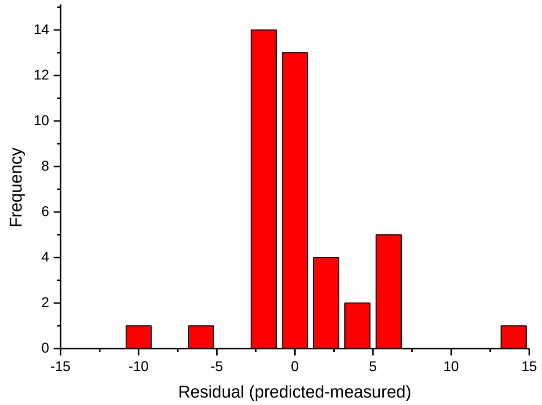


Figure A2. APT performance results for 2002

Results in Table A4, show a number of features of the model performance. The first was that across all sites the average modelled and measured NO_X agree to within 0.1 ppb. For NO_2 the maximum difference between model and measured averages was 1.8 ppb and for PM_{10} was within 0.4 $\mu g\ m^{-3}$. RMS error results also indicate good model performance and for annual mean NO_X, annual mean NO_2, and annual mean PM_{10} are: ± 24 %, ± 13 %, ± 13 %.

The fractional bias statistics for the toolkit predictions for 2002 were never greater than ± 0.07 and it can therefore be concluded that the model is relatively free from bias.

Table A4. Model and measurement results for 2002

Pollutant	Year	Number of sites	Measured average & error[1]	Model average & ± RMS error	Model Fractional Bias
NO_X (ppb)	2002	56	57.3 ± 5.7	57.2 ± 13.7	-0.002
NO_2 (ppb)	2002	56	24.4 ± 2.4	26.2 ± 3.4	0.071
PM_{10} mean ($\mu g\ m^{-3}$)	2002	41	28.1 ± 1.38	28.5 ± 3.8	0.003

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[1] Measurement error is assumed to be ± 10% (2 σ). These estimates are described in (ERG, 2002). PM10 measurement error (2 σ) assumed to be the same as daily estimates (Bureau Veritas, 2006)

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Abbreviations

APT	King's College London, Air Pollution Toolkit
CO_2	carbon dioxide
DfT	Department for Transport
ET	King's College London, Emissions Toolkit
GLA	Greater London Authority
HGVs	heavy goods vehicles
LAEI	London Atmospheric Emissions Inventory
LEZ	London-wide Low Emission Zone
LGVs	light goods vehicles
LT	London Transport
NAEI	National Atmospheric Emissions Inventory
NO_2	nitrogen dioxide
NO_2p	primary nitrogen dioxide
NO_x	oxides of nitrogen
OX	oxidant
O_3	ozone
OS	Ordnance Survey
$PM_{2.5}$	particles with an aerodynamic diameter of 2.5 µm or smaller
PM_{10}	particles with an aerodynamic diameter of 10 µm or smaller
RPC	Reduced Pollution Certificate
SCR	selective catalytic reduction
TfL	Transport for London