APPENDIX 6

BREATHE LONDON FINAL MODELLING REPORT

Cambridge
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Consultants

D9.1 Final Report

Final Report

Breathe London Project

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CERC

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Contents

1. Summary

This report presents the modelling and analysis work done by CERC during the second year of the Breathe London project, building on the achievements of the first year of the project. The work uses the London Atmospheric Emissions Inventory (LAEI) together with the air dispersion model ADMS-Urban to estimate concentrations in high levels of detail across London, taking into account meteorology variations, street canyon geometry, chemical reactions and urban canopy effects. In the second year of the project the modelling has been updated from 2018 emissions to 2019 emissions, and then further updated to incorporate the findings of the 'Hotspot analysis' (Appendix 9). The resulting annual average maps present the authors' best estimates of NO_2, NO_X, PM_{10}, $PM_{2.5}$, O_3 and CO_2 concentration at 10m resolution across Greater London extending out to the M25 Motorway.

The model validation using 107 LAQN sites, 43 AQE sites and 144 AQMesh sites shows good agreement for all pollutants. The 7-day factors introduced in the Hotspot2019 modelling scenario improved the correlation between modelled and measured concentrations for all pollutants; the application of adjustments to non-exhaust PM emissions in the Hotspot2019 scenario helped to obtain better agreement for PM_{10} and $PM_{2.5}$. For NO_2, the correlation between modelled and measured values is lower at AQMesh sites than at reference sites, but this is likely to be due to ozone (O_3) interference causing some AQMesh measurements of NO_2 to be too high; the final version of the AQMesh measured dataset (not used in this work) includes a correction to account for this behaviour.

Innovative inversion techniques have been developed during the course of this project to assimilate measurements with modelled data to improve model predictions; these have been applied to assess the impact of the ULEZ on road traffic emissions (this report), and also to estimate the impact of COVID-19 restrictions on road traffic emissions (Appendix 12). This is an exciting area of research that is likely to be highly valuable results in future, particularly in a post-COVID world of changing traffic patterns.

Source apportionment analysis has been carried out for 23 categories for NO_X and 25 categories for $PM_{2.5}$, including 10 traffic exhaust categories, traffic non-exhaust emissions, 4 fuel usage categories and 11 other non-traffic categories. Traffic sources dominate the NO_X concentrations, with the concentrations at all sites from traffic sources attributable to at least 32% of the total concentrations and reaching a maximum of 73% at Kerbside monitoring sites outside the ULEZ. Of the traffic sources, Diesel Cars, Diesel LGVs and TfL Buses are the highest contributors. Inside the ULEZ, concentrations are higher across all site types, with a marked increase of 40 µg/m³ from Hospital sites outside the ULEZ compared to inside. The percentage of commercial and domestic fuel usage approximately doubles inside the ULEZ, which is largely dominated by gas combustion.

Three policy scenarios have been assessed to estimate the impact of: (a) replacing all TfL buses with zero emission buses; (b) making all taxis zero emission taxis; and (c) implementing (a) and (b) together. The largest NO_X reductions are at kerbside sites within the ULEZ when both TfL Buses and Taxis have zero exhaust emissions, with a reduction of 27.3 µg/m³ (23%) in NO_X concentrations, and a reduction of 9.1 µg/m³ (18%) in NO_2. A larger proportion of the reduction is attributable to the zero emission TfL Buses. There is minimal (<1 µg/m³) reduction in $PM_{2.5}$ annual average concentrations, because the policy action only targets exhaust emissions, and the bulk of road traffic $PM_{2.5}$ emissions are associated with the non-exhaust component of emissions.

2. Introduction

Throughout the Breathe London project, CERC has applied the ADMS-Urban air pollution dispersion model to simulate air pollution levels in London, for comparison with the new Breathe London network of over 100 AQMesh sensors and Google Car measurements, to investigate the impact of air quality policy actions such as the implementation of the Ultra-Low Emissions Zone (ULEZ) and to provide support to the work of Breathe London partners. During the course of the project, the modelling has been continually refined to improve model accuracy, with the aim of providing the most accurate picture possible of air quality in London in 2019, including updated high-resolution maps of air pollution and an assessment of the contribution from different activity sectors. This report provides a comprehensive account of the modelling and results. The modelled data presented here is available to project partners for further analysis.

The modelling methodology is described in Section 3, including a description of how pollution sources are represented in ADMS-Urban, the complex effects accounted for, the locations modelled, and the meteorological data and background data used. Section 4 describes the modelling scenarios, including emissions data, and Section 5 describes the measured concentration data. The performance of the model compared with measured data is presented in Section 6. Modelled and measured data have been combined using inversion techniques to estimate the impact of the implementation of the ULEZ; this work is presented in Section 7. Updated annual average maps of NO_X, NO_2, PM_{10}, $PM_{2.5}$, O_3 and CO_2 are presented in Section 8, together with an assessment of the activity sectors that contribute most to NO_X and $PM_{2.5}$ at monitoring sites and at care homes, schools and hospitals in London. Section 8 also includes the estimated impact of a selection of policy actions on annual average levels of NO_X, NO_2 and $PM_{2.5}$ at these locations. Section 9 provides some concluding remarks.

3. Methodology

3.1 Source characterisation

The ADMS-Urban model that has been used in this analysis includes the following source types:

- **Roads**, for which emissions are calculated from vehicle flows and speeds and the additional initial dispersion caused by moving vehicles is also taken into account;
- **Industrial points**, for which plume rise and stack downwash are included in the modelling; and
- **Aircraft sources,** for which buoyancy, momentum, aircraft motion and high-speed exit velocities, relative to ambient wind conditions, are accounted for.

In addition, sources are also modelled as a regular grid of well-mixed emissions. This allows the contributions of large numbers of minor sources to be efficiently included while the majority of the modelling effort is used for the relatively few significant sources. The emissions for any sources (domestic and commercial fuel combustion, minor roads, shipping etc.) that are not explicitly modelled are aggregated into 1km ground-based square grid cells. The grid cells are square volume sources that cover the modelling domain.

For this work, road geometry, average traffic flows and speeds, industrial point sources, rail emissions and gridded emissions of NO_X, NO_2, PM_{10}, $PM_{2.5}$ and CO_2 from other sources have been taken from the London Atmospheric Emissions Inventory (LAEI) published by the GLA. This work used ‘LAEI 2013’, which was published in 2016, has a base year of 2013 and includes projections for 2020. Specifically, this work used annual average values for 2019, obtained by interpolating between the base year values and the projections for 2020. LAEI average traffic flows in 11 vehicle categories[1] were combined with LAEI average traffic speeds and the appropriate emission factors from the Emission Factor Toolkit (EFT) v8, published by Defra, to calculate the annual average emission rate of these five pollutants from each road source modelled. This is discussed in more detail in Section 4.1. Major roads are modelled explicitly as road sources; emissions from minor roads are included in the gridded emissions. The grid cells in this work were 1km by 1km with a depth of 10m and cover the region inside the M25, in accordance with the extent of the LAEI dataset.

For this project the model included the following explicit sources: 35 point sources, 72602 major road sources, 1605 major overground rail links together with 75 aircraft sources to correctly account for the pollution due to Heathrow Airport. The rail sources were all modelled as road sources, with a height of 4m, and all other non-explicit sources were modelled over 2483 1km grid cells that cover the area within the M25 Motorway. All explicit and non-explicit sources modelled are shown in Figure 3-1. The aircraft sources, shown in purple, are modelled at height, and therefore the initial climb and descent can be seen extending beyond Heathrow.

[1] Motorcycles, cars, taxis, light goods vehicles (LGVs), buses and coaches, rigid heavy goods vehicles (HGVs) 2 axles, rigid HGVs 3 axles, rigid HGVs 4+ axles, articulated HGVs 3&4 axles, articulated HGVs 5 axles, articulated HGVs 6+ axles

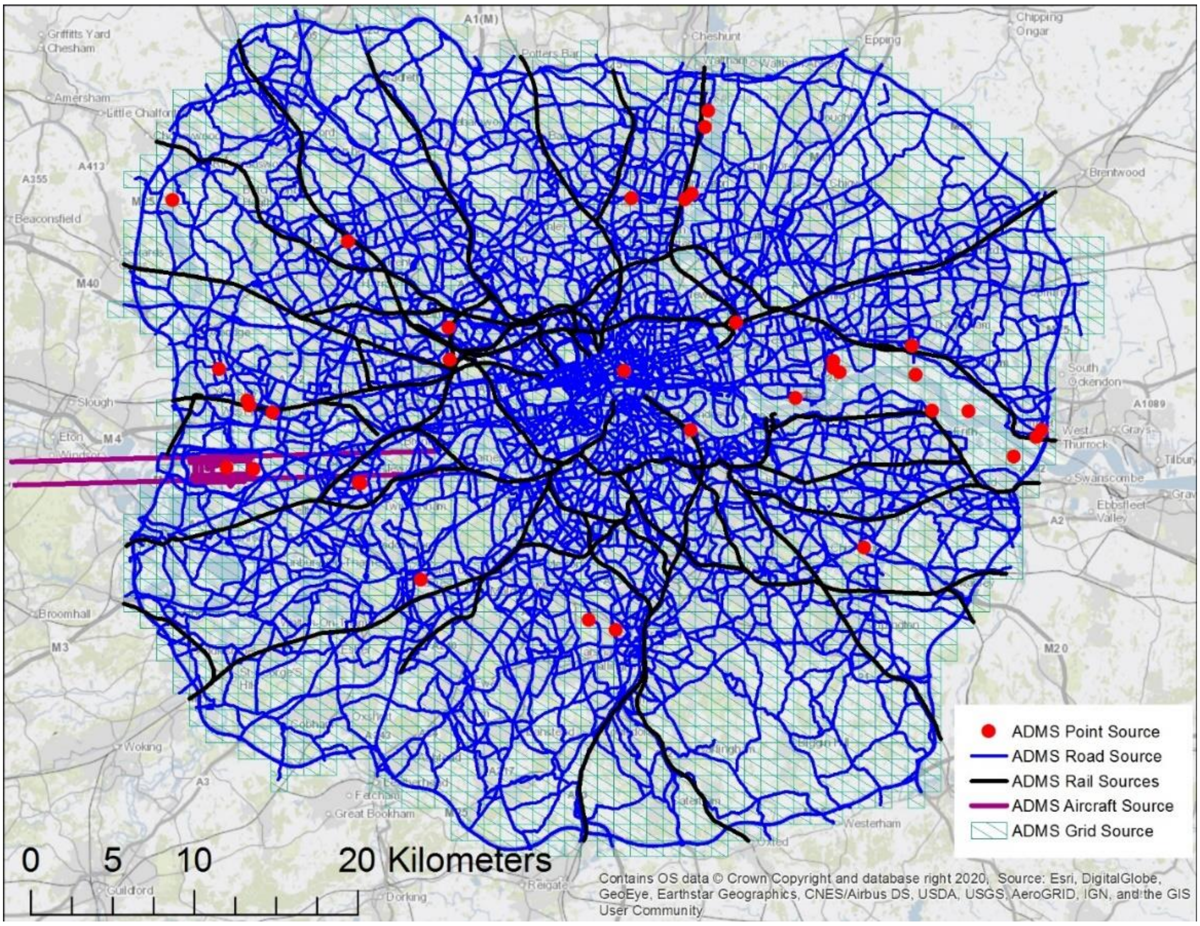

Figure 3-1: A map of the sources modelled

3.2 Complex effects

3.2.1 Urban chemistry

ADMS-Urban includes the *Generic Reaction Set (GRS)*[2] atmospheric chemistry scheme. The original scheme has seven reactions, including those occurring between nitrogen oxides and ozone. The remaining reactions are parameterisations of the large number of reactions involving a wide range of Volatile Organic Compounds (VOCs). In addition, an eighth reaction has been included within ADMS-Urban for the situation when high concentrations of nitric oxide (NO) can convert to nitrogen dioxide (NO_2) using molecular oxygen.

In addition to the basic GRS scheme, ADMS-Urban also includes a trajectory model[3] for use when modelling large areas. This permits the chemical conversions of the emissions and background concentrations upwind of each location to be properly taken into account.

3.2.2 Street canyons

The ADMS-Urban Advanced Street Canyon Scheme represents the effects of channelling flow along and recirculating flow across a street canyon, dispersion out of the canyon through

[2] Venkatram, A., Karamchandani, P., Pai, P. and Goldstein, R., 1994, 'The Development and Application of a Simplified Ozone Modelling System.' *Atmospheric Environment*, Vol 28, No 22, pp3665-3678.

[3] Singles, R.J., Sutton, M.A. and Weston, K.J., 1997, 'A multi-layer model to describe the atmospheric transport and deposition of ammonia in Great Britain.' In: *International Conference on Atmospheric Ammonia: Emission, Deposition and Environmental Impacts. Atmospheric Environment*, Vol 32, No 3.

gaps in the walls, over the top of the buildings or out of the end of the canyon. It can take into account canyon asymmetry and restricts the emissions area to the road carriageway.

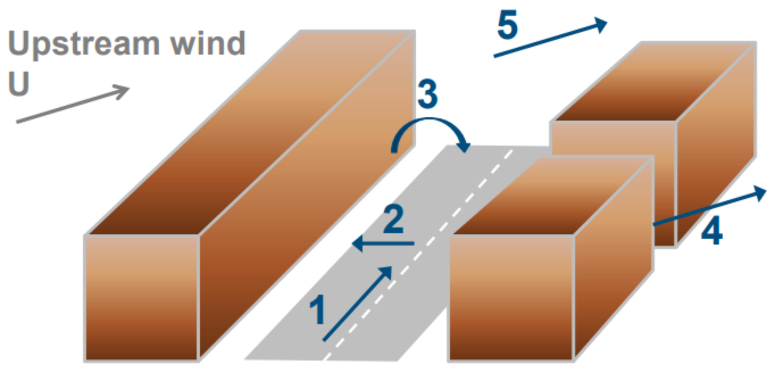

Figure 3-2 Schematic diagram of the ADMS-Urban Advanced Street Canyon Scheme. Pollutants (1) are channelled along street canyons; (2) are dispersed across street canyons by circulating flow at road height; (3) are trapped in recirculation regions; (4) leave the canyon through gaps between buildings as if there was no canyon; and (5) leave the canyon from the canyon top.

To generate the street canyon geometry, 3-D building data and road centreline locations from Ordnance Survey MasterMap (Ordnance Survey, 2014) were processed for use in ADMS-Urban, as described in Jackson et al. (2016)[4], although using the EMEP4UK polar stereographic projected coordinate system.

3.2.3 Urban canopy

ADMS-Urban includes an "urban canopy" flow field module[5], which modifies the atmospheric velocity and turbulence flow profiles that relate to the spatial variation of the surface roughness length to account for a higher density of buildings in an urban area. As wind approaching densely packed buildings the wind profile is displaced vertically, whilst the flow and corresponding turbulence within the buildings canopy is reduced. The urban canopy module does not account for any heat effects of buildings in an urban area. The urban canopy profile was calculated in this project using the same data as the advanced street canyons in 3.2.2.

3.3 Modelled locations

3.3.1 Static Monitoring Sites

Static monitoring sites have been modelled as discrete receptors with the appropriate position and height. They represent reference monitors from the London Air Quality Network (LAQN) and Air Quality England (AQE) networks, and the locations of the Breathe London AQMesh Sensors. There are 306 monitoring site receptor locations in total, with 107 LAQN, 43 AQE and 144 AQMesh receptors. The AQMesh receptor locations account for pods that have been relocated over the modelled period. Table 3-1 contains the number of static monitoring locations that have been included in the modelling, split down by network, site type and whether they are located within the boundary of the Ultra-Low Emission Zone (ULEZ). Figure 3-3 shows the distribution of the static monitoring sites across London. Comparisons between modelled and measured concentrations are presented in Section 6.1.

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[4] http://technical.cloud-journals.com/index.php/IJARSG/article/view/Tech-602

[5] Hood C, Carruthers D, Seaton M, Stocker J and Johnson K, 2014: *Urban canopy flow field and advanced street canyon modelling in ADMS-Urban*.16th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Varna, Bulgaria, September 2014.

For the source apportionment analysis in Section 8.2, industrial and suburban sites have been included under the "Urban Background" category.

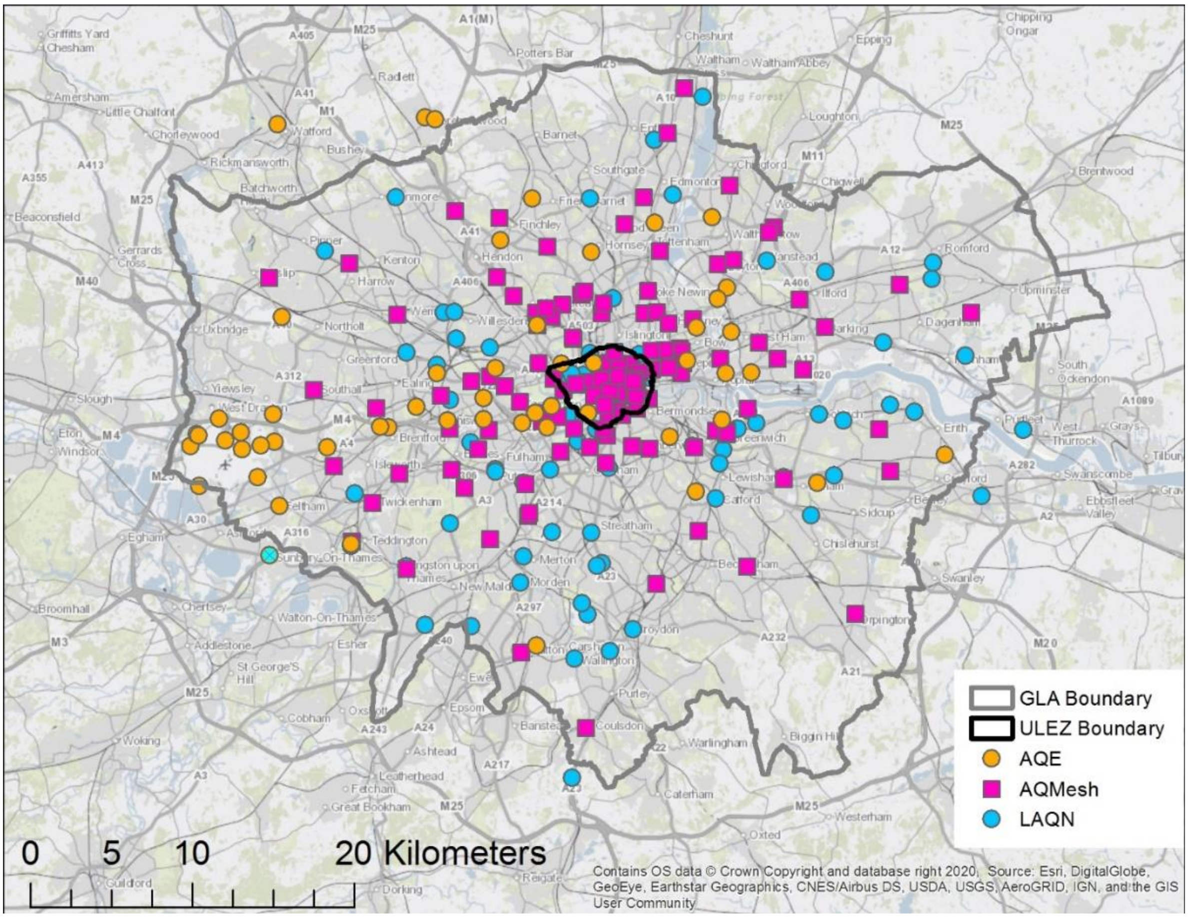

Figure 3-3: Map of the static monitoring site locations across London, split by network

Table 3-1: Table showing the number of static monitoring locations available, broken down by site type and location.

Network	Type	Inside ULEZ	Outside ULEZ	Total
AQE	Airport	0	3	3
AQE	Industrial	0	1	1
AQE	Kerbside	0	3	3
AQE	Roadside	0	15	15
AQE	Suburban	0	3	3
AQE	Urban Background	1	17	18
AQMESH	Kerbside	15	34	49
AQMESH	Roadside	8	38	46
AQMESH	Urban Background	11	38	49
LAQN	Industrial	0	6	6
LAQN	Kerbside	3	8	11
LAQN	Roadside	7	47	54
LAQN	Suburban	0	13	13
LAQN	Urban Background	5	18	23

3.3.2 Mobile simulations

Mobile measurements have been represented in the model by placing discrete receptors at points along the road centrelines, for roads that have been driven by the Google Cars and are included in the LAEI, with a limiting distance of 12m to ensure the correct data points were assigned to the nearest road. Data points were excluded from the comparison if there were no emissions inventory roads within this distance; this equated to 30,445 explicit road sources. Any roads that are not explicitly modelled are included in the grid. Figure 3-4 displays the location of the driven 30m road segments with valid data that lie within 12m of a road in the inventory, and that were therefore included in the modelling.

Each receptor has been assigned to a 30m road segment for the calculation of hourly and period averages per road segment. All receptors were assumed to 1.5m above the ground to accurately reflect the inlet height on the Google Cars, and were located approximately every 15m down a road centreline. In total 394,205 discrete receptors were modelled. The model calculates hourly averages from 1st September 2018 to 31st October 2019, and then only the hourly measurements for hours in which there are valid Google car measurements are extracted for comparison. Comparisons between measured and modelled concentrations are presented in Section 6.2.

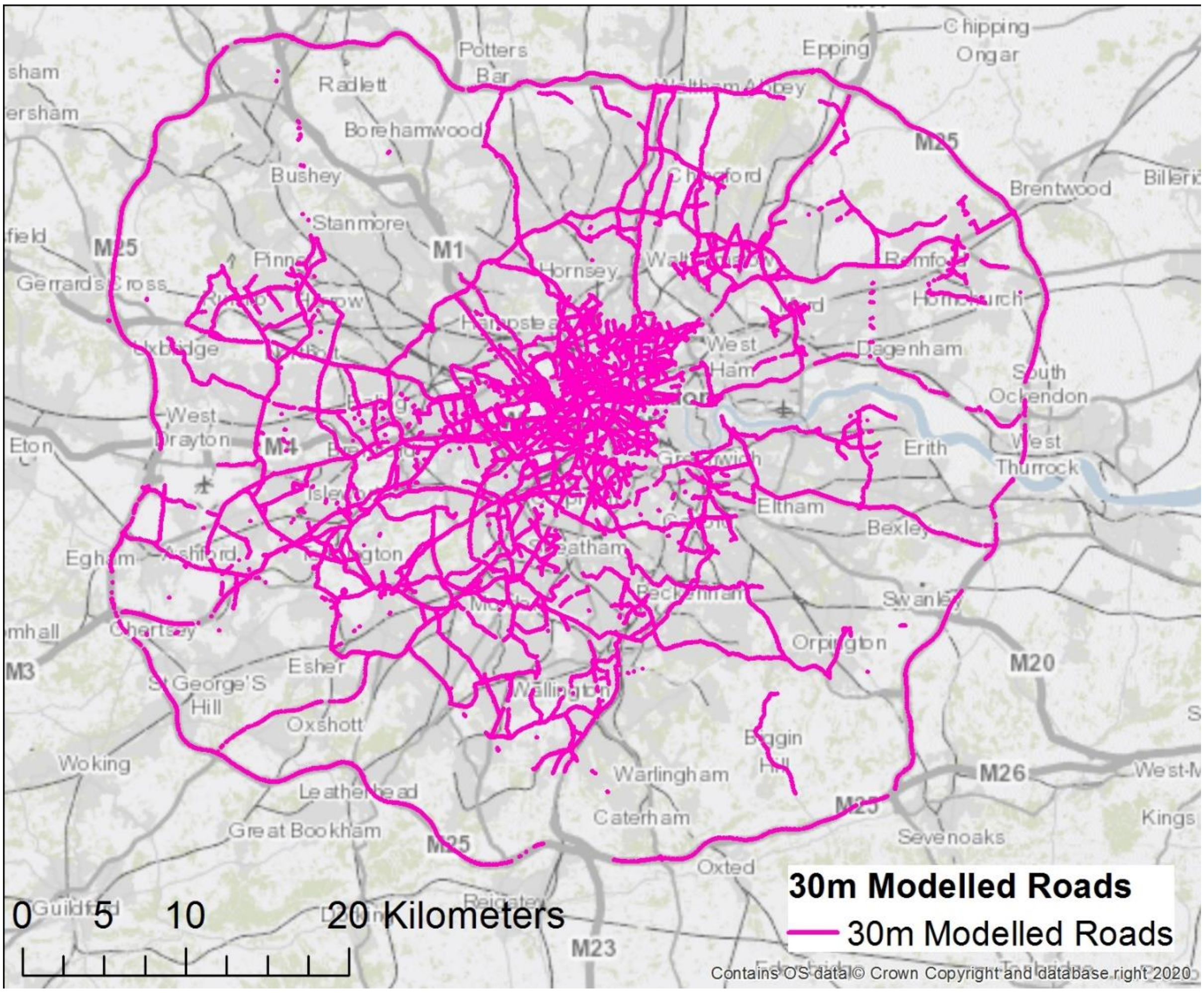

Figure 3-4: A map of the 30m driven road segments that were within 12m of a road in the inventory

3.3.3 High Resolution Contour Simulations

To represent the concentrations across London from all sources at high spatial resolution, an irregular grid of 1,349,418 points across London is modelled. This combines regular gridded points every 200m, with additional points added around roads, rail and aircraft sources to capture the high concentrations gradients near to these sources. Once modelled, these points are interpolated further, adding approximately 350,000 additional receptors. These irregular gridded points are then further processed to produce a regular interpolated grid at 10m resolution across the entire modelled area in order to generate pollution maps. High resolution maps of annual average NO_X, NO_2, PM_{10}, $PM_{2.5}$, Ozone and CO_2 are presented in Section 8.1.

3.3.4 Sensitive Receptors

For the source apportionment analysis (Section 8.2), an additional 3623 discrete receptors were included representing schools, care homes and hospitals across London. Figure 3-5 shows the location of the sensitive receptors within the GLA boundary, and Table 3-2 contains the number of sensitive receptors, grouped by type and location with respect to the ULEZ boundary. The receptors were modelled at 1m above ground and their locations were the roadside location nearest to the establishment postcode.

Table 3-2: Table showing the number of sensitive receptors, grouped by site type and split by location

Site Type	Outside ULEZ	Inside ULEZ	Total
Schools[6]	1852	38	1890
Care Homes[7]	1568	6	1574
Hospitals[8]	134	25	159

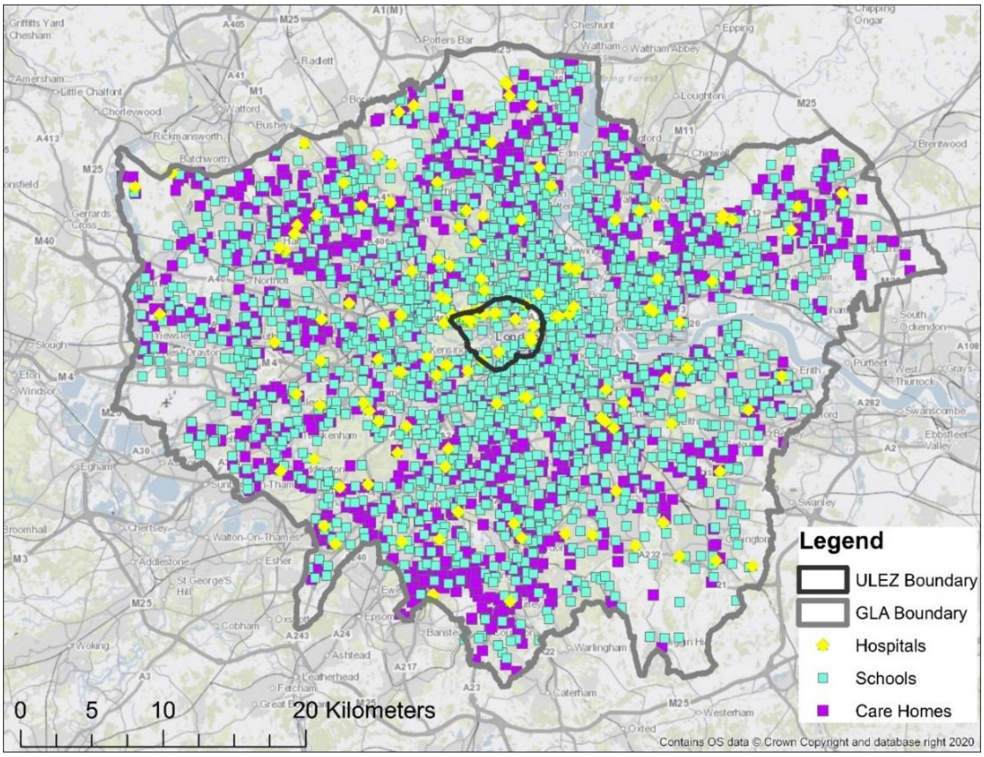

Figure 3-5: A map of the sensitive receptors at selected schools, care homes and hospitals within the GLA boundary

[6] Nurseries and primary schools, from https://get-information-schools.service.gov.uk/Establishments/Search
[7] Care homes that are currently open, from https://data.england.nhs.uk/dataset/ods-care-homes
[8] Data from NHS Choices dataset, https://data.gov.uk/dataset/f4420d1c-043a-42bc-afbc-4c0f7d3f1620/hospitals

3.4 Background Data

3.4.1 Version 1

For NO_X, NO_2, PM_{10}, $PM_{2.5}$ and Ozone, hourly background concentrations to represent the contribution from sources outside the modelled area were derived from one of four rural AURN (Automatic Rural and Urban Network) stations located outside the M25, depending on which station was upwind at that hour. The wind direction is taken from the meteorology data collected at Heathrow Airport, and is split into 10° segments. The AURN stations, and their respective wind directions, used for the background calculations are Chilbolton Observatory (230°- 300°), Rochester Stoke (70°- 130°), Lullington Heath (140°- 220°) and Wicken Fen (310°- 60°). Particulates are only measured at Rochester Stoke and Chilbolton Observatory, and are therefore portioned into easterly and westerly winds respectively. For CO_2, the rural BEIS (UK Government Department of Business, Energy and Industrial Strategy) sites used were Ridge Hill, Tacolneston and Heathfield . Figure 3-6 shows the locations of all the monitors, Table 3-3 lists the pollutants measured at each and Table 3-4 contains the annual average background concentrations for 2019.

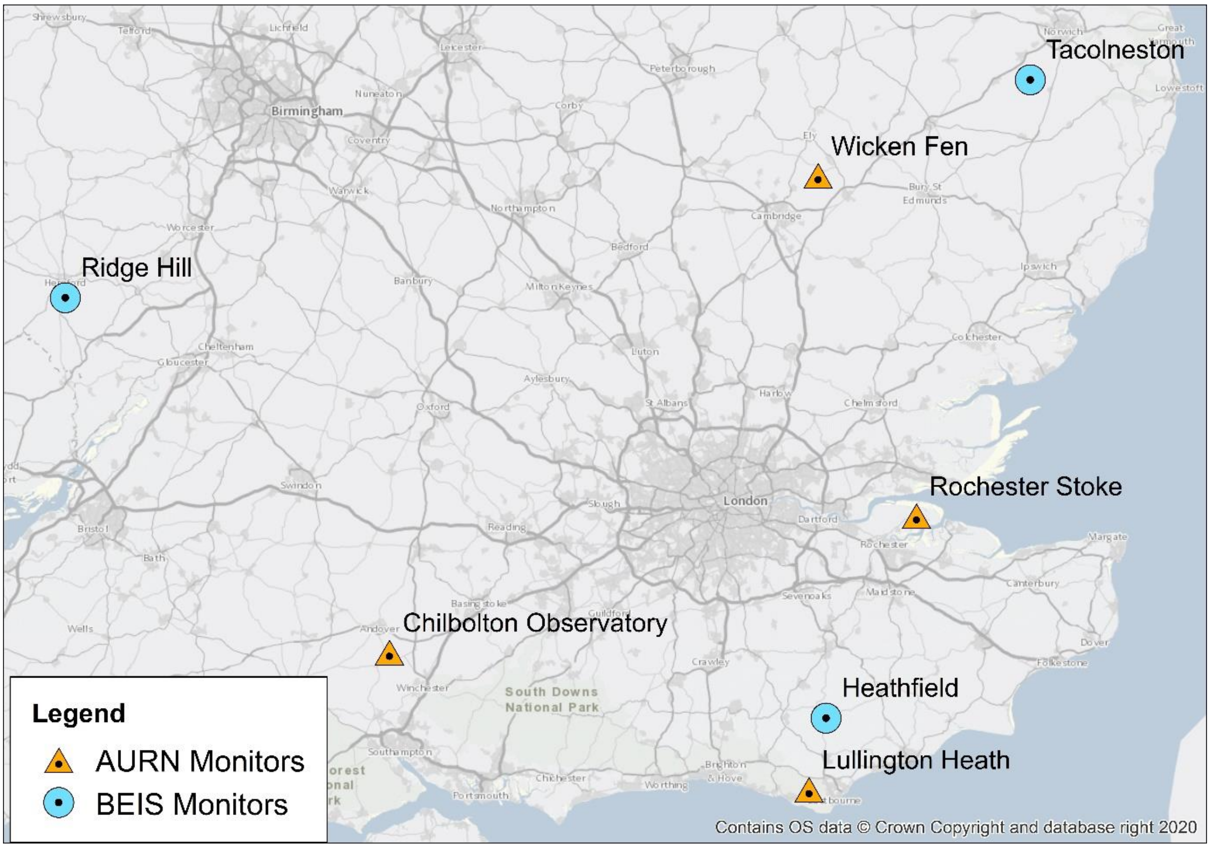

Figure 3-6 A map of the rural monitoring stations used in the background calculations

Table 3-3 List of the pollutants are measured at each station

Station	Network	NO_X	NO_2	O_3	$PM_{2.5}$	PM_{10}	CO_2
Chilbolton Observatory	AURN	X	X	X	X	X	
Lullington Heath	AURN	X	X	X			
Heathfield	BEIS						X
Ridge Hill	BEIS						X
Rochester Stoke	AURN	X	X	X	X	X	
Tacolneston	BEIS						X
Wicken Fen	AURN	X	X	X			

Table 3-4 Annual average background concentrations for 2019. All units are µg/m³, except CO2 which is in ppm

Pollutant	Annual Average Background Concentrations
NOX	9.67
NO2	7.73
O3	56.33
PM10	13.44
PM2.5	9.56
CO2	415.52

3.4.2 Version 2

The "background" monitoring sites are rural sites, away from emission sources, where the concentrations should represent regional concentration levels which can be assumed to be constant over the city; taking the upwind values ensures that the "background" does not include any impact of London emissions. This approach generally works well, however the Hotspot analysis (Appendix 9) identified that the upwind background PM was higher than the local measured concentrations for a significant number of hours. The reasons for this are likely to be complex, and due to the nature of rural PM, which is dominated by secondary particles, particularly ammonium nitrate from agriculture, which is sensitive to temperature and humidity. As a result of these findings, a maximum was imposed here on PM_{10} and $PM_{2.5}$ each hour that was the 50th percentile measurement across all available LAQN and AQE reference monitors in London. In the Hotspot analysis, the 5th percentile measurement was used as the cap, but this led to a large negative bias in the modelled results. There is large great deal of uncertainty in PM emissions, particularly brake, road and tyre wear and resuspension, and it is likely that the overestimated background here is compensating for underestimated emissions. Table 3-5 contains the annual average background concentration used in this modelling scenario.

Table 3-5 Annual average background concentrations for 2019. All units are µg/m³, except CO2 which is in ppm

Pollutant	Annual Average Background Concentrations
NOX	9.67
NO2	7.73
O3	56.33
PM10	12.41
PM2.5	8.37
CO2	415.52

3.5 Meteorological Data

The modelling uses hourly meteorological data collected at London Heathrow Airport, for these parameters: wind speed and direction (at height 10m), surface temperature and cloud cover. Two different periods were modelled. Static sites were modelled from 1st January 2019 to 31 December 2019. Mobile data locations were modelled from 1 September 2018 to 31 October 2019, to represent the drive period. Figure 3-7 to Figure 3-10 show the wind roses for the modelled periods at Heathrow Airport: Figure 3-7 and Figure 3-9 show the input wind roses at the meteorological site for the two periods; Figure 3-8 and Figure 3-10 show the wind roses used in the modelling for the two periods, which have been modified by the model[9] to account for differences in surface roughness. Wind speeds are reduced in the built-up area of London due to the higher surface roughness there (1 m) compared with Heathrow airport (0.1 m), and there are small changes in wind direction.

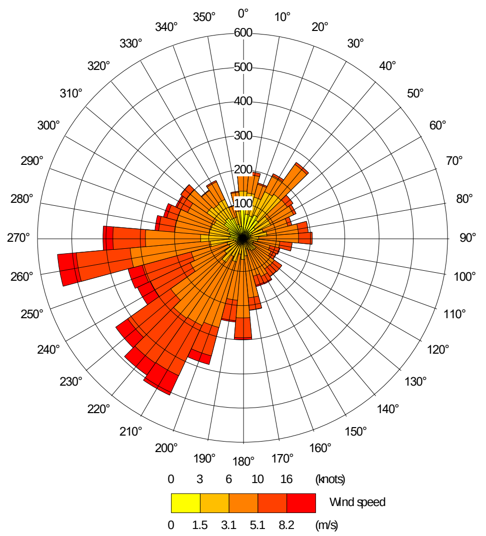

Figure 3-7: Wind Rose for January 2019 to December 2019 at Heathrow Airport

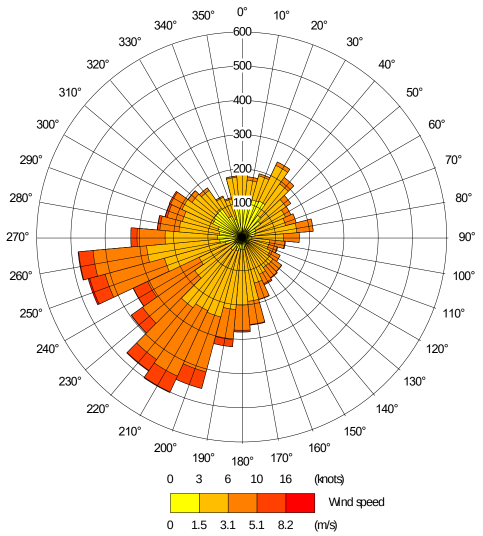

Figure 3-8: Wind Rose for January 2019 to December 2019 in London

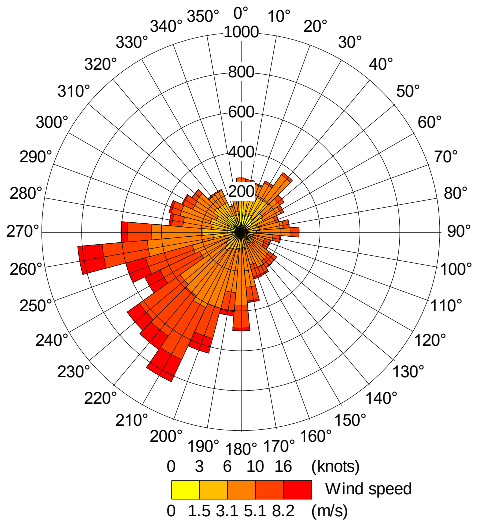

Figure 3-9: Wind Rose for September 2018 to October 2019 at Heathrow Airport

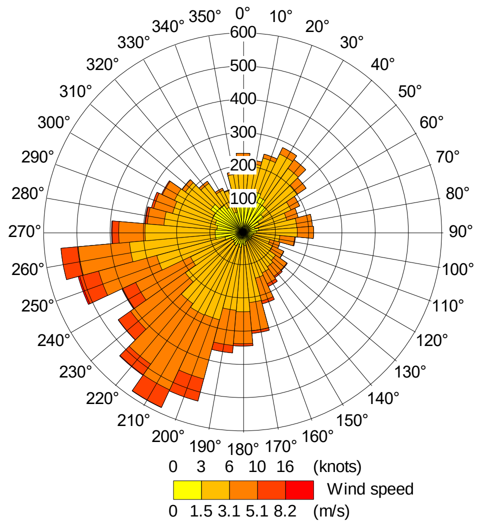

Figure 3-10: Wind Rose for September 2018 to October 2019 in London

[9] https://www.cerc.co.uk/environmental-software/assets/data/doc_techspec/P05_01T.pdf

4. Modelling Scenarios

4.1 Baseline 2019

The Baseline 2019 modelling scenario used traffic flows and speeds and 1km gridded emissions of NO_X, NO_2, PM_{10}, $PM_{2.5}$ and CO_2 from the London Atmospheric Emissions Inventory (LAEI) 2013 dataset (published in 2016), interpolated to 2019 between the 2013 base year and 2020 future predictions, combined with road traffic emissions factors from the Emission Factor Toolkit (EFT) v8 for 2019 to calculate road source emissions. The future predictions in the LAEI 2013[10] dataset incorporated the TfL Business plan, which included the planned introduction of the Ultra-Low Emission Zone (ULEZ) in 2020 in Central London. The ULEZ was introduced on 8th April 2019, one year earlier than planned, so any additional fleet changes that are attributed to this are not accounted for in the emissions. However, the vehicle fleet within the ULEZ is 74% compliant with ULEZ criteria. The road traffic emissions were multiplied by "real world" adjustment factors[11] for NO_2 and NO_x (Table 4-1). The annual average road emission rate, $\dot{\varepsilon}\ (g\ km^{-1}\ s^{-1})$, for a given road and pollutant is given by:

$$\dot{\varepsilon} = \sum_i^{11} \dot{E}_i \qquad (1)$$

where i is one of the 11 vehicle categories and $\dot{E}_i$ is the 2019 annual average emission rate for that road, pollutant and vehicle category. $\dot{E}_i$ is defined by:

$$\dot{E}_\iota = \frac{c_i}{86400} \times \sum_j^M \left(\beta_j \times\ \alpha_j(v) \times \Phi_j\right) \qquad (2)$$

where c_i is the annual average daily traffic flow (vehicles/day) on that road, 86400 is the number of seconds in a day, M is the number of vehicle sub-categories (j), β_j is the "real-world" adjustment factor for that vehicle sub-category, $\alpha_j(v)$ is the pollutant specific emission factor for that vehicle sub-category, location and speed $(g * vehicle^{-1} km^{-1})$, and Φ_j is the route type, which represents the fraction of vehicle subcategories in each vehicle category. To account for different fleet compositions between Central, Inner, Outer and Motorway regions of London, the emission factors and route type are specific for that location. All other vehicle types (Motorcycles, Hybrid and Bioethanol cars for example) were unadjusted (β_j is set to 1). CO_2 and PM emissions were not adjusted and use COPERT emission factors for CO2 or EFT v8 for 2019 emission factors for PM.

Explicit point source emissions were extracted from LAEI 2013, with some corrections from LAEI 2016. Explicit aircraft emissions were calculated using commercial fleet and activity data and emissions corrections for ambient conditions extracted from Ricardo-AEA's *Heathrow Airport 2013 Air Quality Assessment*. Fleet compositions, movements and their corresponding emissions were adjusted to 2019. To adjust to 2019, the total number of aircraft was assumed to be the same and any aircraft that were no longer in use were reallocated to more recent models. Aircraft emissions incorporate the idling of the engine on the stand, taxiing to the runway, acceleration during take-off, the initial climb and descent between the ground and 600m, and the rapid deceleration when the craft lands. Emissions for

[10] LAEI 2013 was used in preference to LAEI 2016 because it includes future projections for 2020; LAEI 2016 does not include any future projections, only data for the base year 2016.

[11] Factor calculations for real world adjustments done by CERC based on the initial work done by: Carslaw, D and Rhys-Tyler, G 2013: New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK. Atmos. Env. 81 pp 339–347.

each component were adjusted each hour to reflect which runway was in use for that time of day, season and meteorological conditions.

The Baseline 2019 modelling scenario uses 'Version 1' of the background dataset described in Section 3.4.1, which uses rural monitoring data only for PM_{10} and $PM_{2.5}$.

Time-varying emissions profiles were used to represent differences in diurnal profiles for different vehicle types. Each modelled road was classified by location (Central, Inner, Outer and Motorway) and type (A Road Single or Dual Carriageway, B Road, Minor Road, Local Street, Motorway). Not all types are in every location, so there are 17 road categories. All roads in each category were grouped together, and average flows and speeds for each road category in terms of 11 vehicle categories were calculated. DFT raw traffic flow data for London in 2018 were used to derive diurnal flow profiles for each vehicle category (DfT data only available weekdays between 07:00 and 18:00). These traffic flow diurnal profiles were then multiplied by the average emissions from each vehicle category, to develop pollutant-dependent emissions profiles for each of the 17 different road categories (Figure 4-1). These were then multiplied by the annual average emission rate ($\dot{\varepsilon}$) for each road, shown in equation (1), to give the time-varying emission rate $\dot{\varepsilon}_{TV}$ for each road:

$$\dot{\varepsilon}_{TV} = \tau\dot{\varepsilon} \qquad (3)$$

where τ is the time varying emission factor for a specific time of the day, for a standard weekday or weekend.

Daylight saving time was accounted for by shifting the hourly emission factors forward by one hour to account for the 1-hour time difference between solar time and local clock time when daylight saving time is in effect.

Vehicle Type	Euro Category	NO_X emissions adjustment factor	Percentage of adjusted NO_X that is NO_2
Diesel Car	Euro0	150%	15%
	Euro1	174%	14%
	Euro2	179%	9%
	Euro3	144%	16%
	Euro4	140%	28%
	Euro5	117%	25%
Petrol Car	Euro0	100%	5%
	Euro1	136%	1%
	Euro2	127%	1%
	Euro3	253%	2%
	Euro4	208%	4%
	Euro5	144%	8%
LGVs	Euro1	165%	12%
	Euro2	141%	8%
	Euro3	147%	12%
	Euro4	139%	27%
	Euro5	103%	24%
Taxis	Euro3	111%	22%
	Euro4	133%	26%
	Euro5	133%	45%
HGV < 12t	Euro2	100%	21%
	Euro3	100%	18%
	Euro4	117%	8%
	Euro5	110%	8%
HGV > 12t	Euro2	108%	12%
	Euro3	117%	24%
	Euro4	161%	3%
	Euro5	217%	4%

Table 4-1 NO_X adjustment factors[12] and the percentage of the resulting NO_X emission rate that is NO_2.

[12] Factor calculations for real world adjustments done by CERC based on the initial work done by: Carslaw, D and Rhys-Tyler, G 2013: New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK. Atmos. Env. 81 pp 339–347.

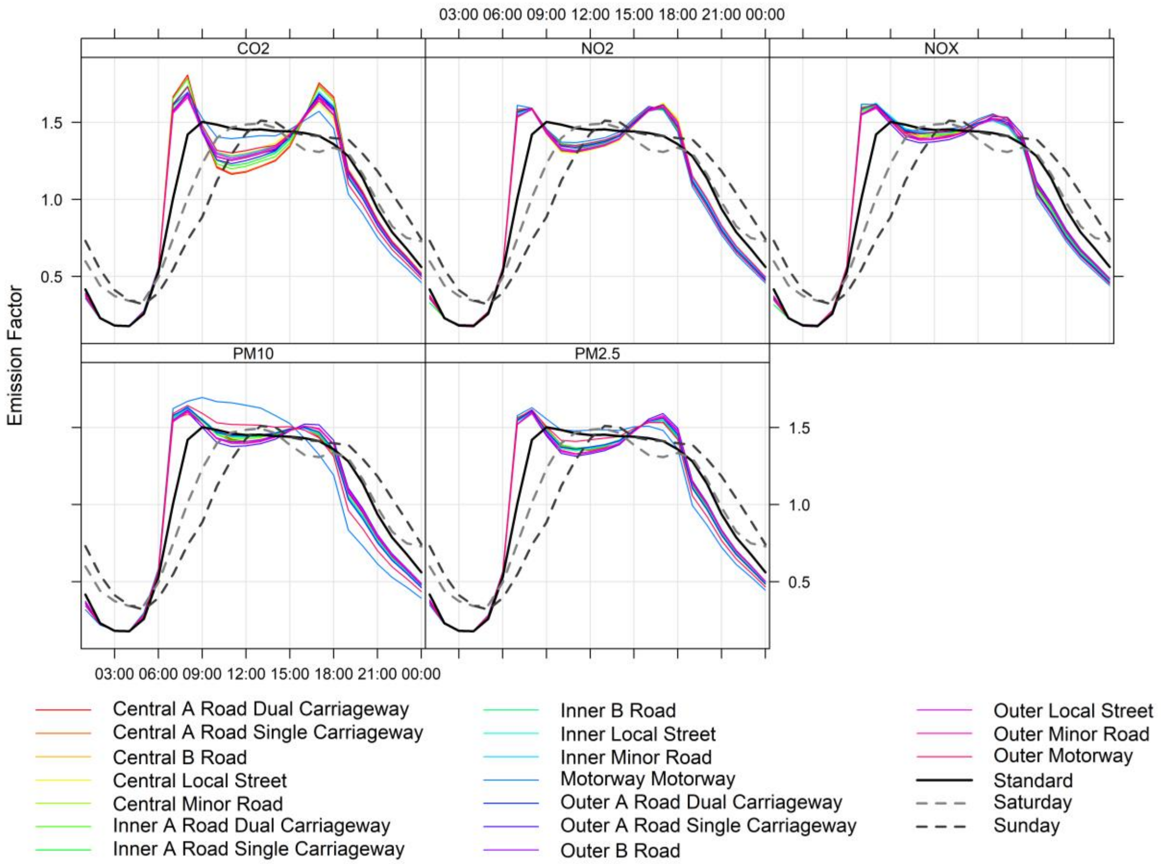

Figure 4-1 Diurnal emissions profiles used in modelling. Coloured lines show the weekday profiles for 17 road categories; black line shows the weekday profile used previously; the grey dotted lines show the profiles used for Saturday and Sunday, which are the same as used previously.

4.2 Hotspot 2019

The Hotspot 2019 modelling scenario was a development of the Baseline 2019 scenario that included modifications resulting from the conclusions of the Hotspot Analysis report (Appendix 9). That report showed that there are some areas where the LAEI appears to significantly underestimate traffic flows, such as the Hangar Lane Gyratory in Ealing, the Strand in Westminster and the London Road junction in Kingston. This modelling scenario includes corrected traffic flows in these areas; receptor locations representing monitoring sites were also further refined. The Hotspot analysis found PM to be underestimated, therefore in this scenario the non-exhaust components of PM for all vehicles in all Euro categories were multiplied by "real world" adjustment factors[13] (Table 4-2).

	PM non-exhaust component adjustment factor
Brake Wear	363%
Tyre Wear	109%

Table 4-2: Adjustment factors applied to non-exhaust PM emissions

In the Baseline 2019 emission scenario, described in Section 4.1, weekday diurnal emissions profiles were developed for each of the 17 road categories for NO_X, $PM_{2.5}$ and CO_2. In this scenario, to better represent traffic flow differences between different days of the week, hourly NO_X concentrations at kerbside reference monitors were used as a proxy for traffic flow; these were averaged over each day of the week from 1st October 2018 to 29th February 2020 (avoiding the period affected by COVID-19) to calculate the average concentration distribution by day of the week. This provided seven daily factors, which were then multiplied by the diurnal emissions profiles, resulting in a different diurnal emissions profile for each day of the week for each road category (Figure 4-2). Equation (3) therefore becomes

$$\dot{\varepsilon}_{TV} = \kappa \tau \dot{\varepsilon} \qquad (4)$$

where $\dot{\varepsilon}$ is the annual average emission rate for that road, τ is the time varying diurnal factor for a specific time of day for a standard weekday and weekend, and κ is the average traffic flow factor for that specific day of the week. Representing the traffic flow in this way enables the higher traffic flow on weekdays and lower traffic flows over the weekend to be better represented.

The Hotspot 2019 modelling scenario uses 'Version 2' of the background dataset described in Section 3.4.2, where for PM10 and PM2.5 a maximum was imposed each hour that was the 50th percentile value across all available LAQN and AQE reference monitors in London.

[13] Factors are extracted from Table 28 in LAEI 2010 methodology

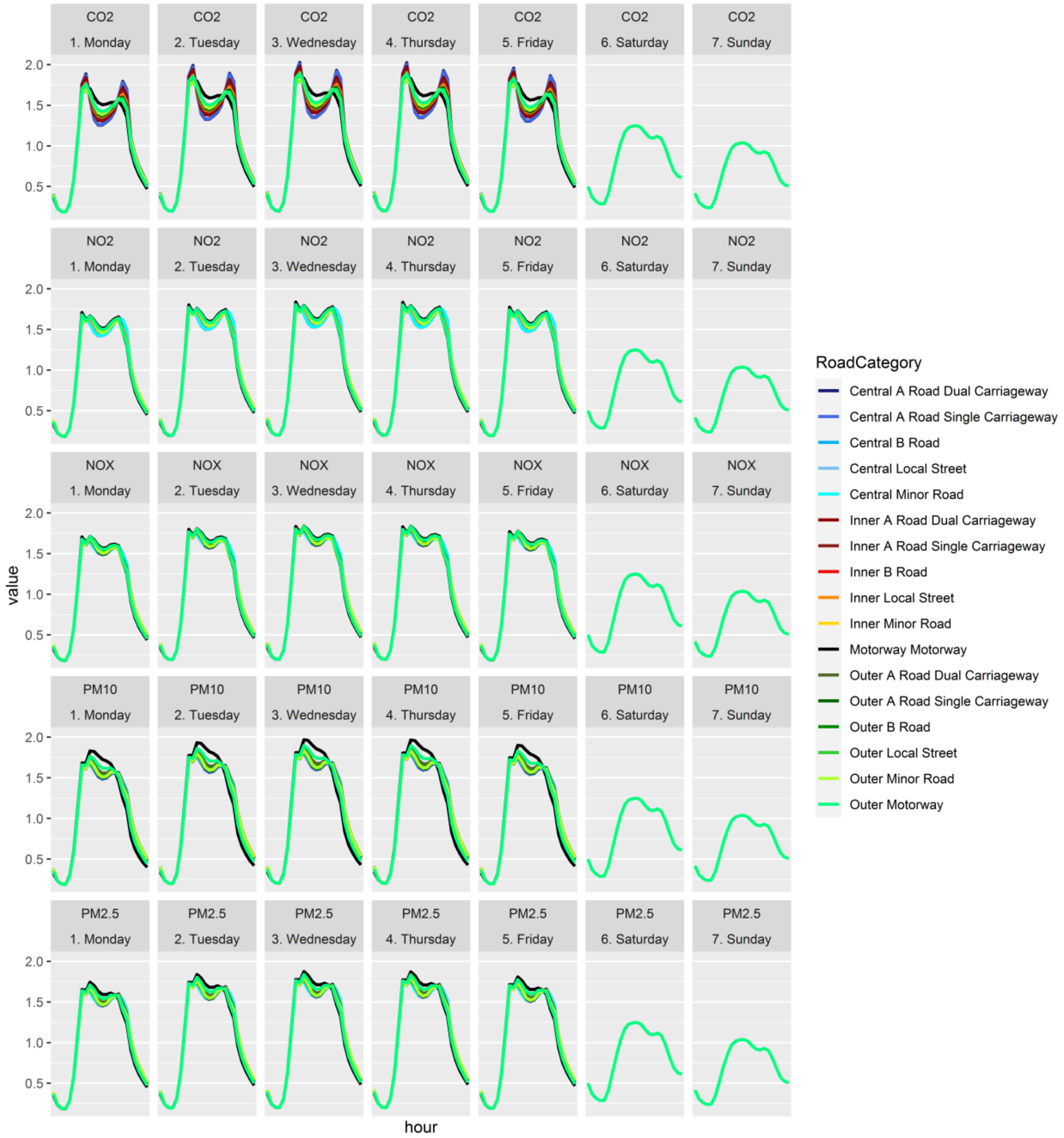

Figure 4-2 Pollutant dependent diurnal emissions profiles for each day of the week, for each road category. The road categories largely overlap because they have a similar fleet split across multiple regions and road categories. For PM10, and PM2.5 to a lesser extent, the fleet split for Motorway roads (the M25) has a higher proportion of HGVs, which prolongs the peak in the morning in the profile. The same profile is used for all roads at weekends.

4.3 Source Apportionment 2019

For the Source Apportionment analysis (Section 8.2), the Hotspot 2019 scenario emissions were apportioned into 23 categories for NO_X and 25 categories for $PM_{2.5}$. Table 4-3 shows the source categories that were modelled. Electric Cars and Electric LGVs have been omitted because their exhaust emissions are zero, although vehicles in these categories will contribute to 'Brake, Tyre and Road Wear' emissions. 'Waste Transfer' sources have zero NO_X emissions and 'Sewage Treatment Works' sources have zero $PM_{2.5}$ emissions. The 'Residual' category includes 'Small Waste and Accidental Fires' emissions for both NO_X and $PM_{2.5}$; it also includes 'Landfill' emissions for $PM_{2.5}$.

DFT raw traffic flow data[14] for London in 2018 were used to derive weekday diurnal traffic flow profiles for four vehicle categories: Cars, Buses, HGVs and LGVs. These were normalised and multiplied by the 7-day daily factors developed for the Hotspot 2019 modelling scenario (described in Section 4.2) to obtain a 7-day diurnal emissions profile for each vehicle (Figure 4-3). No diurnal variation was included for non-traffic and fuel categories; motorcycles use the same profile as petrol and diesel cars.

Table 4-3: Source apportionment emissions categories modelled

Group	Emission Category	NO_X	$PM_{2.5}$
Traffic (Exhaust)	Motorcycles	✓	✓
	Petrol Cars	✓	✓
	Diesel Cars	✓	✓
	Taxis (London Black Cabs)	✓	✓
	Petrol LGVs	✓	✓
	Diesel LGVs	✓	✓
	TfL Buses	✓	✓
	NonTfL Buses and Coaches	✓	✓
	Rigid HGVs	✓	✓
	Articulated HGVs	✓	✓
Traffic (Non-Exhaust)	Brake, Tyre and Road Wear		✓
Commercial and Domestic Fuel Usage	Commercial Gas	✓	✓
	Commercial Other Fuels	✓	✓
	Domestic Gas	✓	✓
	Domestic Other Fuels	✓	✓
Other Non-Traffic	Agriculture	✓	✓
	Aviation	✓	✓
	Commercial Shipping	✓	✓
	House & Garden	✓	✓
	Industry	✓	✓
	Non-Road Mobile Machinery (NRMM)	✓	✓
	Rail	✓	✓
	Sewage Treatment works	✓	
	Dust		✓
	Waste Transfer Services		✓
	Residual	✓	✓

[14] Data available for weekdays only between 07:00 and 18:00

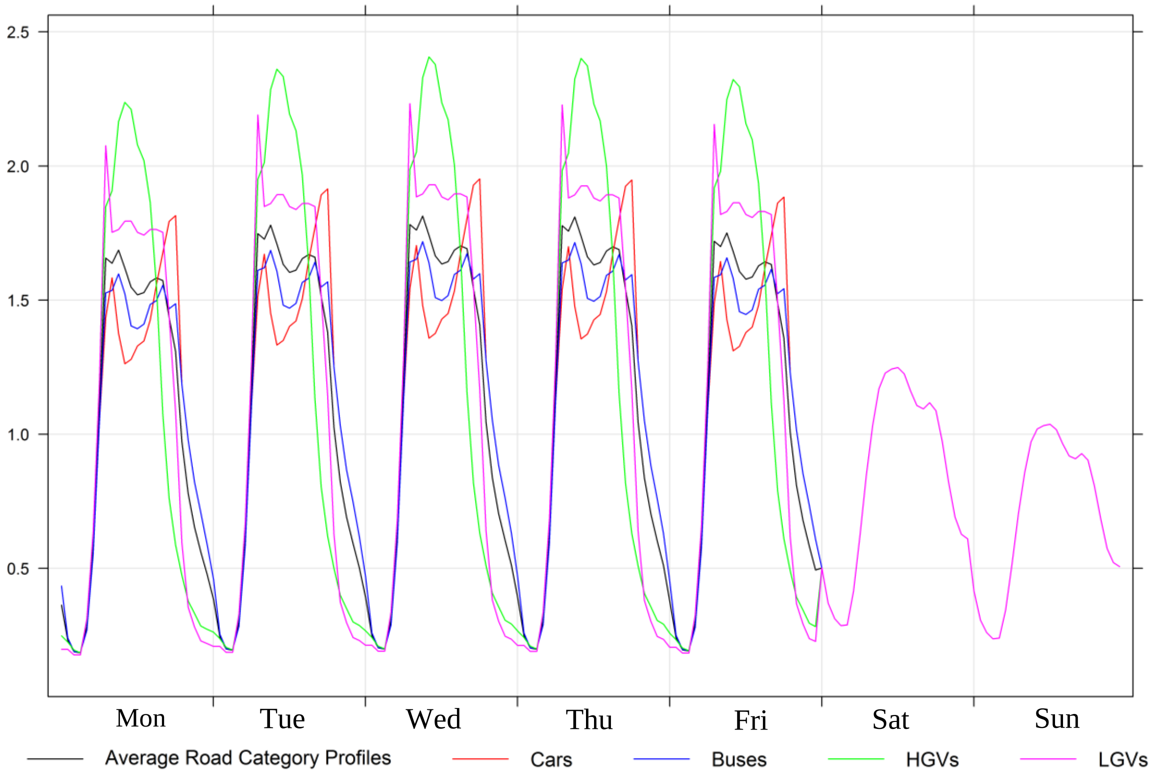

Figure 4-3 Diurnal emissions profiles for each day of the week, for each vehicle category. For comparison, the black line represents the average NO_X emissions profile across the 17 road categories used in the Hotspot 2019 modelling. There is no DfT data available for Saturdays and Sundays and therefore all vehicle categories use the same standard weekend profile multiplied by the 7-day factor. The emissions are normalised with an average of 1 over all days, so there is no change in the overall traffic volumes.

5. Measured data

5.1 Static Measurement Sites

5.1.1 AQMesh

Pre-scaled AQMesh data was downloaded for each station using the AirMonitors web API, at the highest frequency (1 minute for $PM_{2.5}$ and 15 minutes for NO_2 before the 5th April 2019 and 1 minute after). Any data points flagged as invalid were redacted before applying pollutant and station-specific scaling factors, which were derived using three different methods: colocation with a reference monitor, colocation with a gold standard pod or calibrated using baselines extracted across the entire pod network. After applying scaling factors, any negative concentrations were redacted before hourly averages were calculated using a data validity threshold of 85%. Finally, the hourly average NO_2 and NO values were converted from ppb to µg/m³ for comparison with model values. All AQMesh data is provisional at this stage.

5.1.2 LAQN

Hourly average data for NO_2, NO_X, O_3, PM_{10} and $PM_{2.5}$ at each station in the LAQN network was downloaded using the importKCL() openair function in R. For $PM_{2.5}$, any hourly means above 500 µg/m³ were redacted. The data is ratified for the majority of stations up until 31st January 2020 and provisional otherwise.

5.1.3 AQE

Hourly average data for NO_2, NO_X, O_3, PM_{10} and $PM_{2.5}$ at each station in the AQE network was downloaded using the importAQE() function in R. The API does not cover the AURN sites that are controlled by AQE and these must be downloaded separately using the importAURN() openair function in R. For $PM_{2.5}$, any hourly mean values above 500 µg/m³ were redacted. The data is ratified for the majority of stations up until 31st January 2020 and provisional otherwise.

5.2 Mobile measurements

The mobile measurements are downloaded from the aggregated 30m dataset (QAQC version 8) in the Street View Air Quality London data store in Google Big Query. The dataset contained the median for each 1-hour time window the 2 cars were driving of all averages of valid 1-second concentration measurements in unique passes along a 30m road segment (i.e. a series of aggregations starting with the average of 1 hz measurements in a single pass of segment, followed by the median of all pass-averages within the same hour, for every road segment and hour resulting in a value we refer to as the ‘drive-period median concentration’). A corrective scaling factor that accounts for particle loss has been applied to $PM_{2.5}$, but not yet to PM_{10}; the sampling loss for PM_{10} has not been quantified yet. All data is provisional at time of writing.

6. Model Verification

6.1 Static monitoring sites

Static sites have been modelled as discrete receptors with the appropriate position and height. All explicit roads within 500m of a receptor are modelled explicitly as road sources; remaining emissions are aggregated into 1km grid cells. Modelled hourly concentrations of NO_2, NO_X, PM_{10}, $PM_{2.5}$ and Ozone for 2019 have been compared with hourly measurements from the Breathe London AQMesh sensors[15] and the LAQN and AQE reference networks. A summary table of model evaluation statistics for each modelling scenario for each pollutant, by monitoring network is provided in Table 6-1. The graphs in Figure 6-1 to Figure 6-5 compare annual mean modelled and measured concentrations for 2019 at each receptor for each modelling scenario by monitoring network, site type and location with respect to the ULEZ boundary. Model evaluation statistics for each modelling scenario for each pollutant, by monitoring network, site type, and location with respect to the ULEZ boundary are provided in Table 6-2 to Table 6-6.

Network	**Pollutant**	**Scenario**	**$N_{stations}$**	**N_{hours}**	**Mean.Obs**	**Mean.Mod**	**MB**	**R**	**FAC2**
AQMESH	NO2	BASELINE_2019	104	651573	38.1	36.2	-1.93	0.50	0.77
AQMESH	NO2	HOTSPOT_2019	104	651569	38.1	36.6	-1.50	0.51	0.78
AQMESH	*NOX*	*BASELINE_2019*	91	*455563*	*68.2*	*66.0*	*-2.16*	*0.55*	*0.70*
AQMESH	*NOX*	*HOTSPOT_2019*	91	*455539*	*68.2*	*68.0*	*-0.17*	*0.58*	*0.70*
AQMESH	PM2.5	BASELINE_2019	85	589113	11.8	11.1	-0.74	0.60	0.81
AQMESH	PM2.5	HOTSPOT_2019	85	564825	11.8	10.8	-0.96	0.67	0.82
LAQN_AQE	NO2	BASELINE_2019	129	1063520	38.4	38.7	0.36	0.65	0.79
LAQN_AQE	NO2	HOTSPOT_2019	129	1063400	38.4	39.1	0.71	0.68	0.81
LAQN_AQE	NOX	BASELINE_2019	129	1061378	79.9	76.0	-3.91	0.59	0.68
LAQN_AQE	NOX	HOTSPOT_2019	129	1061242	79.9	77.6	-2.36	0.63	0.70
LAQN_AQE	O3	BASELINE_2019	26	203270	35.7	38.2	2.52	0.73	0.67
LAQN_AQE	O3	HOTSPOT_2019	26	203246	35.7	38.4	2.65	0.73	0.67
LAQN_AQE	PM10	BASELINE_2019	110	850934	19.9	17.8	-2.06	0.61	0.82
LAQN_AQE	PM10	HOTSPOT_2019	110	815434	19.9	19.6	-0.23	0.66	0.85
LAQN_AQE	PM2.5	BASELINE_2019	42	318463	11.2	11.7	0.49	0.75	0.82
LAQN_AQE	PM2.5	HOTSPOT_2019	42	305140	11.2	11.4	0.26	0.82	0.85

Table 6-1 Overall model evaluation statistics for each pollutant by network and modelling scenario. $N_{stations}$ = number of stations included; N_{hours} = number of valid hours included; Mean.Obs = annual mean measured concentration (ug/m3); Mean.Mod = annual mean modelled value (ug/m3); MB = Mean Bias (ug/m3); R = Correlation Coefficient; FAC2 = Fraction of modelled hourly values within a factor of 2 of the measured hourly value. Statistics are calculated over all the valid mod-obs pairs of hourly values for each network, pollutant and scenario combination. AQMesh NO_X is shown in italics because AQMesh measured NO_X is only available from 20 April 2019 onwards, therefore these statistics are not for the whole year.

[15] AQMesh NO_X is only available from 20 April 2019

The lowest bias (0.71 µg/m^3) and highest correlation (0.68) between modelled and observed hourly NO_2 concentrations were obtained with reference network data. There was poorer agreement with AQMesh data (bias -1.5 µg/m^3, correlation 0.51); this is likely to be due to the effects of ozone interference in the AQMesh measurements that caused low levels to be biased high (this issue will be corrected in the future versions of the AQMesh measurements dataset). The developments in the HOTSPOT2019 modelling scenario improved the correlation of the modelled NO_2 concentrations with measurements compared with the BASELINE2019 scenario, but slightly increased the bias compared with reference data. When disaggregated by site type and location, on average only roadside and kerbside sites exceed the UK Government's 40 µg/m^3 annual mean limit for NO_2. The results suggest that roadside and kerbside LAQN sites inside the ULEZ are located in more polluted places than the AQMesh roadside and kerbside sites.

Comparing the model performance for NO_X between reference sites and AQMesh sites is challenging because AQMesh NO_X data are not available until 20th April 2019, meaning that the AQMesh evaluation is missing values from a time of year when higher NO_X levels are typically recorded; however, as with NO_2, the highest NO_X correlation (0.63) was obtained with reference network data. The developments in the HOTSPOT2019 modelling scenario significantly improved the NO_X correlation and bias at both reference and AQMesh sites compared with the BASELINE2019 scenario.

For $PM_{2.5}$, the lowest bias (0.26 µg/m^3) and highest correlation (0.82) between modelled and observed hourly concentrations were obtained with reference network data, while there was poorer agreement with AQMesh data (bias -0.96 µg/m^3, correlation 0.67). The AQMesh evaluation covers approximately twice the number of sites as the reference networks. Disaggregating the evaluation by site type and location, the model predicts higher concentrations than the measurements in some reference site categories and lower concentrations in others, whereas in all AQMesh categories the model predicts lower concentrations than the measurements, suggesting that the AQMesh measurements may, on average, be biased high. The developments in the HOTSPOT2019 modelling scenario significantly improved the $PM_{2.5}$ correlations at both reference and AQMesh sites compared with the BASELINE2019 scenario and reduced the bias at reference sites.

Model verification for PM_{10} was carried out with reference network measurements only since no calibrated AQMesh measurements were available. Over all hours at all sites, the modelled PM_{10} data shows a very small negative bias (-0.23 µg/m^3) and good correlation (0.66) compared with measurements. The developments in the HOTSPOT2019 modelling scenario significantly improved the PM_{10} correlation and reduced the bias compared with the BASELINE2019 scenario.

Model verification for O_3 was carried out with reference network measurements only since no calibrated AQMesh measurements were available. While correlation of modelled results with measurements was good (0.73), the model had a significant positive bias (2.65 µg/m^3) compared with measurements, with a tendency to predict higher levels than measured at roadside and kerbside sites and better agreement at urban background and suburban sites.

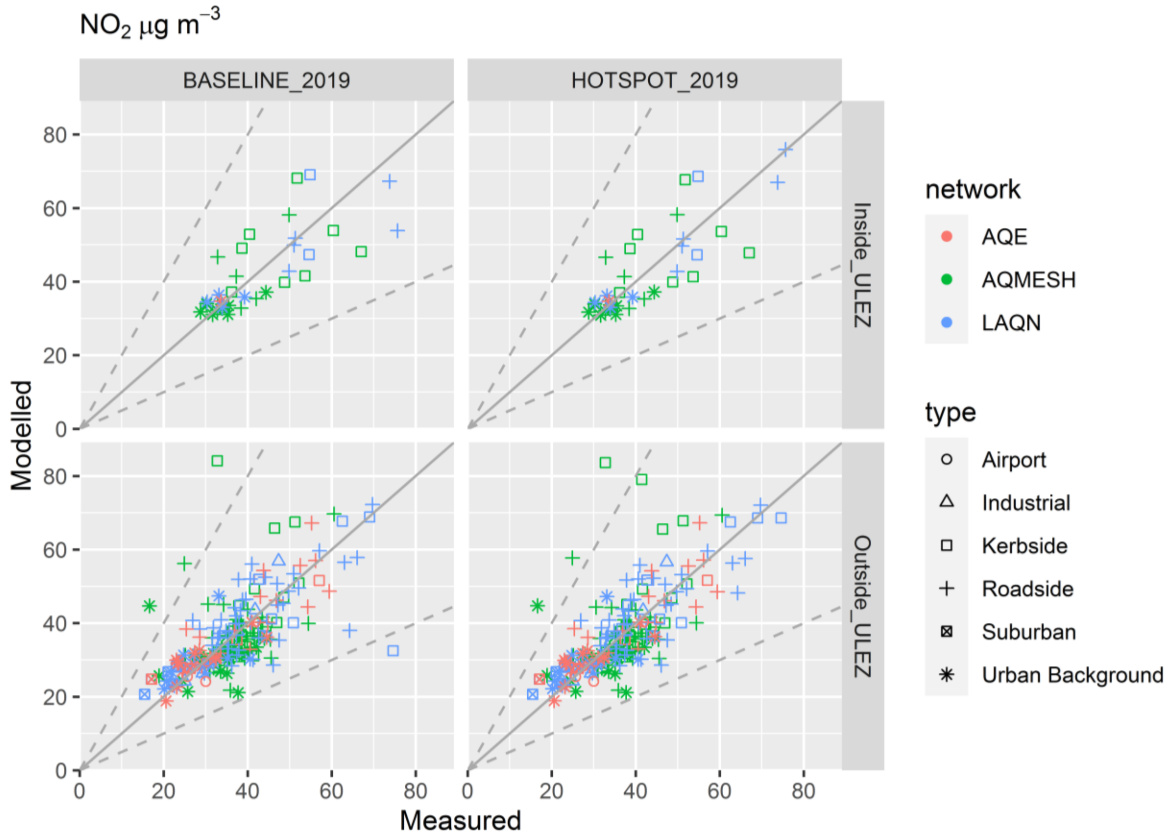

Figure 6-1 Modelled versus measured annual mean NO_2 ($\mu g\ m^{-3}$) for 2019 for each modelling scenario by site location with respect to the ULEZ boundary. The colour indicates the network; the shape indicates the site type.

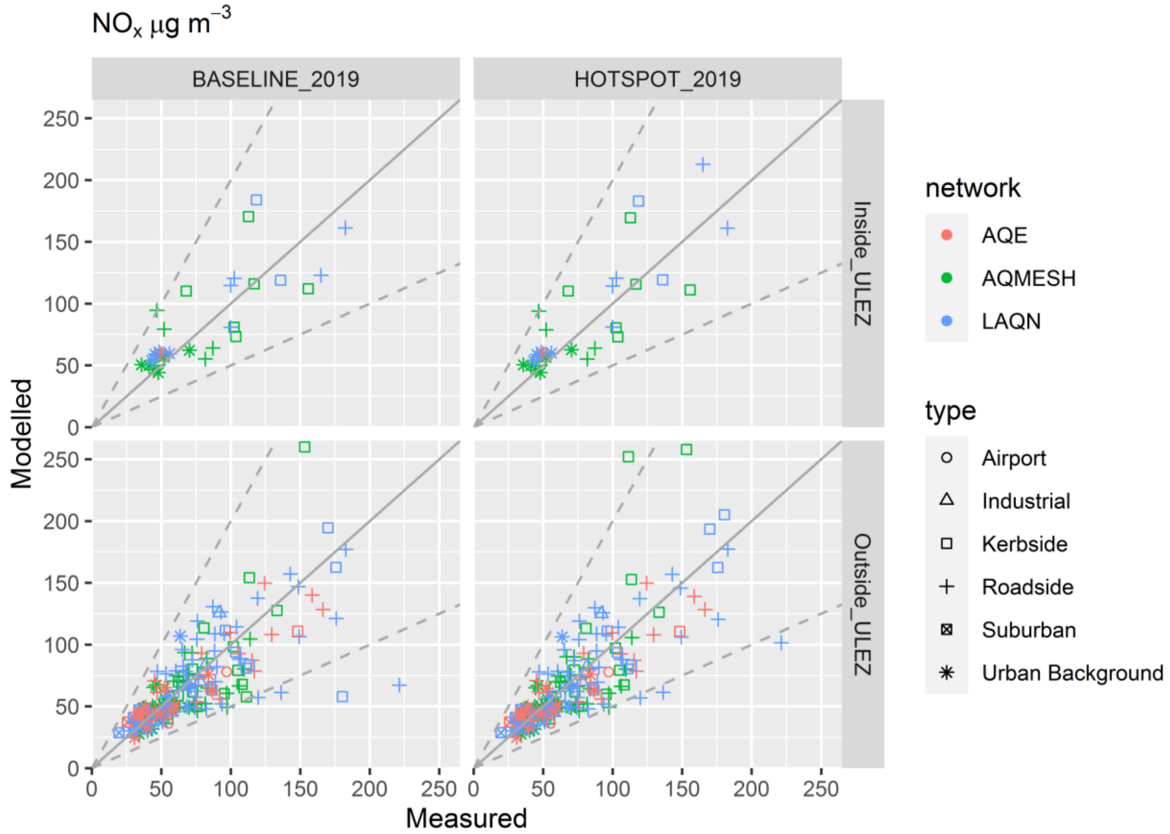

Figure 6-2 Modelled versus measured annual mean NO_X ($\mu g\ m^{-3}$) for 2019 for each modelling scenario by site location with respect to the ULEZ boundary. The colour indicates the network; the shape indicates the site type.

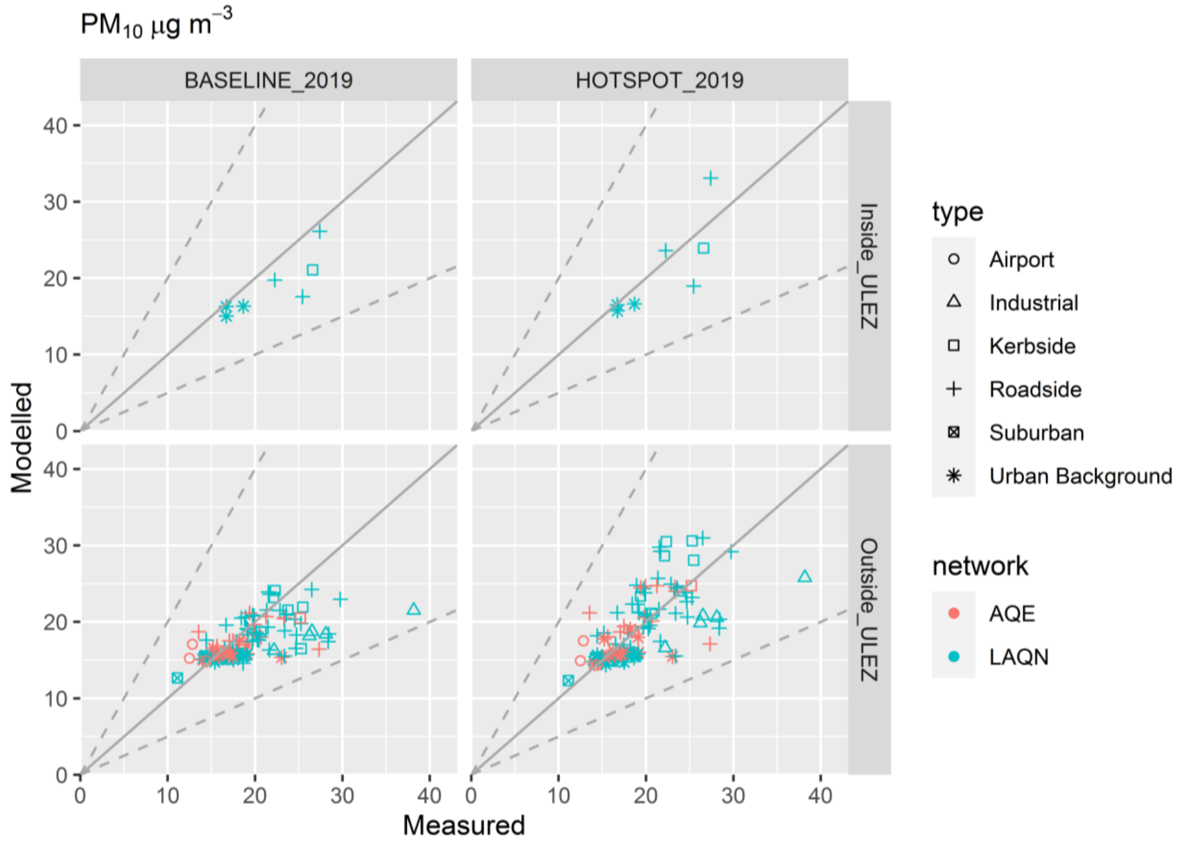

Figure 6-3 Modelled versus measured annual mean PM_{10} ($\mu g\ m^{-3}$) for 2019 for each modelling scenario by site location with respect to the ULEZ boundary. The colour indicates the network; the shape indicates the site type.

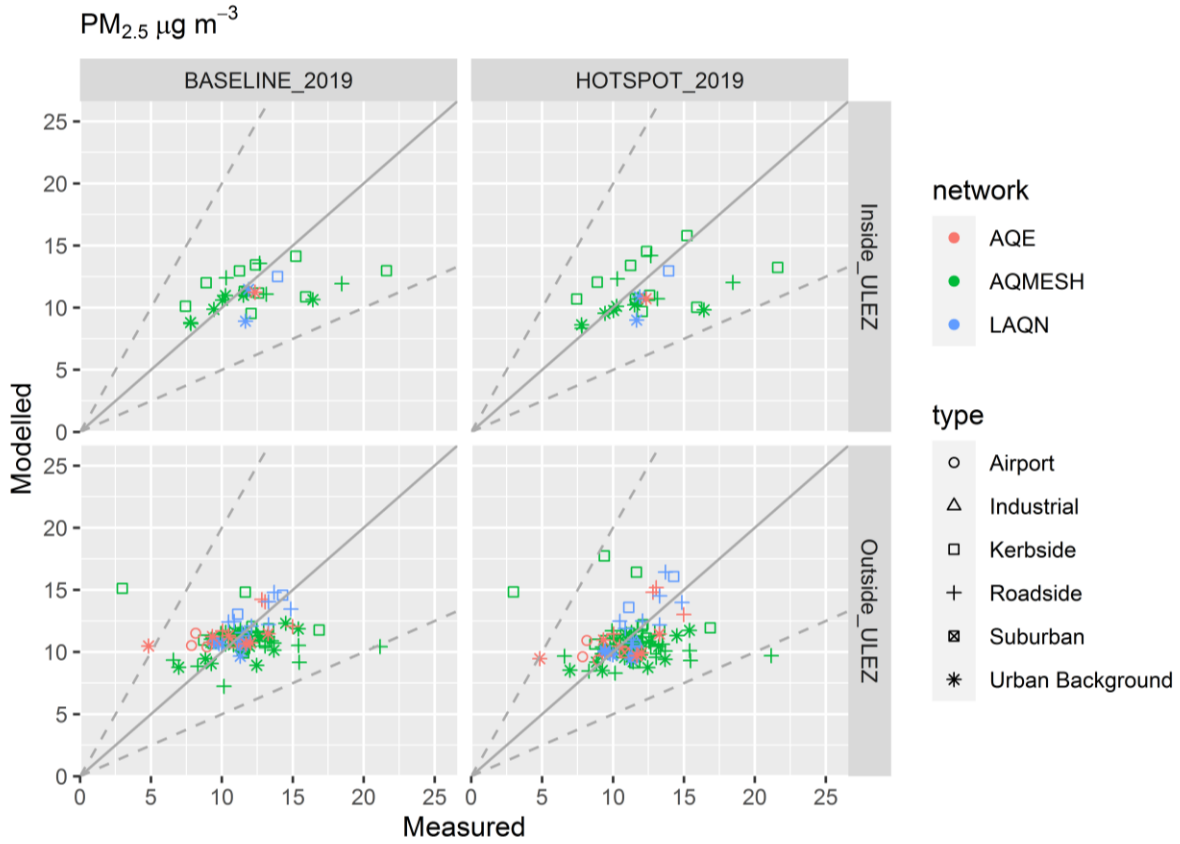

Figure 6-4 Modelled versus measured annual mean $PM_{2.5}$ ($\mu g\ m^{-3}$) for 2019 for each modelling scenario by site location with respect to the ULEZ boundary. The colour indicates the network; the shape indicates the site type.

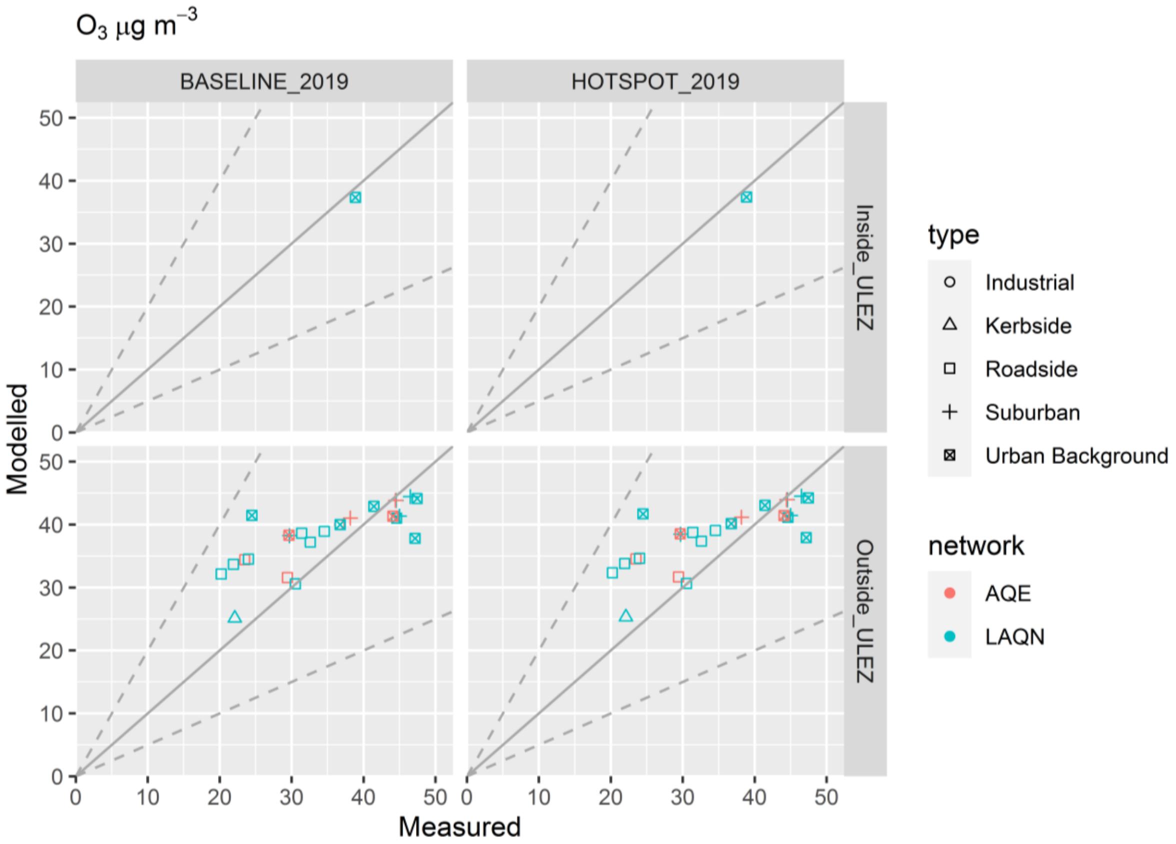

Figure 6-5 Modelled versus measured annual mean Ozone (µg m^{-3}) for 2019 for each modelling scenario by site location with respect to the ULEZ boundary. The colour indicates the network; the shape indicates the site type.

Table 6-2
Model evaluation statistics for NO_2 (ug/m^3), disaggregated by network, location with respect to the ULEZ, site type and modelling scenario. $N_{stations}$ = number of stations included; N_{hours} = number of hourly mod-obs pairs included; mean.obs = annual mean measured concentration (ug/m^3); mean.mod = annual mean modelled value (ug/m3); MB = Mean Bias (ug/m3); R = Correlation Coefficient; FAC2 = Fraction of modelled values within a factor of 2 of the measured value. Statistics are calculated over all the valid mod-obs pairs of hourly values for each network, location with respect to the ULEZ, site type and modelling scenario combination.

network	**ulez**	**type**	**scenario**	**$N_{stations}$**	**N_{hours}**	**mean.obs**	**mean.mod**	**MB**	**R**	**FAC2**
AQE	Inside_ULEZ	Urban Background	BASELINE_2019	1	6692	33.7	34.6	0.97	0.68	0.88
AQE	Inside_ULEZ	Urban Background	HOTSPOT_2019	1	6691	33.7	34.6	0.95	0.70	0.89
AQE	Outside_ULEZ	Airport	BASELINE_2019	3	24159	32.8	30.1	-2.64	0.63	0.77
AQE	Outside_ULEZ	Airport	HOTSPOT_2019	3	24156	32.8	30.1	-2.67	0.64	0.77
AQE	Outside_ULEZ	Industrial	BASELINE_2019	1	8596	30.6	29.0	-1.67	0.60	0.76
AQE	Outside_ULEZ	Industrial	HOTSPOT_2019	1	8595	30.6	29.0	-1.60	0.61	0.77
AQE	Outside_ULEZ	Kerbside	BASELINE_2019	3	25329	45.7	46.3	0.61	0.67	0.86
AQE	Outside_ULEZ	Kerbside	HOTSPOT_2019	3	25326	45.7	46.3	0.59	0.69	0.87
AQE	Outside_ULEZ	Roadside	BASELINE_2019	14	116187	44.2	45.3	1.06	0.64	0.82
AQE	Outside_ULEZ	Roadside	HOTSPOT_2019	14	116174	44.2	45.3	1.05	0.66	0.83
AQE	Outside_ULEZ	Suburban	BASELINE_2019	3	25702	22.0	25.4	3.38	0.61	0.73
AQE	Outside_ULEZ	Suburban	HOTSPOT_2019	3	25699	22.0	25.4	3.38	0.62	0.74
AQE	Outside_ULEZ	Urban Background	BASELINE_2019	15	124972	28.8	29.7	0.97	0.65	0.78
AQE	Outside_ULEZ	Urban Background	HOTSPOT_2019	15	124958	28.8	29.8	1.00	0.66	0.78
AQMESH	Inside_ULEZ	Kerbside	BASELINE_2019	9	61243	48.4	47.0	-1.44	0.46	0.80
AQMESH	Inside_ULEZ	Kerbside	HOTSPOT_2019	9	61243	48.4	46.8	-1.61	0.49	0.81
AQMESH	Inside_ULEZ	Roadside	BASELINE_2019	5	26921	37.6	40.4	2.73	0.41	0.79
AQMESH	Inside_ULEZ	Roadside	HOTSPOT_2019	5	26921	37.6	40.2	2.62	0.43	0.80
AQMESH	Inside_ULEZ	Urban Background	BASELINE_2019	8	48204	33.9	32.9	-0.96	0.41	0.77
AQMESH	Inside_ULEZ	Urban Background	HOTSPOT_2019	8	48204	33.9	32.8	-1.03	0.43	0.78
AQMESH	Outside_ULEZ	Kerbside	BASELINE_2019	23	144277	40.9	41.9	1.04	0.45	0.76
AQMESH	Outside_ULEZ	Kerbside	HOTSPOT_2019	23	144277	40.9	44.1	3.20	0.46	0.77
AQMESH	Outside_ULEZ	Roadside	BASELINE_2019	28	174648	39.2	34.4	-4.78	0.53	0.78
AQMESH	Outside_ULEZ	Roadside	HOTSPOT_2019	28	174647	39.2	34.4	-4.82	0.56	0.78
AQMESH	Outside_ULEZ	Urban Background	BASELINE_2019	31	196280	33.1	30.4	-2.62	0.49	0.77
AQMESH	Outside_ULEZ	Urban Background	HOTSPOT_2019	31	196277	33.1	30.4	-2.65	0.51	0.77
LAQN	Inside_ULEZ	Kerbside	BASELINE_2019	2	16025	54.7	57.7	2.93	0.52	0.84
LAQN	Inside_ULEZ	Kerbside	HOTSPOT_2019	2	16023	54.7	57.4	2.70	0.55	0.85
LAQN	Inside_ULEZ	Roadside	BASELINE_2019	5	42719	60.3	53.1	-7.23	0.55	0.84
LAQN	Inside_ULEZ	Roadside	HOTSPOT_2019	5	42714	60.3	57.4	-2.96	0.66	0.88
LAQN	Inside_ULEZ	Urban Background	BASELINE_2019	4	30875	34.0	35.0	0.98	0.63	0.85
LAQN	Inside_ULEZ	Urban Background	HOTSPOT_2019	4	30871	34.0	34.9	0.87	0.65	0.85
LAQN	Outside_ULEZ	Industrial	BASELINE_2019	5	42600	36.3	37.9	1.61	0.66	0.80
LAQN	Outside_ULEZ	Industrial	HOTSPOT_2019	5	42595	36.3	37.8	1.54	0.69	0.82
LAQN	Outside_ULEZ	Kerbside	BASELINE_2019	7	56261	55.0	49.1	-5.90	0.56	0.77
LAQN	Outside_ULEZ	Kerbside	HOTSPOT_2019	7	56255	55.0	53.4	-1.64	0.68	0.84
LAQN	Outside_ULEZ	Roadside	BASELINE_2019	45	371492	41.3	42.2	0.86	0.59	0.78
LAQN	Outside_ULEZ	Roadside	HOTSPOT_2019	45	371451	41.3	42.1	0.76	0.62	0.80
LAQN	Outside_ULEZ	Suburban	BASELINE_2019	8	60596	24.2	26.8	2.58	0.65	0.76
LAQN	Outside_ULEZ	Suburban	HOTSPOT_2019	8	60590	24.2	26.8	2.60	0.66	0.76
LAQN	Outside_ULEZ	Urban Background	BASELINE_2019	13	111315	28.1	29.2	1.11	0.63	0.78
LAQN	Outside_ULEZ	Urban Background	HOTSPOT_2019	13	111302	28.1	29.2	1.11	0.64	0.79

Table 6-3
Model evaluation statistics for NO_X (ug/m^3), disaggregated by network, location with respect to the ULEZ, site type and modelling scenario. $N_{stations}$ = number of stations included; N_{hours} = number of hourly mod-obs pairs included; mean.obs = annual mean measured concentration (ug/m^3); mean.mod = annual mean modelled value (ug/m3); MB = Mean Bias (ug/m3); R = Correlation Coefficient; FAC2 = Fraction of modelled values within a factor of 2 of the measured value. Statistics are calculated over all the valid mod-obs pairs of hourly values for each network, location with respect to the ULEZ, site type and modelling scenario combination. AQMesh NO_X is shown in italics because AQMesh measured NO_X is only available from 20 April 2019 onwards, therefore these statistics are not for the whole year.

network	**ulez**	**type**	**scenario**	**$N_{stations}$**	**N_{hours}**	**mean.obs**	**mean.mod**	**MB**	**r**	**FAC2**
AQE	Inside_ULEZ	Urban Background	BASELINE_2019	1	6692	49.9	59.6	9.72	0.63	0.79
AQE	Inside_ULEZ	Urban Background	HOTSPOT_2019	1	6691	49.9	59.7	9.75	0.64	0.81
AQE	Outside_ULEZ	Airport	BASELINE_2019	3	24156	66.1	52.4	-13.65	0.45	0.66
AQE	Outside_ULEZ	Airport	HOTSPOT_2019	3	24153	66.1	52.3	-13.77	0.45	0.66
AQE	Outside_ULEZ	Industrial	BASELINE_2019	1	8596	50.5	45.3	-5.24	0.53	0.68
AQE	Outside_ULEZ	Industrial	HOTSPOT_2019	1	8595	50.5	45.3	-5.28	0.54	0.69
AQE	Outside_ULEZ	Kerbside	BASELINE_2019	3	25325	109.8	95.8	-13.98	0.66	0.75
AQE	Outside_ULEZ	Kerbside	HOTSPOT_2019	3	25322	109.8	95.6	-14.13	0.69	0.77
AQE	Outside_ULEZ	Roadside	BASELINE_2019	14	116176	101.2	91.8	-9.36	0.61	0.70
AQE	Outside_ULEZ	Roadside	HOTSPOT_2019	14	116163	101.2	91.7	-9.53	0.63	0.71
AQE	Outside_ULEZ	Suburban	BASELINE_2019	3	25707	35.2	38.1	2.90	0.51	0.69
AQE	Outside_ULEZ	Suburban	HOTSPOT_2019	3	25704	35.2	38.1	2.92	0.52	0.70
AQE	Outside_ULEZ	Urban Background	BASELINE_2019	15	124972	49.8	47.9	-1.97	0.57	0.69
AQE	Outside_ULEZ	Urban Background	HOTSPOT_2019	15	124958	49.8	47.9	-1.97	0.58	0.70
AQMESH	*Inside_ULEZ*	*Kerbside*	*BASELINE_2019*	*7*	*40624*	*101.9*	*103.1*	*1.12*	*0.45*	*0.68*
AQMESH	*Inside_ULEZ*	*Kerbside*	*HOTSPOT_2019*	*7*	*40624*	*101.9*	*102.6*	*0.65*	*0.49*	*0.69*
AQMESH	*Inside_ULEZ*	*Roadside*	*BASELINE_2019*	*4*	*21822*	*66.8*	*73.7*	*6.86*	*0.28*	*0.60*
AQMESH	*Inside_ULEZ*	*Roadside*	*HOTSPOT_2019*	*4*	*21822*	*66.8*	*73.4*	*6.52*	*0.32*	*0.61*
AQMESH	*Inside_ULEZ*	*Urban Background*	*BASELINE_2019*	*7*	*35898*	*49.0*	*52.5*	*3.50*	*0.47*	*0.72*
AQMESH	*Inside_ULEZ*	*Urban Background*	*HOTSPOT_2019*	*7*	*35898*	*49.0*	*52.3*	*3.35*	*0.50*	*0.73*
AQMESH	*Outside_ULEZ*	*Kerbside*	*BASELINE_2019*	*20*	*99852*	*87.6*	*88.5*	*0.92*	*0.57*	*0.70*
AQMESH	*Outside_ULEZ*	*Kerbside*	*HOTSPOT_2019*	*20*	*99828*	*87.6*	*98.4*	*10.81*	*0.60*	*0.70*
AQMESH	*Outside_ULEZ*	*Roadside*	*BASELINE_2019*	*25*	*123243*	*70.1*	*58.9*	*-11.19*	*0.52*	*0.68*
AQMESH	*Outside_ULEZ*	*Roadside*	*HOTSPOT_2019*	*25*	*123243*	*70.1*	*58.7*	*-11.44*	*0.54*	*0.69*
AQMESH	*Outside_ULEZ*	*Urban Background*	*BASELINE_2019*	*28*	*134126*	*47.0*	*46.9*	*-0.13*	*0.49*	*0.72*
AQMESH	*Outside_ULEZ*	*Urban Background*	*HOTSPOT_2019*	*28*	*134126*	*47.0*	*46.7*	*-0.29*	*0.50*	*0.73*
LAQN	Inside_ULEZ	Kerbside	BASELINE_2019	2	16025	127.7	149.8	22.08	0.43	0.64
LAQN	Inside_ULEZ	Kerbside	HOTSPOT_2019	2	16023	127.7	149.5	21.80	0.47	0.65
LAQN	Inside_ULEZ	Roadside	BASELINE_2019	5	42717	129.9	119.9	-10.02	0.54	0.74
LAQN	Inside_ULEZ	Roadside	HOTSPOT_2019	5	42710	129.9	137.9	7.93	0.62	0.77
LAQN	Inside_ULEZ	Urban Background	BASELINE_2019	4	28849	48.7	58.8	10.08	0.59	0.77
LAQN	Inside_ULEZ	Urban Background	HOTSPOT_2019	4	28846	48.7	58.8	10.12	0.60	0.79
LAQN	Outside_ULEZ	Industrial	BASELINE_2019	5	42597	70.6	72.8	2.24	0.58	0.69
LAQN	Outside_ULEZ	Industrial	HOTSPOT_2019	5	42592	70.6	72.5	1.92	0.61	0.72
LAQN	Outside_ULEZ	Kerbside	BASELINE_2019	7	56245	134.3	113.1	-21.20	0.59	0.67
LAQN	Outside_ULEZ	Kerbside	HOTSPOT_2019	7	56224	134.3	130.5	-3.80	0.69	0.76
LAQN	Outside_ULEZ	Roadside	BASELINE_2019	45	371414	90.9	86.5	-4.37	0.51	0.65
LAQN	Outside_ULEZ	Roadside	HOTSPOT_2019	45	371373	90.9	86.4	-4.55	0.56	0.66
LAQN	Outside_ULEZ	Suburban	BASELINE_2019	8	60600	39.6	41.4	1.74	0.56	0.67
LAQN	Outside_ULEZ	Suburban	HOTSPOT_2019	8	60594	39.6	41.4	1.81	0.57	0.68
LAQN	Outside_ULEZ	Urban Background	BASELINE_2019	13	111307	45.5	47.1	1.53	0.54	0.70
LAQN	Outside_ULEZ	Urban Background	HOTSPOT_2019	13	111294	45.5	47.0	1.52	0.55	0.71

network	ulez	type	scenario	$N_{stations}$	N_{hours}	mean.obs	mean.mod	MB	r	FAC2
AQE	Outside_ULEZ	Airport	BASELINE_2019	3	24183	13.2	15.8	2.63	0.72	0.85
AQE	Outside_ULEZ	Airport	HOTSPOT_2019	3	23176	13.2	15.7	2.52	0.80	0.86
AQE	Outside_ULEZ	Industrial	BASELINE_2019	1	8432	15.0	15.6	0.56	0.73	0.89
AQE	Outside_ULEZ	Industrial	HOTSPOT_2019	1	8081	15.0	15.4	0.38	0.84	0.92
AQE	Outside_ULEZ	Kerbside	BASELINE_2019	3	24774	21.1	19.3	-1.80	0.70	0.87
AQE	Outside_ULEZ	Kerbside	HOTSPOT_2019	3	23744	21.1	22.3	1.22	0.75	0.90
AQE	Outside_ULEZ	Roadside	BASELINE_2019	12	85978	20.4	18.7	-1.74	0.57	0.83
AQE	Outside_ULEZ	Roadside	HOTSPOT_2019	12	82391	20.5	21.3	0.84	0.62	0.85
AQE	Outside_ULEZ	Suburban	BASELINE_2019	1	8610	16.2	15.6	-0.64	0.72	0.88
AQE	Outside_ULEZ	Suburban	HOTSPOT_2019	1	8250	16.2	15.4	-0.79	0.81	0.91
AQE	Outside_ULEZ	Urban Background	BASELINE_2019	13	107619	17.2	15.9	-1.31	0.64	0.82
AQE	Outside_ULEZ	Urban Background	HOTSPOT_2019	13	103133	17.2	16.2	-1.01	0.72	0.85
LAQN	Inside_ULEZ	Kerbside	BASELINE_2019	1	8485	26.5	21.0	-5.44	0.42	0.81
LAQN	Inside_ULEZ	Kerbside	HOTSPOT_2019	1	8132	26.6	23.9	-2.69	0.45	0.86
LAQN	Inside_ULEZ	Roadside	BASELINE_2019	3	18838	25.5	21.1	-4.39	0.52	0.78
LAQN	Inside_ULEZ	Roadside	HOTSPOT_2019	3	18051	25.6	25.0	-0.56	0.53	0.81
LAQN	Inside_ULEZ	Urban Background	BASELINE_2019	3	23757	17.4	15.9	-1.53	0.70	0.84
LAQN	Inside_ULEZ	Urban Background	HOTSPOT_2019	3	22768	17.4	16.3	-1.14	0.78	0.87
LAQN	Outside_ULEZ	Industrial	BASELINE_2019	6	48049	26.3	18.2	-8.11	0.44	0.70
LAQN	Outside_ULEZ	Industrial	HOTSPOT_2019	6	46040	26.4	19.9	-6.50	0.55	0.77
LAQN	Outside_ULEZ	Kerbside	BASELINE_2019	7	44164	22.1	20.7	-1.39	0.64	0.84
LAQN	Outside_ULEZ	Kerbside	HOTSPOT_2019	7	42319	22.1	26.4	4.33	0.66	0.87
LAQN	Outside_ULEZ	Roadside	BASELINE_2019	38	297632	21.3	19.0	-2.31	0.60	0.81
LAQN	Outside_ULEZ	Roadside	HOTSPOT_2019	38	285216	21.3	21.7	0.40	0.63	0.84
LAQN	Outside_ULEZ	Suburban	BASELINE_2019	7	49459	17.1	15.5	-1.61	0.72	0.84
LAQN	Outside_ULEZ	Suburban	HOTSPOT_2019	7	47391	17.1	15.3	-1.80	0.79	0.87
LAQN	Outside_ULEZ	Urban Background	BASELINE_2019	12	100954	16.4	15.5	-0.91	0.72	0.85
LAQN	Outside_ULEZ	Urban Background	HOTSPOT_2019	12	96742	16.3	15.3	-0.96	0.80	0.88

Table 6-4
Model evaluation statistics for PM_{10} (ug/m^3), disaggregated by network, location with respect to the ULEZ, site type and modelling scenario. $N_{stations}$ = number of stations included; N_{hours} = number of hourly mod-obs pairs included; mean.obs = annual mean measured concentration (ug/m^3); mean.mod = annual mean modelled value (ug/m3); MB = Mean Bias (ug/m3); R = Correlation Coefficient; FAC2 = Fraction of modelled values within a factor of 2 of the measured value. Statistics are calculated over all the valid mod-obs pairs of hourly values for each network, location with respect to the ULEZ, site type and modelling scenario combination.

network	ulez	type	scenario	$N_{stations}$	N_{hours}	mean.obs	mean.mod	MB	r	FAC2
AQE	Inside_ULEZ	Urban Background	BASELINE_2019	1	7961	12.4	11.3	-1.13	0.76	0.82
AQE	Inside_ULEZ	Urban Background	HOTSPOT_2019	1	7628	12.3	10.7	-1.61	0.85	0.87
AQE	Outside_ULEZ	Airport	BASELINE_2019	3	24183	8.3	10.9	2.57	0.77	0.81
AQE	Outside_ULEZ	Airport	HOTSPOT_2019	3	23176	8.3	10.0	1.74	0.88	0.85
AQE	Outside_ULEZ	Industrial	BASELINE_2019	1	8432	9.5	10.9	1.41	0.77	0.89
AQE	Outside_ULEZ	Industrial	HOTSPOT_2019	1	8081	9.4	10.0	0.56	0.89	0.93
AQE	Outside_ULEZ	Kerbside	BASELINE_2019	1	8410	11.1	13.0	1.90	0.80	0.82
AQE	Outside_ULEZ	Kerbside	HOTSPOT_2019	1	8057	11.1	13.6	2.47	0.86	0.81
AQE	Outside_ULEZ	Roadside	BASELINE_2019	4	26205	12.9	13.1	0.19	0.70	0.81
AQE	Outside_ULEZ	Roadside	HOTSPOT_2019	4	25103	12.9	13.8	0.93	0.79	0.83
AQE	Outside_ULEZ	Suburban	BASELINE_2019	2	15482	11.3	10.9	-0.42	0.83	0.82
AQE	Outside_ULEZ	Suburban	HOTSPOT_2019	2	14828	11.2	10.0	-1.20	0.89	0.85
AQE	Outside_ULEZ	Urban Background	BASELINE_2019	6	48016	10.3	11.0	0.68	0.68	0.77
AQE	Outside_ULEZ	Urban Background	HOTSPOT_2019	6	46016	10.3	10.3	0.05	0.78	0.80
AQMESH	Inside_ULEZ	Kerbside	BASELINE_2019	10	72999	13.0	12.0	-0.99	0.55	0.80
AQMESH	Inside_ULEZ	Kerbside	HOTSPOT_2019	10	69996	12.9	12.2	-0.69	0.59	0.78
AQMESH	Inside_ULEZ	Roadside	BASELINE_2019	5	26552	12.7	11.2	-1.53	0.53	0.77
AQMESH	Inside_ULEZ	Roadside	HOTSPOT_2019	5	25459	12.7	11.0	-1.70	0.60	0.80
AQMESH	Inside_ULEZ	Urban Background	BASELINE_2019	7	47161	11.3	10.6	-0.71	0.63	0.82
AQMESH	Inside_ULEZ	Urban Background	HOTSPOT_2019	7	45218	11.2	9.9	-1.35	0.71	0.84
AQMESH	Outside_ULEZ	Kerbside	BASELINE_2019	15	94901	12.7	11.4	-1.25	0.38	0.79
AQMESH	Outside_ULEZ	Kerbside	HOTSPOT_2019	15	90963	12.6	12.0	-0.69	0.40	0.76
AQMESH	Outside_ULEZ	Roadside	BASELINE_2019	22	159454	11.7	10.9	-0.81	0.58	0.81
AQMESH	Outside_ULEZ	Roadside	HOTSPOT_2019	22	152894	11.6	10.5	-1.19	0.66	0.84
AQMESH	Outside_ULEZ	Urban Background	BASELINE_2019	26	188373	11.5	10.9	-0.61	0.67	0.82
AQMESH	Outside_ULEZ	Urban Background	HOTSPOT_2019	26	180617	11.5	10.2	-1.22	0.76	0.85
LAQN	Inside_ULEZ	Kerbside	BASELINE_2019	1	8372	13.9	12.5	-1.43	0.66	0.82
LAQN	Inside_ULEZ	Kerbside	HOTSPOT_2019	1	8024	13.9	13.0	-0.97	0.71	0.88
LAQN	Inside_ULEZ	Urban Background	BASELINE_2019	2	9566	11.8	10.9	-0.92	0.59	0.74
LAQN	Inside_ULEZ	Urban Background	HOTSPOT_2019	2	9162	11.8	10.4	-1.39	0.64	0.77
LAQN	Outside_ULEZ	Industrial	BASELINE_2019	1	8533	11.7	11.4	-0.35	0.74	0.78
LAQN	Outside_ULEZ	Industrial	HOTSPOT_2019	1	8176	11.6	10.7	-0.94	0.82	0.81
LAQN	Outside_ULEZ	Kerbside	BASELINE_2019	2	16270	12.7	13.8	1.09	0.78	0.82
LAQN	Outside_ULEZ	Kerbside	HOTSPOT_2019	2	15585	12.6	14.8	2.14	0.83	0.82
LAQN	Outside_ULEZ	Roadside	BASELINE_2019	9	67186	12.5	12.8	0.31	0.77	0.84
LAQN	Outside_ULEZ	Roadside	HOTSPOT_2019	9	64375	12.4	13.0	0.58	0.81	0.85
LAQN	Outside_ULEZ	Suburban	BASELINE_2019	3	23549	11.4	10.8	-0.59	0.80	0.81
LAQN	Outside_ULEZ	Suburban	HOTSPOT_2019	3	22559	11.3	9.9	-1.42	0.88	0.85
LAQN	Outside_ULEZ	Urban Background	BASELINE_2019	6	46298	9.8	10.7	0.93	0.76	0.87
LAQN	Outside_ULEZ	Urban Background	HOTSPOT_2019	6	44370	9.7	9.9	0.18	0.86	0.91

Table 6-5
Model evaluation statistics for $PM_{2.5}$ (ug/m^3), disaggregated by network, location with respect to the ULEZ, site type and modelling scenario. $N_{stations}$ = number of stations included; N_{hours} = number of hourly mod-obs pairs included; mean.obs = annual mean measured concentration (ug/m^3); mean.mod = annual mean modelled value (ug/m3); MB = Mean Bias (ug/m3); R = Correlation Coefficient; FAC2 = Fraction of modelled values within a factor of 2 of the measured value. Statistics are calculated over all the valid mod-obs pairs of hourly values for each network, location with respect to the ULEZ, site type and modelling scenario combination.

network	ulez	type	scenario	$N_{stations}$	N_{hours}	mean.obs	mean.mod	MB	r	FAC2
AQE	Outside_ULEZ	Industrial	BASELINE_2019	1	8482	36.7	40.0	3.32	0.75	0.70
AQE	Outside_ULEZ	Industrial	HOTSPOT_2019	1	8481	36.7	40.1	3.46	0.76	0.71
AQE	Outside_ULEZ	Roadside	BASELINE_2019	2	14239	26.4	33.0	6.65	0.69	0.60
AQE	Outside_ULEZ	Roadside	HOTSPOT_2019	2	14238	26.4	33.1	6.77	0.70	0.61
AQE	Outside_ULEZ	Suburban	BASELINE_2019	2	17280	41.3	42.4	1.12	0.78	0.73
AQE	Outside_ULEZ	Suburban	HOTSPOT_2019	2	17278	41.3	42.6	1.24	0.78	0.73
AQE	Outside_ULEZ	Urban Background	BASELINE_2019	2	16653	36.6	39.8	3.14	0.70	0.64
AQE	Outside_ULEZ	Urban Background	HOTSPOT_2019	2	16651	36.6	39.9	3.30	0.71	0.64
LAQN	Inside_ULEZ	Urban Background	BASELINE_2019	1	8539	38.9	37.3	-1.54	0.76	0.73
LAQN	Inside_ULEZ	Urban Background	HOTSPOT_2019	1	8538	38.9	37.4	-1.49	0.76	0.73
LAQN	Outside_ULEZ	Kerbside	BASELINE_2019	1	8496	22.1	25.1	3.02	0.54	0.49
LAQN	Outside_ULEZ	Kerbside	HOTSPOT_2019	1	8495	22.1	25.3	3.21	0.56	0.50
LAQN	Outside_ULEZ	Roadside	BASELINE_2019	7	53689	28.0	35.1	7.15	0.68	0.61
LAQN	Outside_ULEZ	Roadside	HOTSPOT_2019	7	53682	28.0	35.2	7.28	0.69	0.61
LAQN	Outside_ULEZ	Suburban	BASELINE_2019	4	34473	41.4	42.0	0.52	0.75	0.70
LAQN	Outside_ULEZ	Suburban	HOTSPOT_2019	4	34469	41.4	42.1	0.65	0.75	0.70
LAQN	Outside_ULEZ	Urban Background	BASELINE_2019	6	41419	43.5	41.2	-2.35	0.77	0.73
LAQN	Outside_ULEZ	Urban Background	HOTSPOT_2019	6	41414	43.5	41.3	-2.23	0.77	0.74

Table 6-6
Model evaluation statistics for Ozone (ug/m^3), disaggregated by network, location with respect to the ULEZ, site type and modelling scenario. $N_{stations}$ = number of stations included; N_{hours} = number of hourly mod-obs pairs included; mean.obs = annual mean measured concentration (ug/m^3); mean.mod = annual mean modelled value (ug/m3); MB = Mean Bias (ug/m3); R = Correlation Coefficient; FAC2 = Fraction of modelled values within a factor of 2 of the measured value. Statistics are calculated over all the valid mod-obs pairs of hourly values for each network, location with respect to the ULEZ, site type and modelling

6.2 Mobile locations

To compare with the Breathe London hyperlocal mobile data, measurement locations have been represented as discrete model receptors placed along the centrelines of all the driven roads that are included in the LAEI. Hourly values at these receptors have been aggregated to the same 30m segments as the measured data, and average values have been calculated for each segment. Table 6-7 and Figure 6-6 to Figure 6-10 compare the modelled and measured average values on each 30m road segment, where only driven hours are included in the average. Interpretation of these comparisons should be done with care, because the modelled data represents an average of hourly averages, whereas measured values may represent only a small number of 1 second measurements within the hours included in the average, therefore the measurements will be much more sensitive to sub-hourly variations in air flow, turbulence and traffic conditions than the model, which smooths these out over an hour.

The results for NO_X and NO_2 show a relatively poor correlation and large negative bias, compared with the performance at static sites (Section 6.1), which is partly to be expected due to the differences in averaging times highlighted above. However, the statistics are also likely to be affected by a relatively small number of roads where the measured mean is very high compared with the modelled mean (Figure 6-1, Figure 6-2). These high values are not seen in other primary traffic pollutants, suggesting that these roads may have been congested during the driven hours, leading to above normal levels of vehicle acceleration, which is linked to incomplete fuel combustion and higher NO_X emissions. Further analysis of the results for these road segments would be needed to draw any further conclusions.

The results for PM_{10} and $PM_{2.5}$ also show a relatively poor correlation compared with the performance at static sites (Section 6.1), but this time with a significant positive bias. Modelled mean values are consistent with modelled mean values at kerbside static sites; however the mobile measurements are significantly lower than the measurements at static kerbside sites, suggesting higher measurement uncertainty. The PM_{10} measured values are lower than expected because they have not been corrected for sampling loss (Appendix 3) This is expected for particle measurements and had not been quantified for PM_{10} in this analysis; all measured data is provisional at this stage.

Pollutant	Scenario	Number of road segments	Observed mean	Modelled mean	MB	R	FAC2	RMSE
CO2	BASELINE2019	39877	450.2	450.5	0.2	0.44	0.93	30.05
CO2	HOTSPOT2019	39877	450.2	454.5	4.3	0.42	0.94	30.68
NO2	BASELINE2019	37596	71.5	56.9	-14.6	0.46	0.74	42.79
NO2	HOTSPOT2019	37596	71.5	60.1	-11.4	0.43	0.77	42.42
NOX	BASELINE2019	30436	236.8	141.1	-95.7	0.39	0.45	229.01
NOX	HOTSPOT2019	30436	236.8	151.0	-85.8	0.38	0.48	221.73
O3	BASELINE2019	35490	32.0	35.0	3.0	0.76	0.66	12.91
O3	HOTSPOT2019	35490	32.0	33.4	1.4	0.69	0.67	13.48
PM10	BASELINE2019	30665	12.8	18.8	6.1	0.40	0.47	11.64
PM10	HOTSPOT2019	30665	12.8	27.4	14.6	0.30	0.26	19.05
PM2.5	BASELINE2019	29525	11.1	10.2	-0.9	0.65	0.62	5.65
PM2.5	HOTSPOT2019	29525	11.1	15.1	4.0	0.52	0.55	7.78

Table 6-7 Statistics comparing hourly modelled and observed concentrations aggregated into 30m road segments and averaged over the whole period. MB = Mean Bias; FAC2 = fraction of hourly modelled values within a factor of 2 of the observed; R = Correlation Coefficient; RMSE = root-mean-square error. Units are µg/m^3 for all pollutants except CO2 which is ppm.

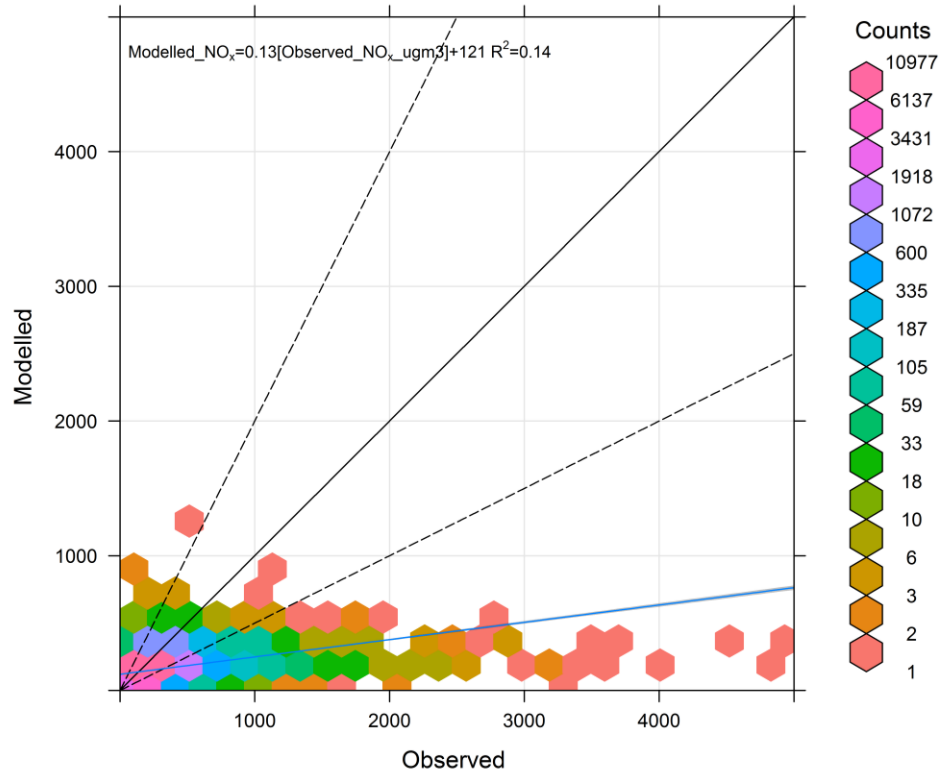

Figure 6-6 Frequency scatter plot of observed and modelled NO_X concentrations (µg/m³). Each point represents the average NO_X concentration over all driven hours per 30m road segment. The slope, offset and regression are shown in the top corner, with the 1:1 line in black and the dashed lines representing the 1:2 and 2:1 lines.

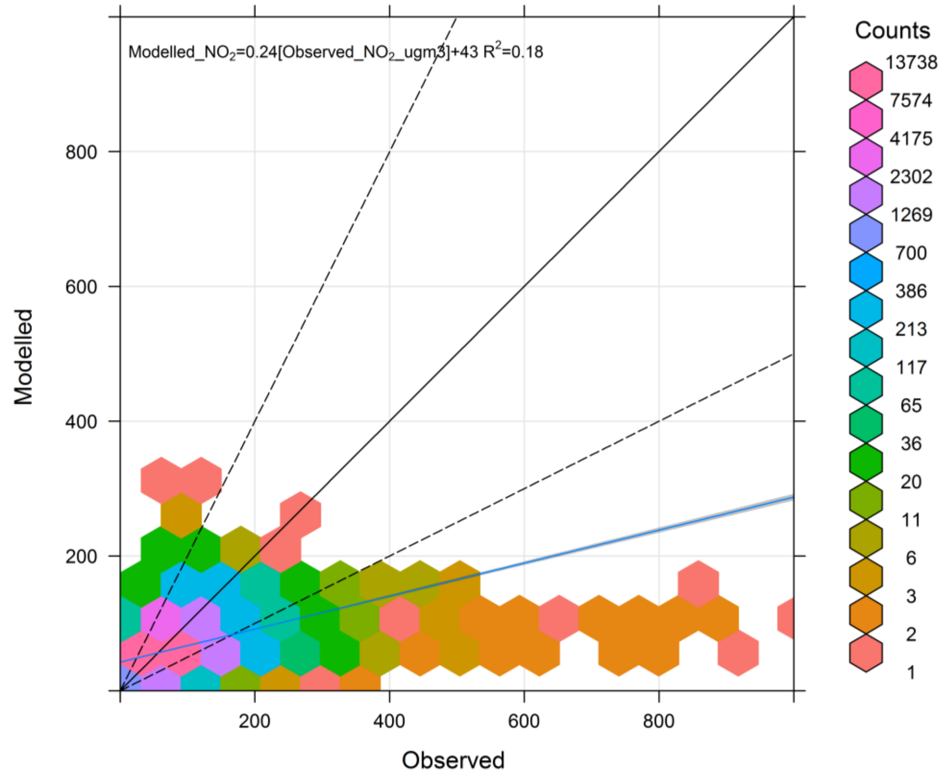

Figure 6-7 Frequency scatter plot of observed and modelled NO_2 concentrations (µg/m³). Each point represents the average NO_2 concentration over all driven hours per 30m road segment. The slope, offset and regression are shown in the top corner, with the 1:1 line in black and the dashed lines representing the 1:2 and 2:1 lines.

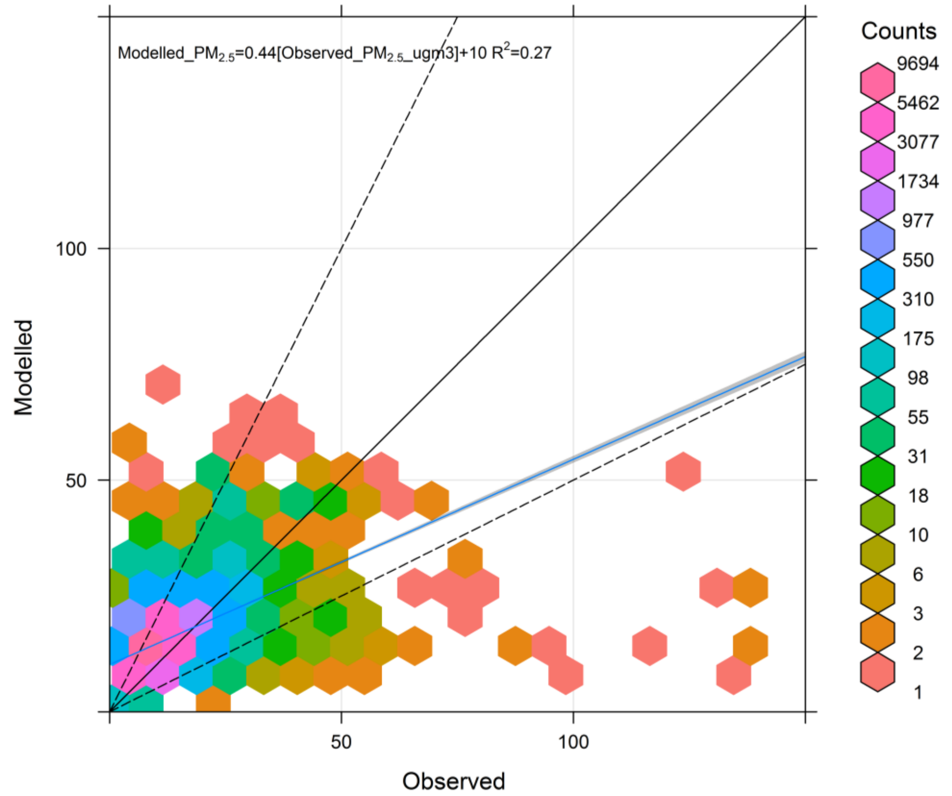

Figure 6-8 Frequency scatter plot of observed and modelled $PM_{2.5}$ concentrations (µg/m³). Each point represents the average $PM_{2.5}$ concentrations over all driven hours per 30m road segment. The slope, offset and regression are shown in the top corner, with the 1:1 line in black and the dashed lines representing the 1:2 and 2:1 lines.

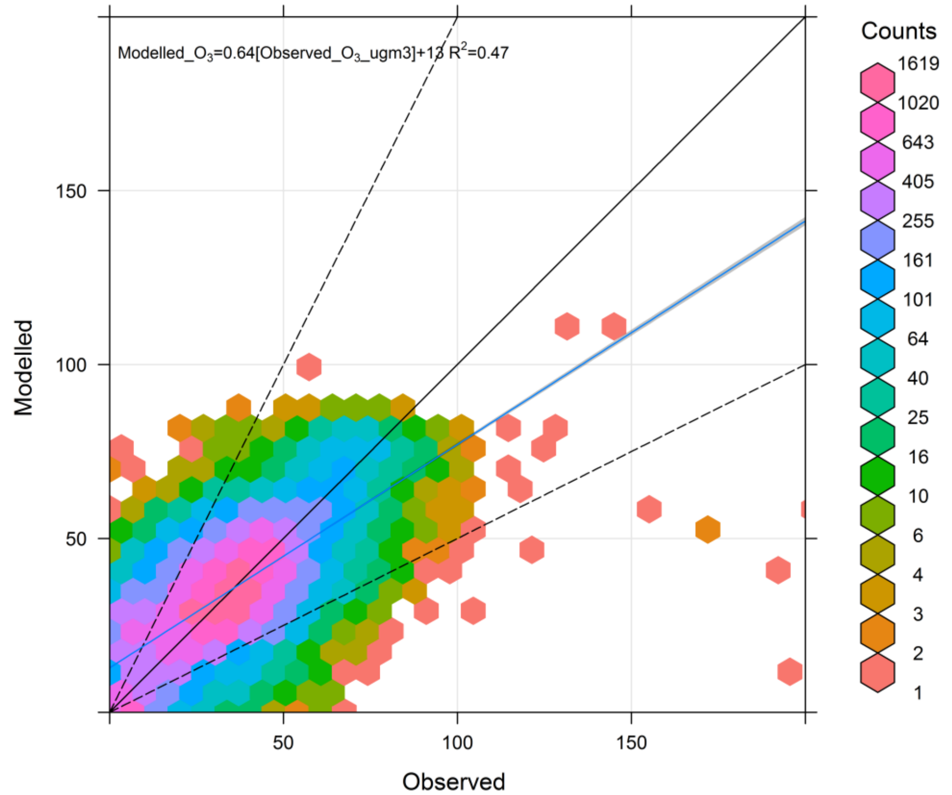

Figure 6-9 Frequency scatter plot of observed and modelled O_3 concentrations (µg/m³). Each point represents the average O_3 concentrations over all driven hours per 30m road segment. The slope, offset and regression are shown in the top corner, with the 1:1 line in black and the dashed lines representing the 1:2 and 2:1 lines.

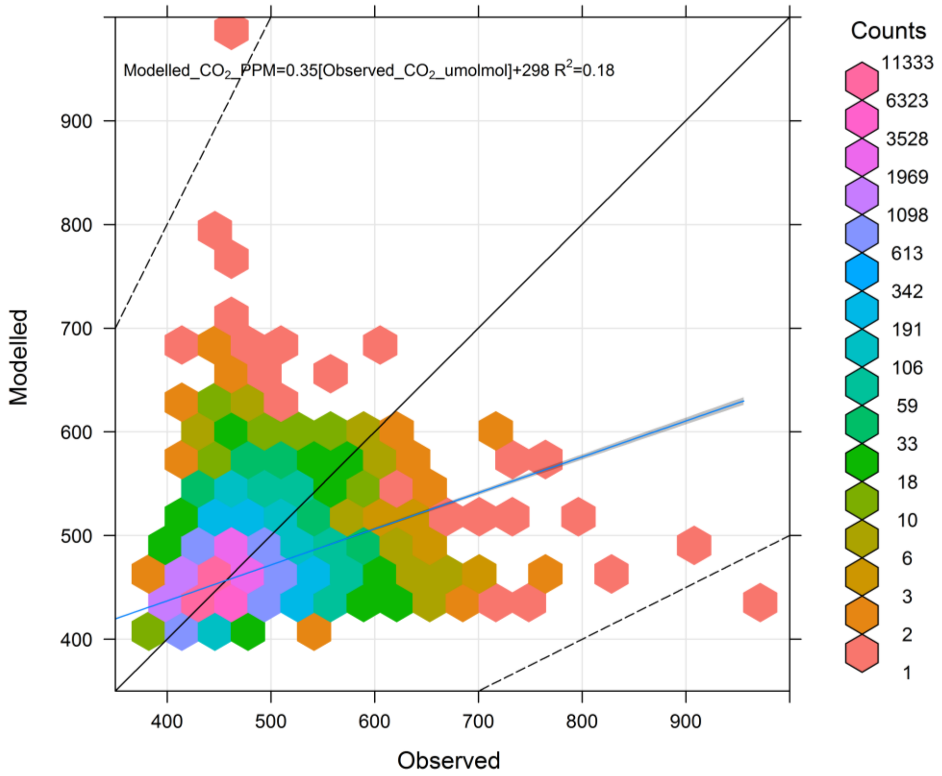

Figure 6-10 Frequency scatter plot of observed and modelled CO_2 concentrations (ppm). Each point represents the average CO_2 concentrations over all driven hours per 30m road segment. The slope, offset and regression are shown in the top corner, with the 1:1 line in black and the dashed lines representing the 1:2 and 2:1 lines.

7. Assessing the ULEZ impact using inversion techniques

7.1 Introduction

CERC have developed a data assimilation scheme that applies a Bayesian inversion technique to a high resolution (street-level) atmospheric dispersion model to modify pollution emission rates based on local measurements (Carruthers et al., 2020[16]). This scheme has been applied to investigate changes in NO_X emissions from traffic in London during the period from 1 October 2018 to 29 February 2020 (avoiding the period affected by COVID-19), to assess the impact of the introduction of the Ultra-Low Emissions Zone (ULEZ) on 8th April 2019.

7.2 Inversion methodology

The CERC Inversion System (Figure 7-1) optimises modelled concentrations in relation to monitored data by adjusting the emissions data that are used to calculate the modelled concentrations, taking into account the known (or estimated) uncertainty in both the *a priori* emissions data and the monitored data. The results are adjusted modelled concentrations for every modelled receptor and associated adjusted emissions for every source, for every hour modelled.

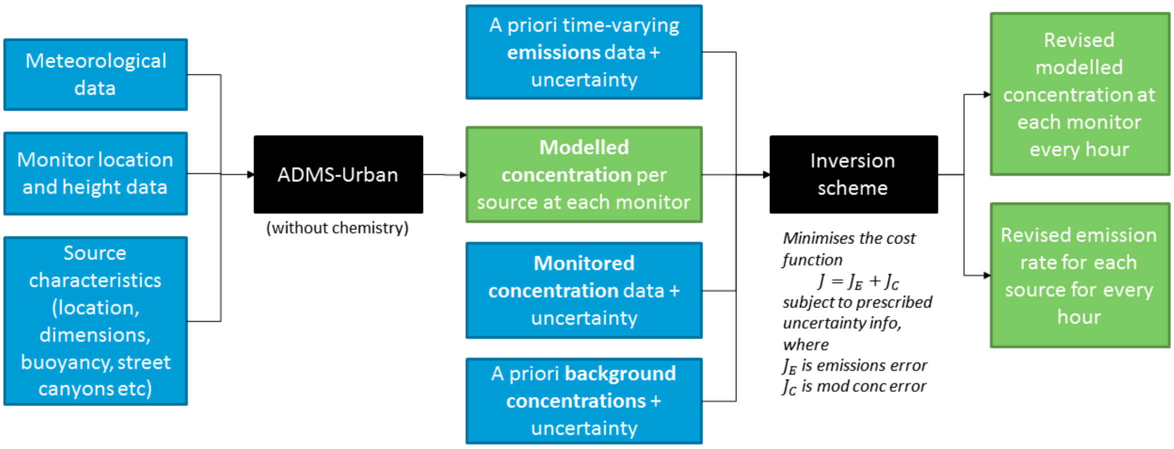

Figure 7-1 Schematic of the CERC Inversion System. Blue represents a non-calculated dataset, green represents a calculated dataset and black represents a process.

In this experiment, assumed *a priori* uncertainties were 100%, 20%, 10% and 30% for road traffic emissions, other emission types, LAQN and AQE measurements and AQMesh measurements respectively. Assumed minimum absolute uncertainties were 0.2 g/km/s for road source emissions and 0.0000005 g/m^2/s for other emission types. Emissions were from the 2013 edition of the LAEI (published in 2016) interpolated to 2019 and road traffic emissions calculated using emission factors for 2019 from EFT version 8.0, including adjustments for real-world conditions.

[16] Carruthers D, Stidworthy A, Clarke D, Dicks J, Jones R, Leslie I, Popoola OAM and Seaton M, 2019: *Urban emission inventory optimisation using sensor data, an urban air quality model and inversion techniques*. International Journal of Environment and Pollution, vol. 66, issue 4, pp. 252-266, DOI: 10.1504/IJEP.2019.104878.

7.3 Results

For each day in the period, the median of the site-specific daily average of the hourly measured, original modelled and adjusted modelled NO_X concentrations has been calculated, disaggregated by network type (Figure 7-2). As expected, the adjusted modelled concentrations are generally closer to the observed values than the original modelled levels. Also as expected, the impact is greater at reference sites than at AQMesh sites, due to the lower *a priori* measurement uncertainty for reference sites. These results give confidence that the Inversion System is behaving as expected and successfully assimilating measurements.

For each day in the period, the median of the site-specific daily average of the hourly measured NO_X concentrations has been calculated, disaggregated by the site location in relation to the ULEZ boundary. Similarly, the median of the road-specific daily average of the hourly derived NO_X emission rates has been calculated, disaggregated by the road location in relation to the ULEZ boundary. These results are presented in Figure 7-3. While concentrations inside the ULEZ area are generally higher than outside, the derived emissions show that road traffic emissions are generally *lower* inside the ULEZ area, showing that the higher concentrations inside the ULEZ are due to non-traffic sources. Concentrations and derived road traffic emissions both have a seasonal pattern, with higher levels during the Winter months, lower values in the Summer and the lowest levels in July and August. However, the measured concentrations show a decrease from December 2019 through to February 2020, with the largest reduction outside the ULEZ area; this is not seen in the derived road emissions, suggesting this reduction is caused by meteorological effects rather than reduced road traffic emissions.

The ULEZ was implemented in April 2019, therefore it is interesting to look at changes in concentrations and road traffic emissions over time. For each monitoring site, the daily average concentration was normalised by the average for that site over the last three months of 2018. Similarly, the daily average derived emission rate for each road source was normalised by the average derived emission rate over the last three months of 2018. The median concentration and road emission rate each day were re-calculated, disaggregated by the site/source location with respect to the ULEZ boundary; Figure 7-4 shows the results. During the summer months, reductions in road emissions inside the ULEZ were marginally more pronounced than those outside the ULEZ, but the recovery to higher emissions during the Winter of 2019/20 is the same in both areas. Measured concentrations show a marginally weaker seasonal signal inside the ULEZ than outside.

The relationship between the a priori and derived emissions was explored with a view to improving the model performance by the application of monthly factors to the explicit road NO_X emissions; however, this needs more work to disentangle the role of non-road sources, the wide variation in derived emissions also means that simple monthly factors may not be sufficient to lead to modelling improvements; hourly road-specific factors may be necessary. It should also be noted that in this inversion analysis all road sources were treated equivalently, with the same emissions uncertainty and the same error covariance with all other road sources; however, roads inside and outside the ULEZ are in fact subject to different constraints so could be treated as two different source sets, each with its own uncertainty level and a weaker error covariance between sources in one set with sources in the other. Finally, the NO_2 AQMesh data that was used in this inversion analysis is known to be sensitive to ozone at low NO_2 concentrations, and while the uncertainties allowed in the inversion system will account for this to a certain extent, it would be interesting to repeat this analysis with the newly available dataset that includes a correction for this behaviour.

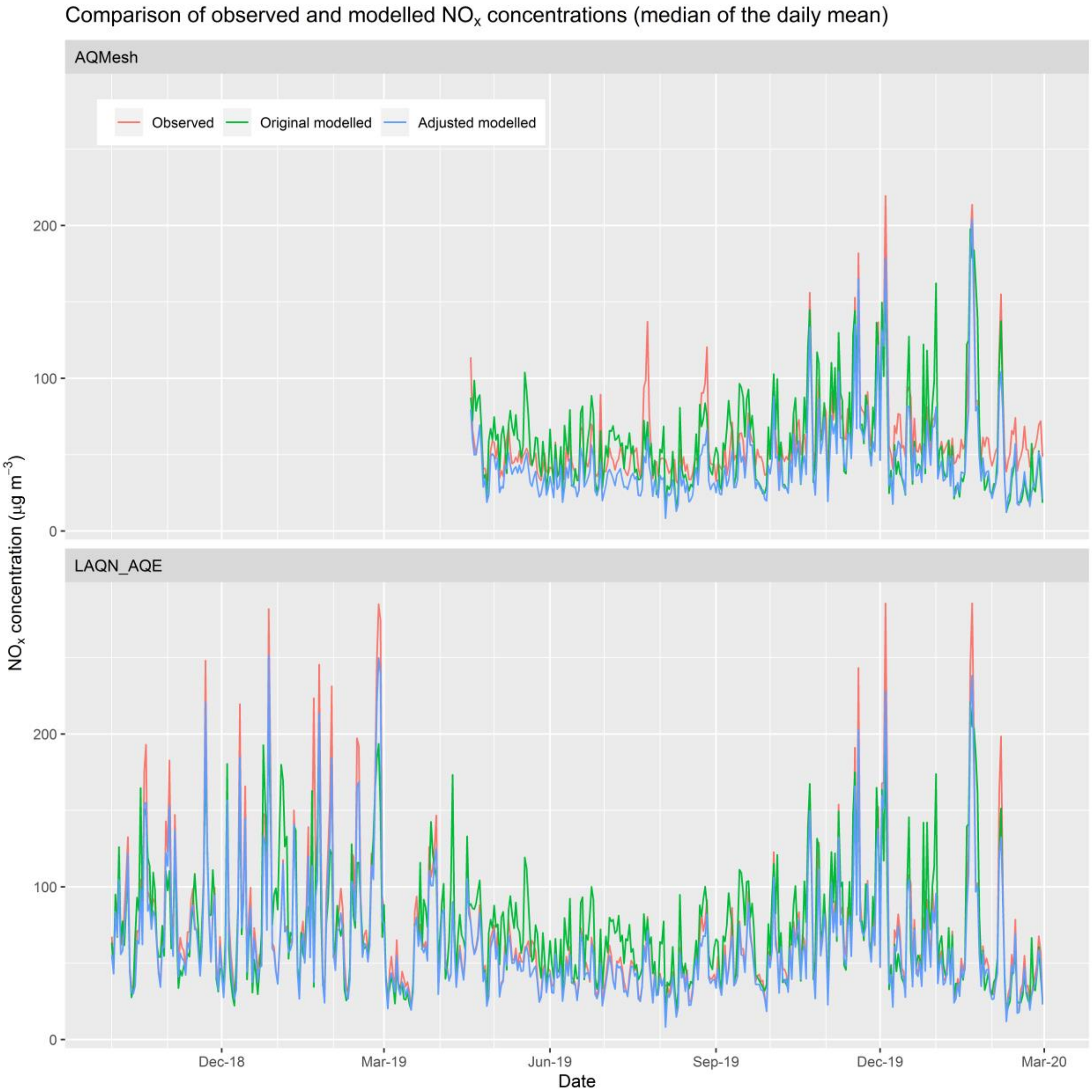

Figure 7-2 Comparison between modelled (original (green) and adjusted (blue)) and observed (red) concentrations at AQMesh (top) and reference (bottom) sites. AQmesh NO_X data are only available from 20 April 2019 onwards.

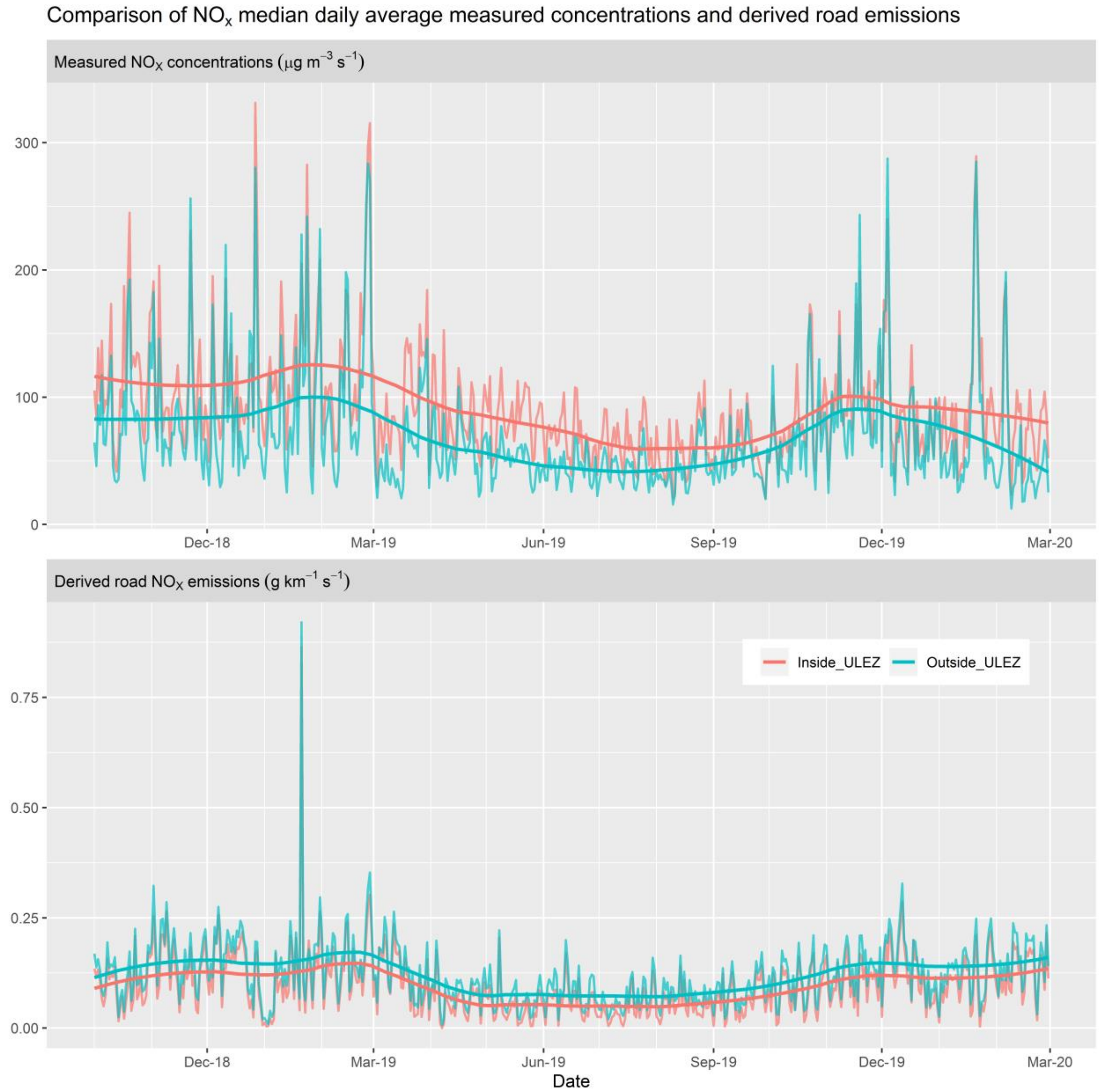

Figure 7-3 Comparison between measured concentrations (top) and derived emissions (bottom) inside (red) and outside (blue) the ULEZ. A smoothed trend line has been fitted to the data. The measured concentrations shown include LAQN and AQE data only; AQmesh NO_X data was included in the inversion analysis, but are not included in the measured NO_X concentrations shown here, because they are only available from 20 April 2019 onwards.

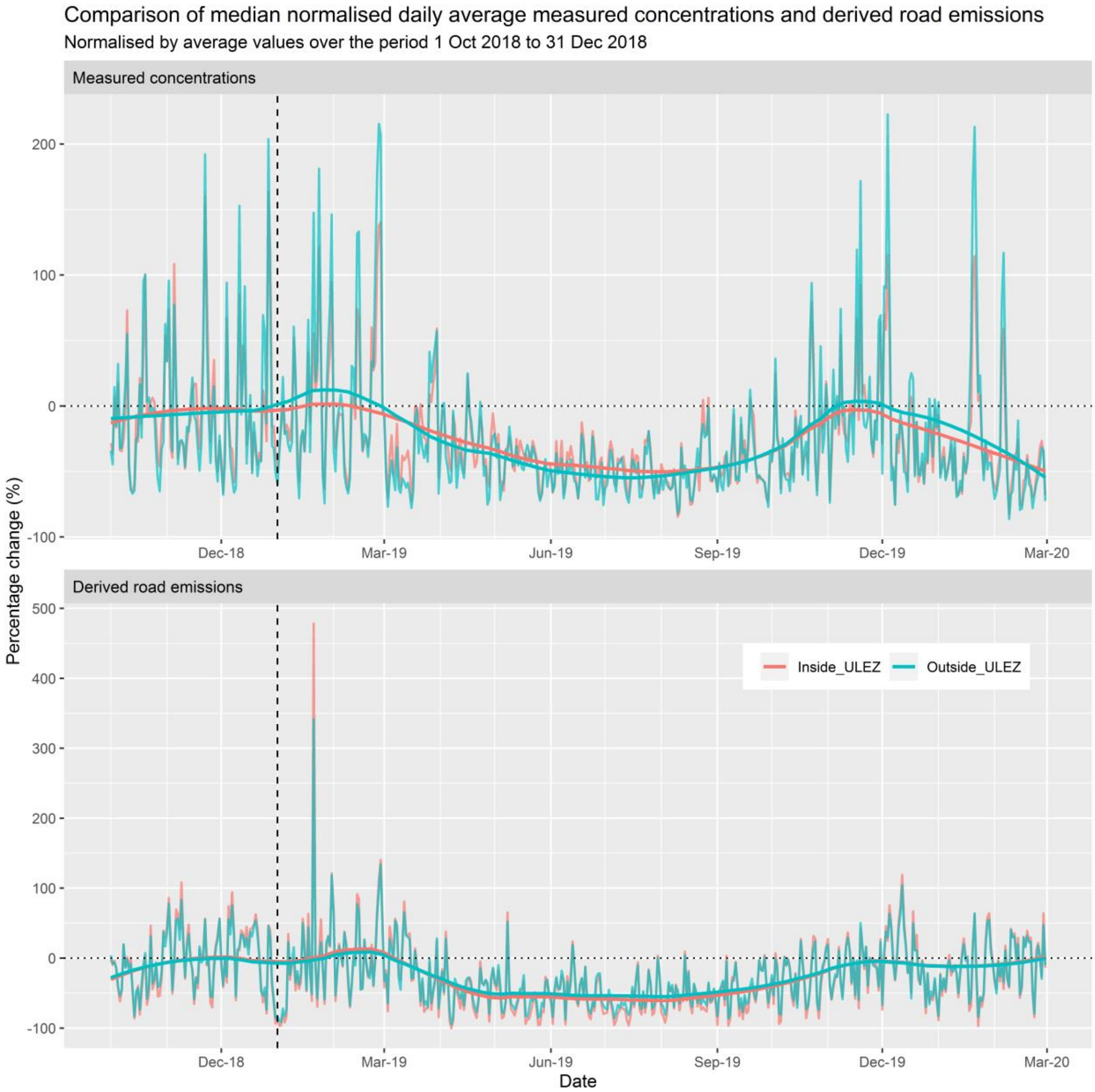

Figure 7-4 Comparison between normalised measured concentrations (top) and normalised derived emissions (bottom) inside (red) and outside (blue) the ULEZ. The vertical dashed line represents 1 Jan 2019. Values are expressed as a percentage change compared to the average of the 3-month period from 1 October 2018 to 31 December 2018. A smoothed trend line has been fitted to the data. The measured concentrations shown include LAQN and AQE data only; AQmesh NO_X data was included in the inversion analysis, but are not included in the measured NO_X concentrations shown here, because they are only available from 20 April 2019 onwards.

8. Results

8.1 Annual average concentration maps

Annual average concentrations of NO_2, NO_X, $PM_{2.5}$, $PM_{10,}$ Ozone and CO_2 have been calculated for 2019 using the HOTSPOT2019 modelling scenario (Section 4.2) at high resolution (Section 0) to enable the generation of detailed pollution maps. The resulting maps are presented in Figure 8-1 through Figure 8-6. The maps cover the area within the M25 Motorway at 10m resolution, and can be used in comparison with the WHO long term guidelines. Table 8-1 summarises the long term WHO guidelines for each pollutant; there are no WHO long term guidelines available for NO_X, Ozone or CO_2. The areas where the annual average concentrations exceed WHO guidelines are shown in yellow to red in the Figures. For all pollutants except Ozone, concentrations are highest near major roads, near Heathrow Airport, near the Dartford Crossing, and in Central London. The majority of London does not exceed the WHO guideline for NO_2 or PM_{10}, however a large portion of the central and inner areas do exceed the $PM_{2.5}$ guideline.

Table 8-1 WHO annual average guidelines for NO_2, $PM_{2.5}$ and PM_{10}

Pollutant	WHO Annual average guideline (µg/m^3)
NO_2	40
$PM_{2.5}$	10
PM_{10}	20

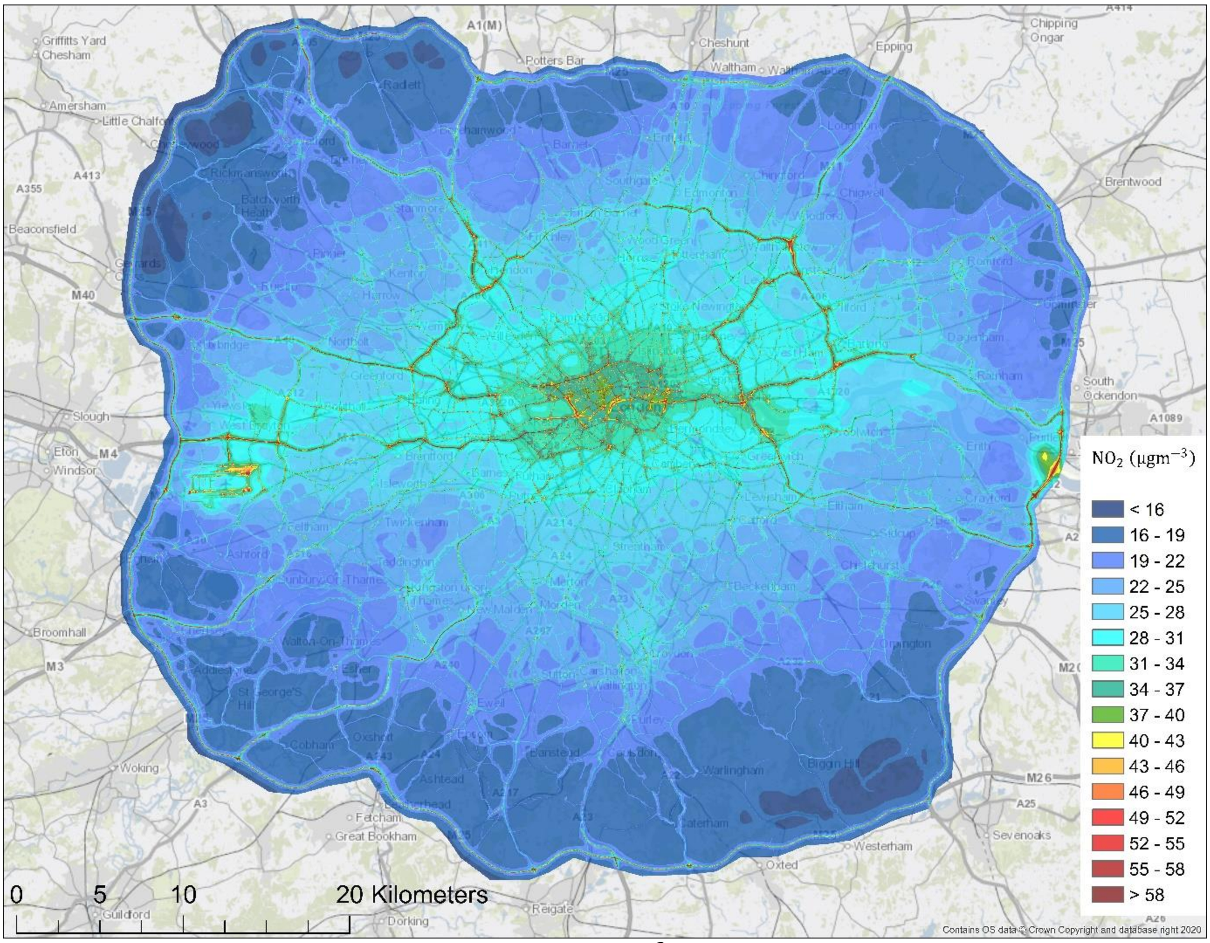

Figure 8-1: Map of annual average NO2 concentrations (µg/m^3) for 2019. The areas exceeding the WHO long term guideline of 40 µg/m^3 are shown in yellow.

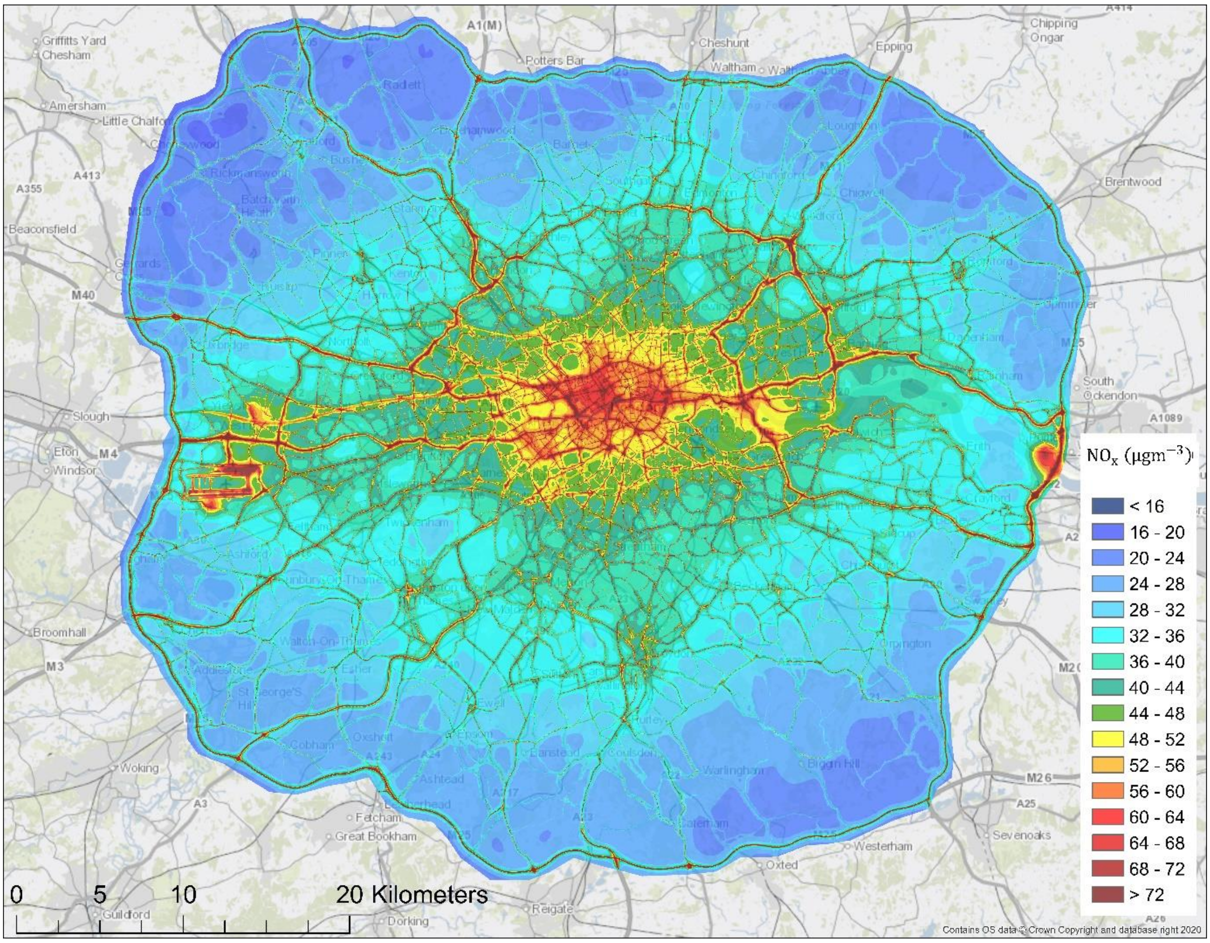

Figure 8-2: Map of annual average NOx concentrations (µg/m³) for 2019. There is no WHO guideline for NOX.

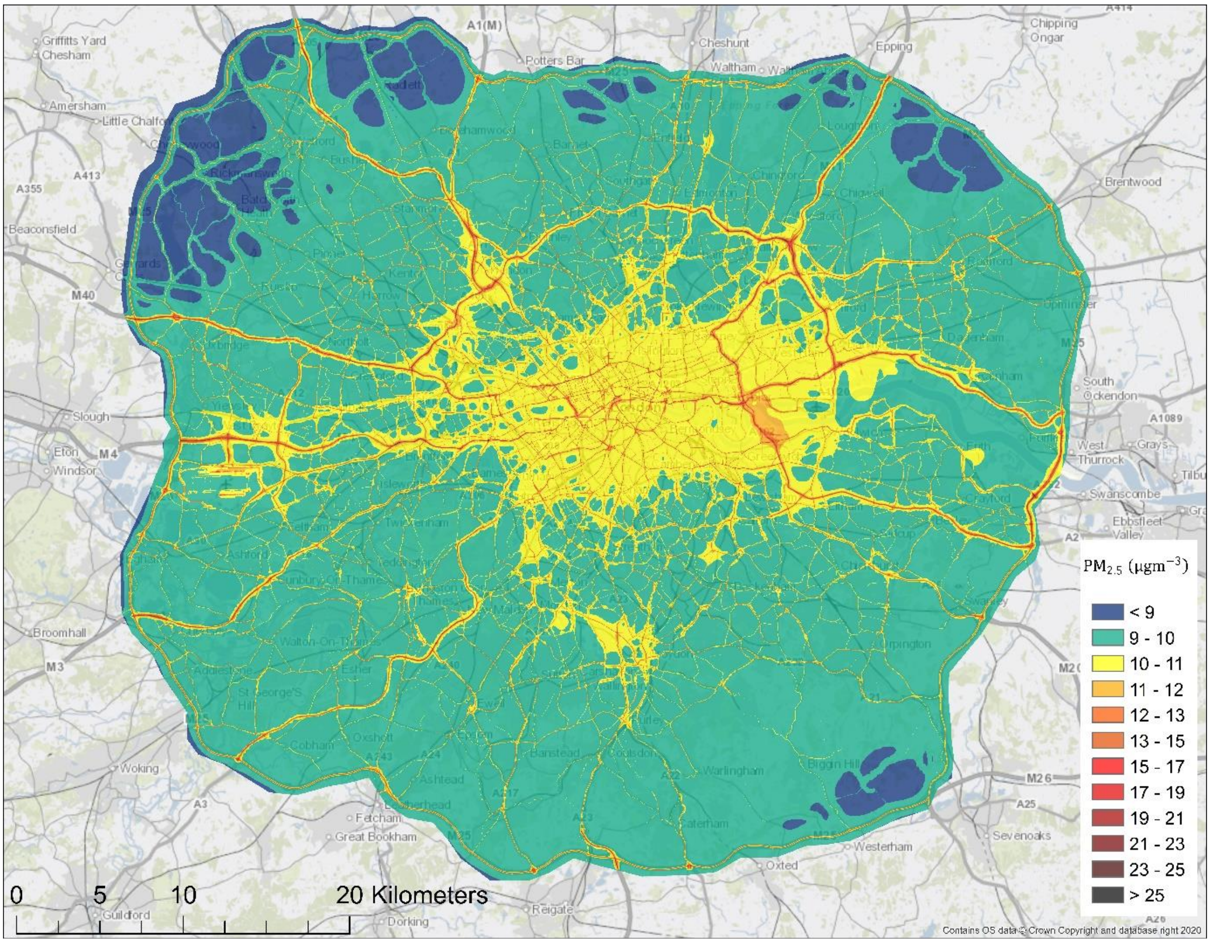

Figure 8-3: Map of annual average PM2.5 concentrations (µg/m³) for 2019. The areas exceeding the WHO long term guideline of 10µg/m³ are shown in yellow.

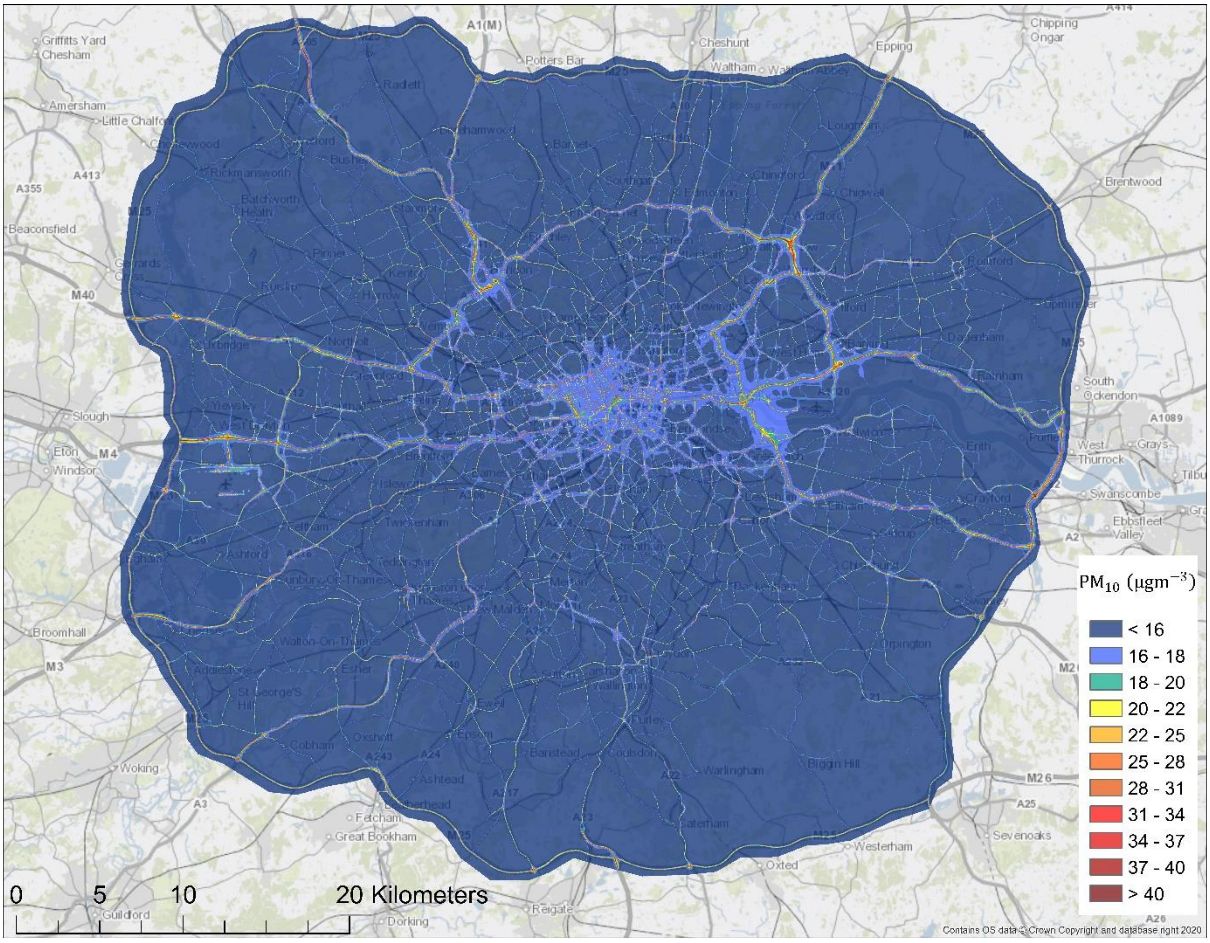

Figure 8-4: Map of annual average PM10 concentrations (µg/m³) for 2019. The areas exceeding the WHO long term guideline of 20 µg/m³ are shown in yellow.

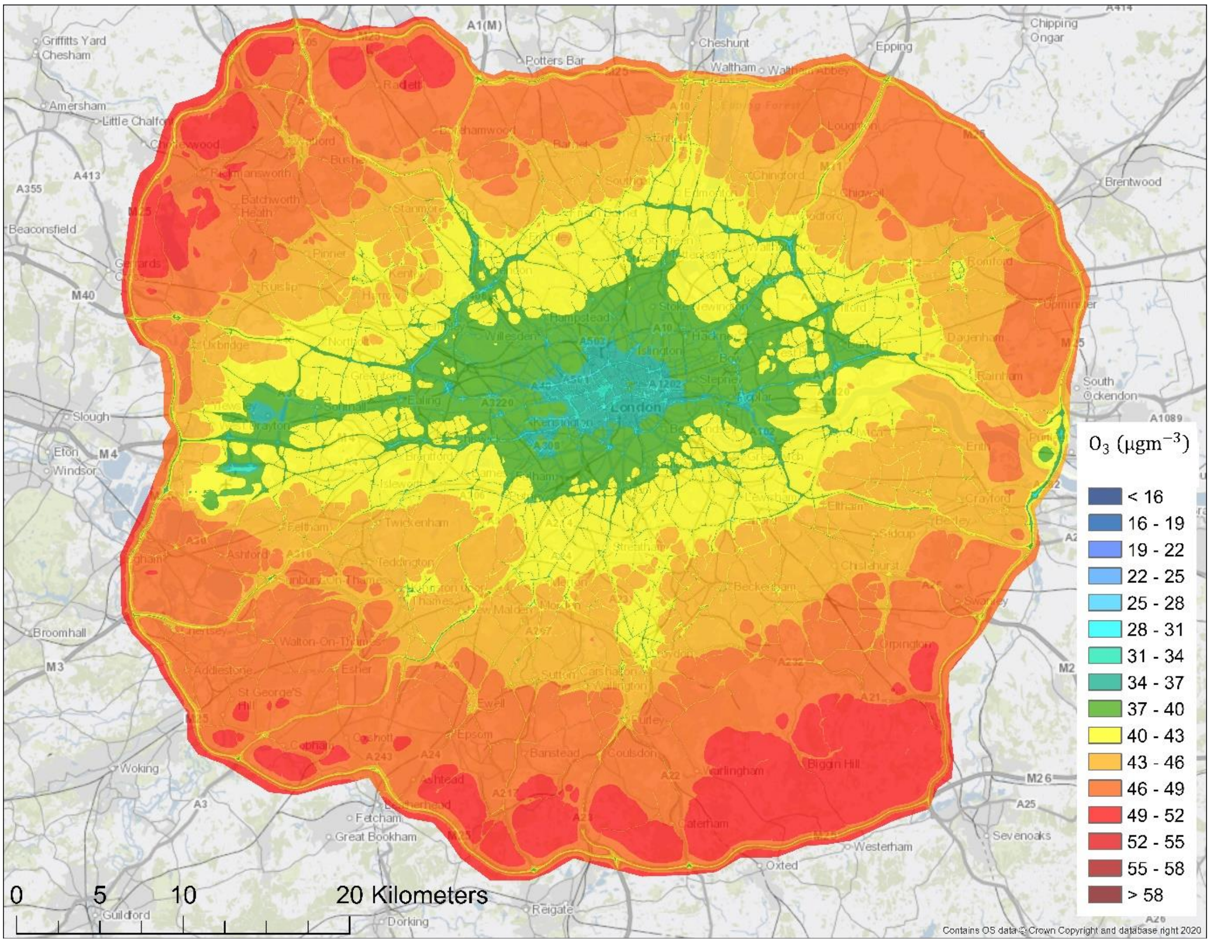

Figure 8-5: Map of annual average Ozone concentrations (µg/m³) for 2019. There is no long term WHO guideline for Ozone.

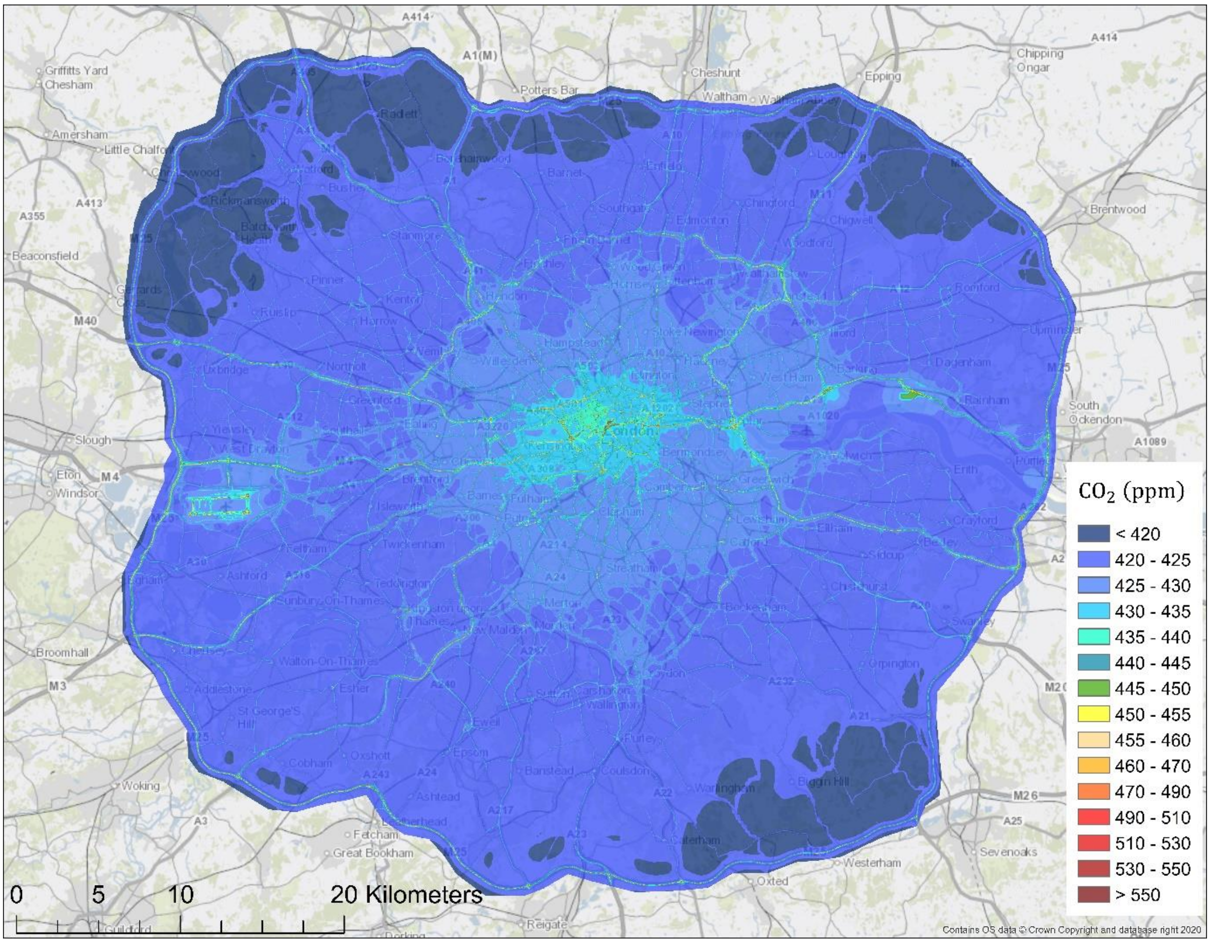

Figure 8-6: Map of annual average CO2 concentrations (ppm). There is no WHO long term guideline for CO2.

8.2 Source apportionment

This section describes the results from the Source Apportionment 2019 modelling scenario, that modelled NO_X and $PM_{2.5}$ at the monitoring locations and sensitive receptor sites for 2019. Traffic sources dominate the NO_X concentrations, as demonstrated in Figure 8-7, with the concentrations at all sites from traffic sources attributable to at least 36% of the total concentrations (for Care Homes inside the ULEZ), and reaching a maximum of 77% at Kerbside sites outside the ULEZ . Of the traffic sources, Diesel Cars, Diesel LGVs and TfL Buses are the highest contributors, as illustrated in Figure 8-8, and quantified in Table 8-2 for stations inside the ULEZ and Table 8-3 for those outside. Inside the ULEZ, the concentrations are higher across all site types, with a marked increase of 40 µg/m³ from Hospital sites outside the ULEZ compared to inside. The percentage of commercial and domestic fuel usage approximately doubles inside the ULEZ, which is largely dominated by gas combustion (Figure 8-9). The concentrations from other non-traffic sources are shown in Figure 8-10, which is largely dominated by Non-Road Mobile Machinery (NRMM) sources, or aircraft for the sites that are located near Heathrow (contributing 17% of the total and over half of the other non-traffic concentrations at these sites).

For $PM_{2.5}$, the concentrations are dominated by background pollution that originates outside London, as highlighted in Figure 8-11. The kerbside, roadside sites inside and outside the ULEZ, and Hospital sites within the ULEZ have the highest traffic components with 30% and 29%, for the sites that are nearby roads in the ULEZ, 31% and 25% for the sites located near the roads outside the ULEZ and 22% for the ULEZ Hospital sites. Figure 8-12 shows the traffic sources are almost entirely dominated by Brake, Tyre and Road wear. Table 8-4 and Table 8-5 shows the full breakdown of the $PM_{2.5}$ concentrations inside and outside the ULEZ respectively.

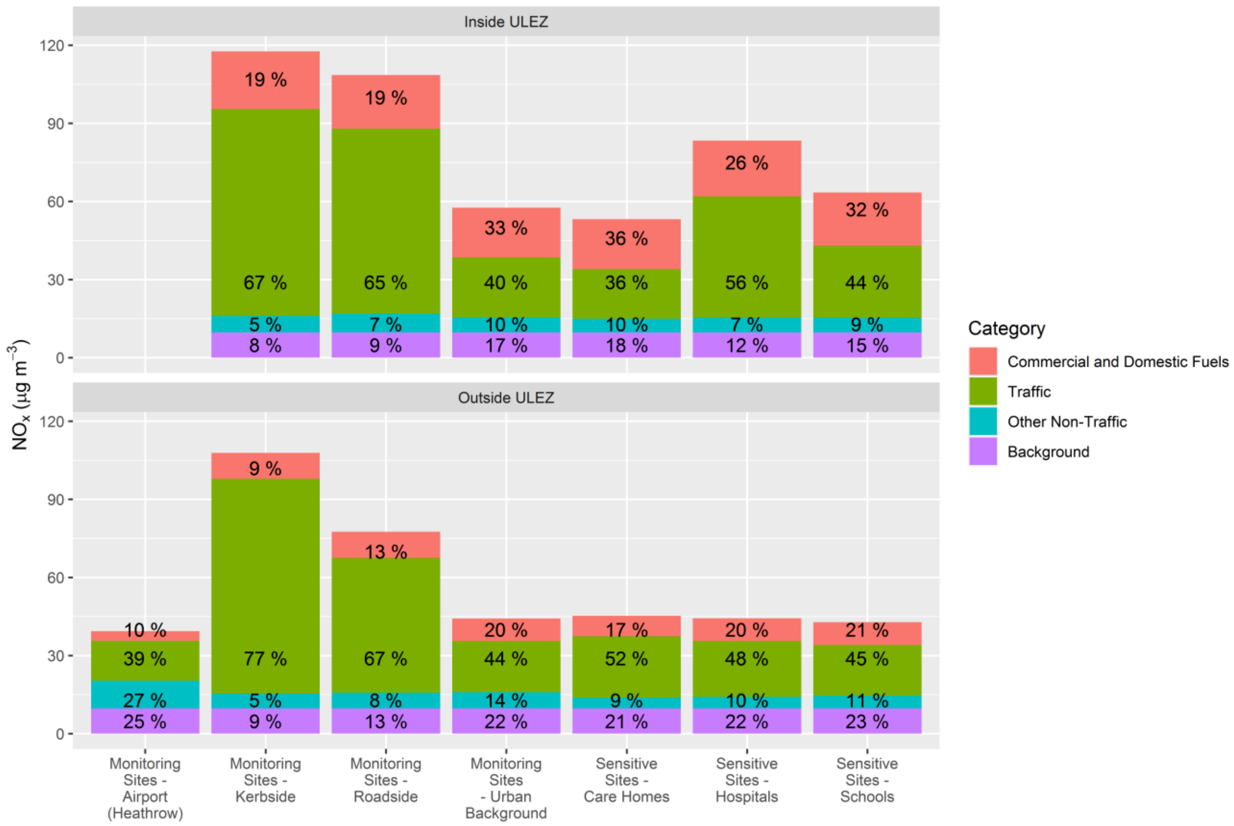

Figure 8-7: Bar Chart of annual average NO_X Concentrations (µg/m³) at static monitoring and sensitive receptor locations, grouped by site type and source category, and split by location. The percentage contribution from each source category is displayed in black.

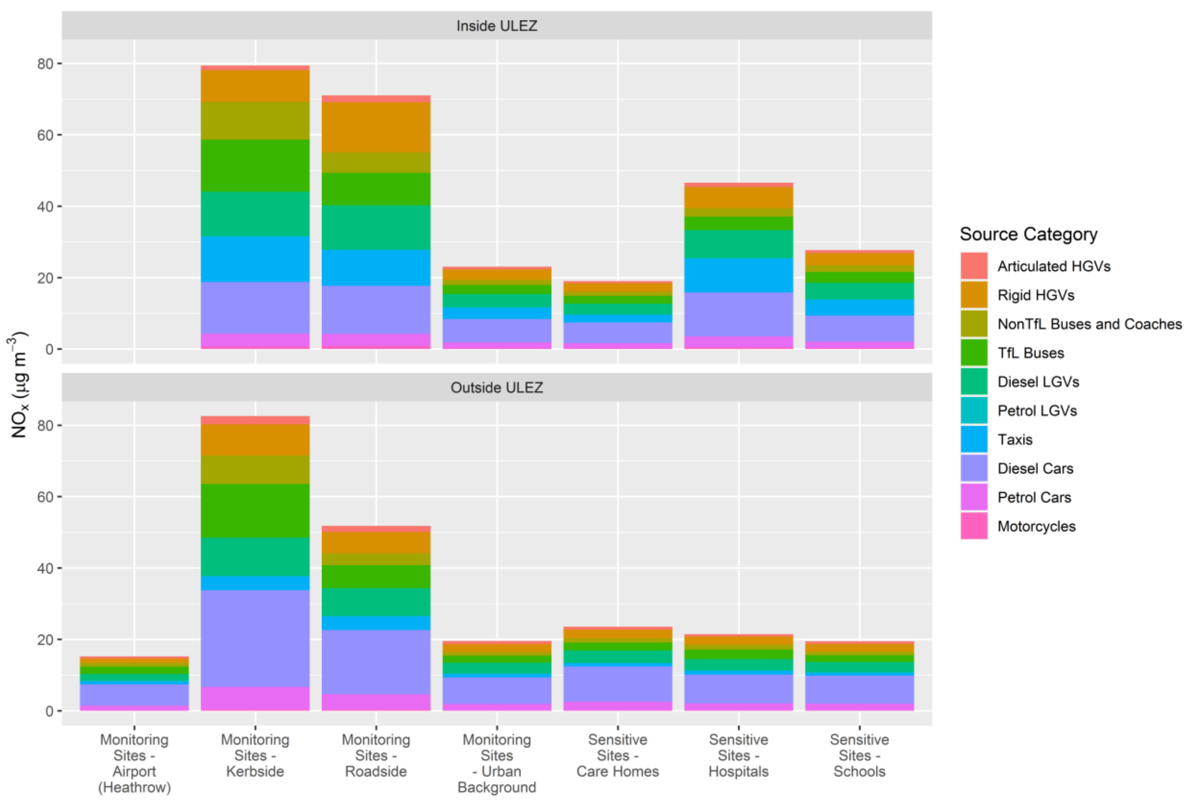

Figure 8-8: Bar chart of annual average NO_X concentrations (µg/m³) from traffic sources at static monitoring and sensitive receptor locations, grouped by site type and split by location

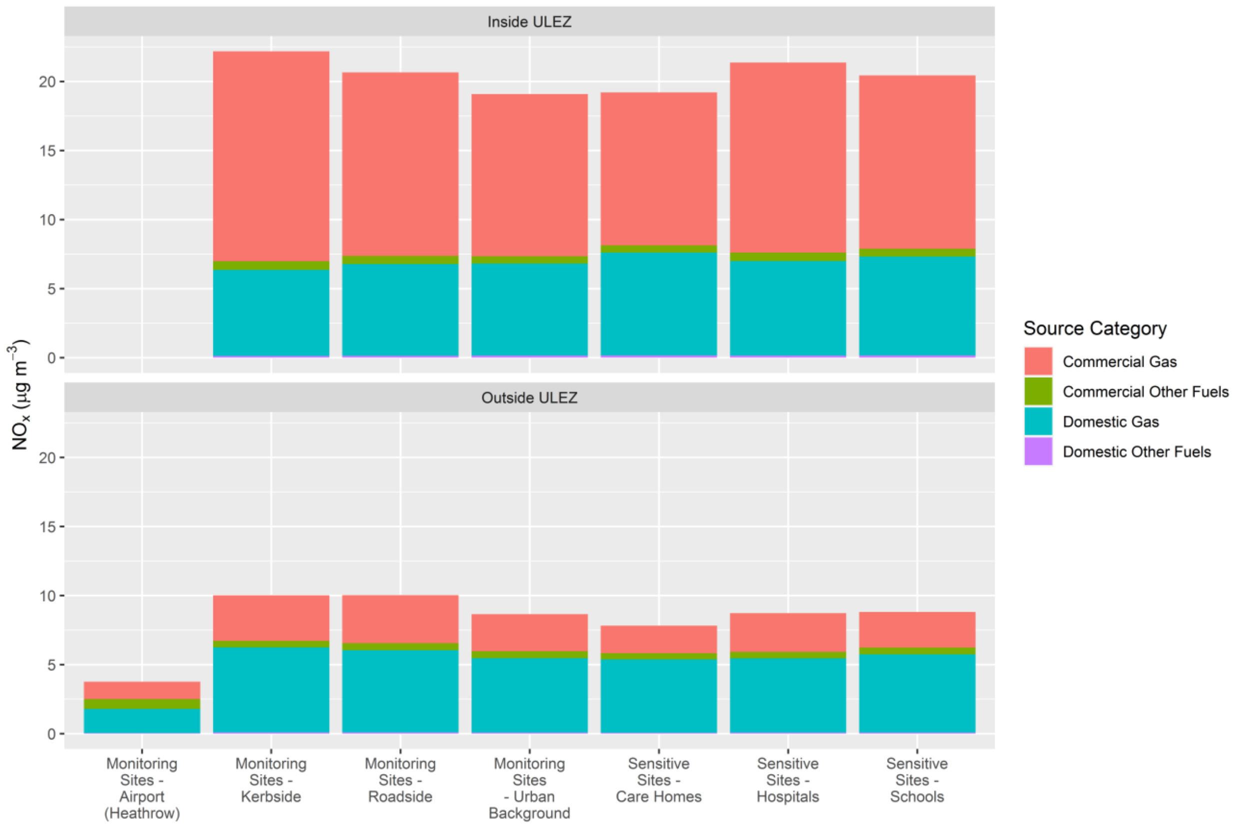

Figure 8-9: Bar Chart of annual average NO_X Concentrations (µg/m^3) from Commercial and Domestic Fuels at static monitoring sites and sensitive receptors ,grouped by site type and split by location

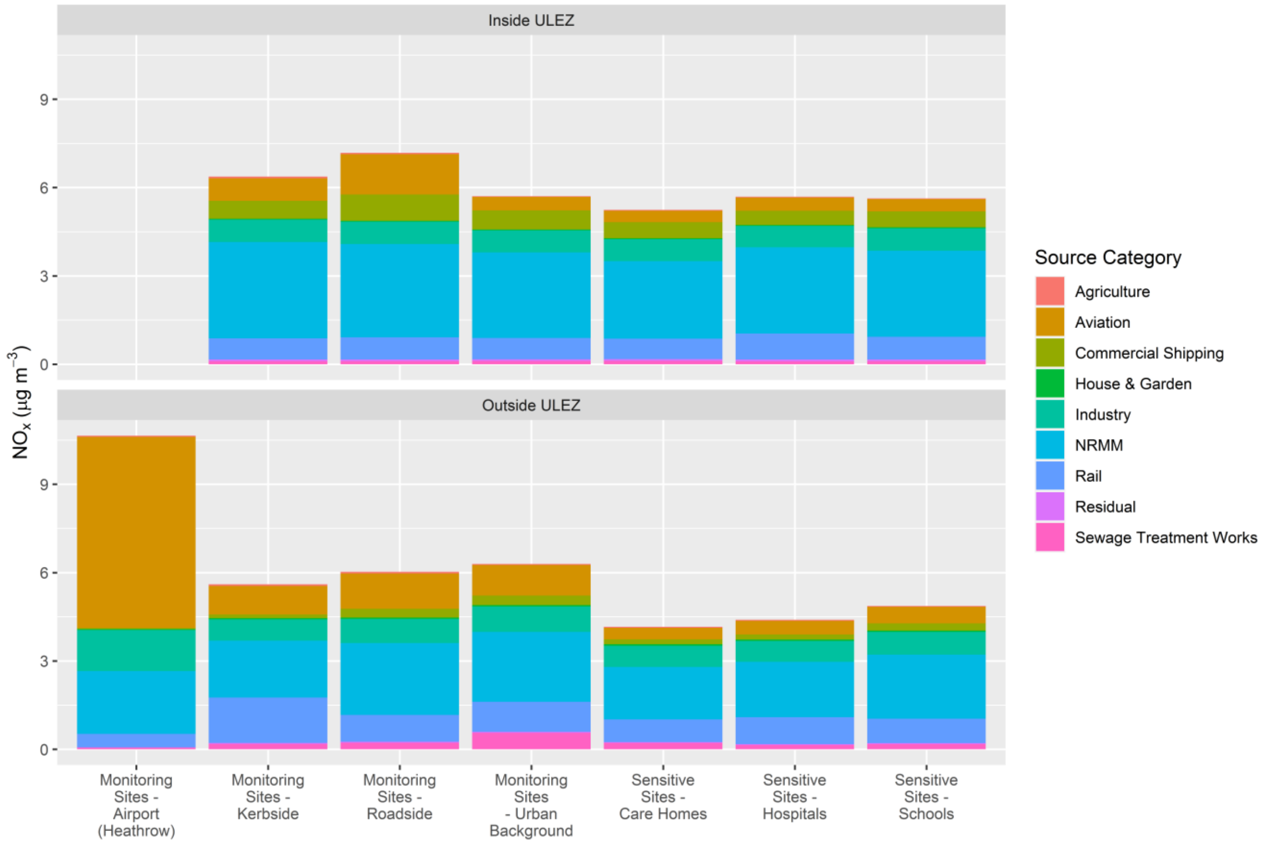

Figure 8-10: Bar chart of annual average NO_X concentrations (µg/m^3) from other non-traffic sources at static monitoring and sensitive receptor locations, grouped by site type and split by location

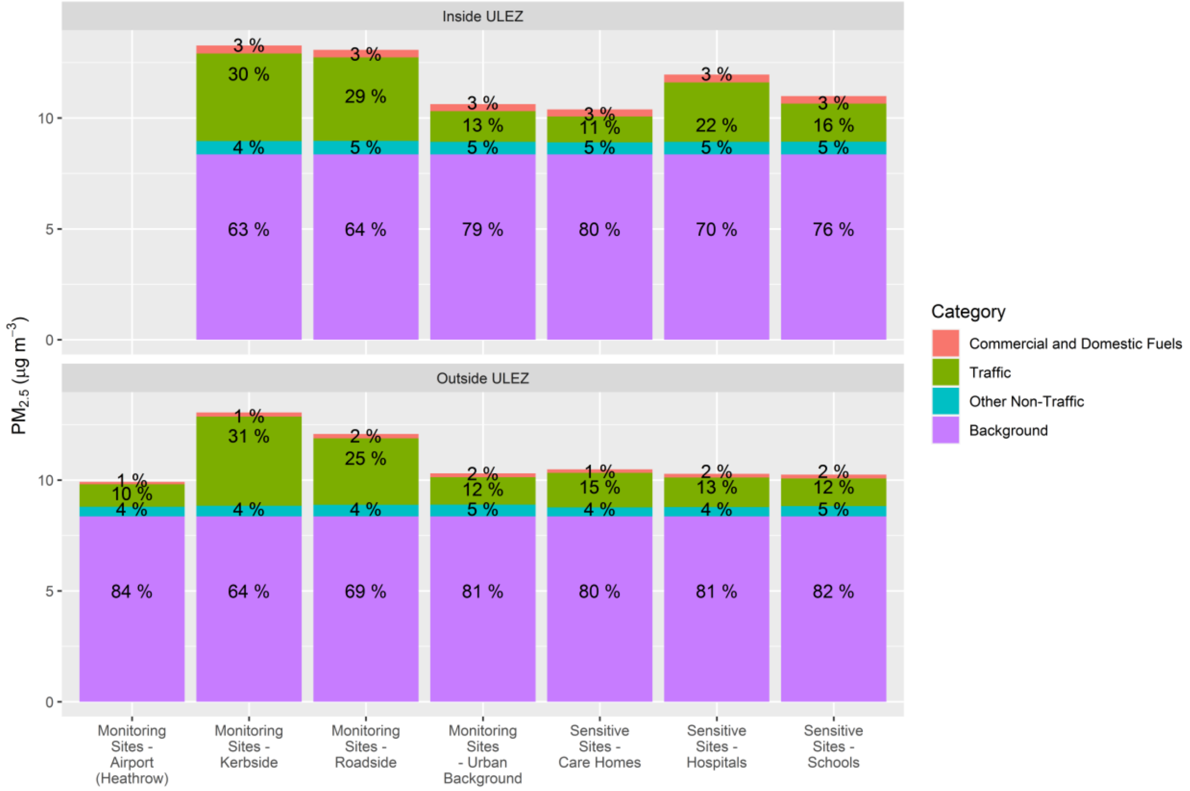

Figure 8-11: Bar chart of annual average PM2.5 concentrations (µg/m^3) at static monitoring and sensitive receptor locations, grouped by source category and site type and split by location. The percentage contribution from each source category is displayed in black.

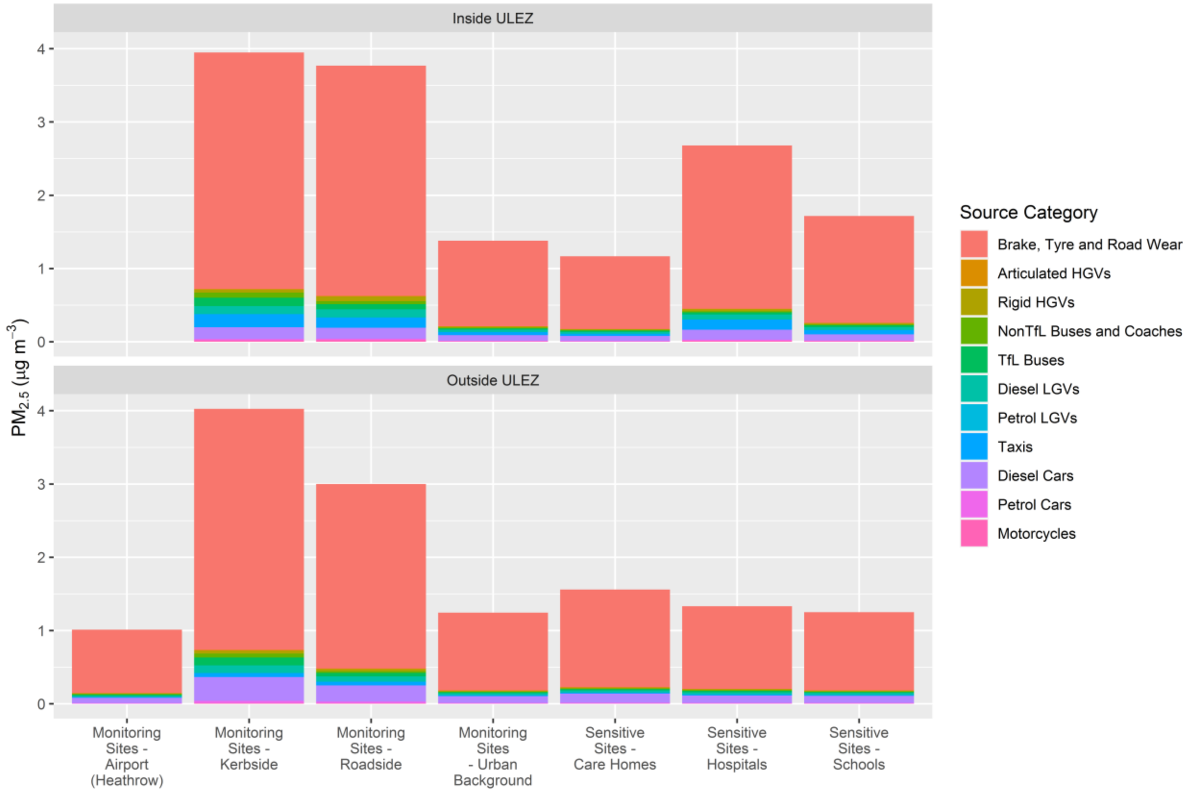

Figure 8-12: Bar chart of annual average PM2.5 concentrations (µg/m^3) from traffic sources at static monitoring and sensitive receptor locations, grouped by site type and split by location

Source category	Source sub-category	Kerbside	Roadside	Urban Background	Care Homes	Hospitals	Schools
Traffic	Motorcycles	0.6%	0.8%	0.3%	0.3%	0.6%	0.4%
	Petrol Cars	3.1%	3.1%	2.8%	2.7%	3.6%	2.9%
	Diesel Cars	12.4%	12.5%	11.5%	11.0%	14.8%	11.4%
	Taxis	10.8%	9.3%	5.7%	4.1%	11.4%	7.1%
	Petrol LGVs	0.1%	0.1%	0.1%	0.0%	0.1%	0.1%
	Diesel LGVs	10.6%	11.5%	6.5%	5.8%	9.4%	7.3%
	TfL Buses	12.4%	8.5%	4.4%	4.0%	4.5%	4.8%
	Non-TfL Buses and Coaches	9.1%	5.3%	2.5%	2.3%	2.8%	2.9%
	Rigid HGVs	7.6%	13.0%	5.1%	4.4%	7.1%	5.5%
	Articulated HGVs	1.1%	1.8%	1.3%	1.2%	1.5%	1.2%
Commercial and Domestic Fuel Usage	Commercial Gas	13.0%	12.3%	20.5%	20.8%	16.5%	19.8%
	Commercial Other Fuels	0.5%	0.6%	0.9%	1.0%	0.7%	0.9%
	Domestic Gas	5.3%	6.2%	11.6%	14.0%	8.2%	11.3%
	Domestic Other Fuels	0.1%	0.1%	0.2%	0.3%	0.2%	0.2%
Other Non-Traffic	Agriculture	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Aviation	0.3%	0.6%	0.4%	0.7%	0.5%	0.7%
	Commercial Shipping	0.5%	0.8%	1.1%	1.0%	0.6%	0.9%
	House & Garden	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%
	Industry	0.6%	0.7%	1.3%	1.4%	0.9%	1.2%
	NRMM	2.8%	2.9%	5.1%	5.0%	3.5%	4.6%
	Rail	0.6%	0.7%	1.3%	1.3%	1.1%	1.2%
	Sewage Treatment Works	0.1%	0.1%	0.2%	0.2%	0.1%	0.2%
	Residual	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Non-London	Background	8.3%	9.0%	16.9%	18.2%	11.6%	15.3%

Table 8-2 Table of percentage contribution for NO_X at each site type for each source category, for stations inside the ULEZ

Source category	Source sub-category	Airport (Heathrow)	Kerbside	Roadside	Urban Background	Care Homes	Hospitals	Schools
Traffic	Motorcycles	0.1%	0.3%	0.4%	0.2%	0.2%	0.2%	0.2%
	Petrol Cars	3.6%	5.9%	5.7%	4.2%	5.4%	4.4%	4.5%
	Diesel Cars	15.0%	25.2%	23.4%	17.0%	21.9%	18.2%	18.3%
	Taxis	2.5%	3.6%	5.0%	2.4%	2.0%	2.7%	2.0%
	Petrol LGVs	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
	Diesel LGVs	5.0%	10.1%	10.2%	7.0%	7.8%	7.1%	6.9%
	TfL Buses	5.2%	14.0%	8.4%	4.4%	4.9%	6.2%	4.4%
	Non-TfL Buses and Coaches	2.8%	7.4%	4.3%	2.3%	2.5%	3.1%	2.3%
	Rigid HGVs	3.0%	8.2%	7.8%	5.2%	5.4%	4.9%	5.0%
	Articulated HGVs	1.6%	2.2%	2.2%	2.1%	1.9%	1.6%	1.8%
Commercial and Domestic Fuel Usage	Commercial Gas	3.2%	3.1%	4.5%	6.1%	4.4%	6.3%	6.0%
	Commercial Other Fuels	1.8%	0.4%	0.7%	1.2%	1.0%	1.1%	1.1%
	Domestic Gas	4.5%	5.7%	7.7%	12.3%	11.7%	12.1%	13.2%
	Domestic Other Fuels	0.1%	0.1%	0.1%	0.2%	0.1%	0.2%	0.2%
Other Non-Traffic	Agriculture	0.1%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
	Aviation	16.5%	0.5%	0.8%	1.2%	0.9%	1.1%	1.3%
	Commercial Shipping	0.1%	0.1%	0.4%	0.7%	0.4%	0.4%	0.6%
	House & Garden	0.1%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%
	Industry	3.5%	0.7%	1.1%	2.0%	1.6%	1.6%	1.8%
	NRMM	5.4%	1.8%	3.2%	5.4%	3.9%	4.2%	5.1%
	Rail	1.2%	1.4%	1.2%	2.3%	1.7%	2.1%	1.9%
	Sewage Treatment Works	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%
	Residual	0.1%	0.2%	0.3%	1.3%	0.5%	0.3%	0.4%
Non-London	Background	24.6%	9.0%	12.6%	22.2%	21.4%	21.9%	22.6%

Table 8-3 of percentage contribution for NO_X at each site type for each source category, for stations outside the ULEZ

Source category	Source sub-category	Kerbside	Roadside	Urban Background	Care Homes	Hospitals	Schools
Traffic	Motorcycles	0.1%	0.2%	0.1%	0.0%	0.1%	0.1%
	Petrol Cars	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
	Diesel Cars	1.2%	1.1%	0.7%	0.7%	1.1%	0.8%
	Taxis	1.4%	1.1%	0.4%	0.3%	1.1%	0.5%
	Petrol LGVs	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Diesel LGVs	0.8%	0.8%	0.3%	0.3%	0.6%	0.4%
	TfL Buses	0.9%	0.5%	0.2%	0.2%	0.2%	0.2%
	NonTfL Buses and Coaches	0.5%	0.3%	0.1%	0.1%	0.1%	0.1%
	Rigid HGVs	0.3%	0.5%	0.1%	0.1%	0.2%	0.2%
	Articulated HGVs	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%
Traffic (Non Exhaust)	Brake Tyre and Road Wear	24.3%	24.0%	11.0%	9.6%	18.6%	13.3%
Commercial and Domestic Fuel Usage	Commercial Gas	1.7%	1.5%	1.7%	1.6%	1.7%	1.7%
	Commercial Other Fuels	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
	Domestic Gas	0.6%	0.7%	0.8%	0.9%	0.7%	0.8%
	Domestic Other Fuels	0.2%	0.2%	0.2%	0.3%	0.2%	0.2%
Other Non-Traffic	Agriculture	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Aviation	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Commercial Shipping	0.1%	0.2%	0.2%	0.1%	0.1%	0.1%
	House & Garden	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Industry	0.5%	0.5%	0.6%	0.6%	0.5%	0.6%
	NRMM	1.7%	1.7%	1.9%	1.8%	1.7%	1.9%
	Rail	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Dust	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
	Waste Transfer Services	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Residual	2.0%	2.0%	2.4%	2.4%	2.2%	2.4%
Non-London	Background	63.0%	64.0%	78.7%	80.5%	69.9%	76.1%

Table 8-4 Table of percentage contribution for $PM_{2.5}$ at each site type for each source category, for stations inside the ULEZ

Source category	Source sub-category	Airport (Heathrow)	Kerbside	Roadside	Urban Background	Care Homes	Hospitals	Schools
Traffic	Motorcycles	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
	Petrol Cars	0.1%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%
	Diesel Cars	0.7%	2.5%	1.8%	0.9%	1.2%	1.0%	0.9%
	Taxis	0.1%	0.4%	0.4%	0.1%	0.1%	0.2%	0.1%
	Petrol LGVs	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Diesel LGVs	0.2%	0.8%	0.6%	0.3%	0.3%	0.3%	0.3%
	TfL Buses	0.2%	0.8%	0.4%	0.1%	0.2%	0.2%	0.1%
	NonTfL Buses and Coaches	0.1%	0.4%	0.2%	0.1%	0.1%	0.1%	0.1%
	Rigid HGVs	0.1%	0.3%	0.2%	0.1%	0.1%	0.1%	0.1%
	Articulated HGVs	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%
Traffic (Non Exhaust)	Brake Tyre and Road Wear	8.7%	25.2%	20.9%	10.3%	12.7%	11.0%	10.4%
Commercial and Domestic Fuel Usage	Commercial Gas	0.2%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%
	Commercial Other Fuels	0.6%	0.3%	0.3%	0.4%	0.4%	0.4%	0.4%
	Domestic Gas	0.2%	0.6%	0.6%	0.7%	0.6%	0.7%	0.7%
	Domestic Other Fuels	0.1%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
Other Non-Traffic	Agriculture	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Aviation	1.3%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%
	Commercial Shipping	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%
	House & Garden	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Industry	0.6%	0.8%	1.0%	1.3%	0.8%	0.8%	0.9%
	NRMM	1.4%	1.0%	1.4%	1.6%	1.2%	1.3%	1.5%
	Rail	0.0%	0.2%	0.0%	0.1%	0.1%	0.1%	0.1%
	Dust	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%
	Waste Transfer Services	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Residual	0.9%	1.4%	1.6%	1.7%	1.6%	1.7%	1.8%
Non-London	Background	84.3%	64.1%	69.3%	81.2%	79.8%	81.3%	81.6%

Table 8-5 Table of percentage contribution for $PM_{2.5}$ at each site type for each source category, for stations outside the ULEZ

8.3 Policy Scenarios

Using the results from Section 8.2 it was possible to estimate the impacts that three policy scenarios would have on annual average NO_X, NO_2 and $PM_{2.5}$ concentrations at monitoring sites and sensitive locations. These policy scenarios assessed the impact of zero emission TfL buses, zero emission London taxis and zero emissions for both. To estimate NO_2 from NO_X, a station-specific annual average f-NO2[17] value has been derived from the ratio between the modelled annual average NO_X and NO_2 concentrations in Section 8.1. An annual average background of 7.45 µg/m³ is included in the NO_2 concentrations. Using source apportionment data in this way to calculate adjusted total NO_X and then applying f-NO2 to estimate NO_2 provides a screening estimate of NO_2 concentrations, but for a more robust study, the adjusted total emissions should be modelled including the effects of chemistry, as in Section 6 and Section 8.1.

Table 8-6 and Table 8-7 show the changes in annual average concentrations due to the policy scenarios, for receptors inside and outside the ULEZ respectively. These are calculated over all modelled hours, so cannot be compared directly with the results in Section 6.1, where modelled hours were only included if valid measurements were available. The largest reductions are at kerbside sites within the ULEZ when both TfL Buses and Taxis have zero exhaust emissions, and there is a reduction of 27.3 µg/m³ (23%) in NO_X concentrations, and a reduction of 9.1 µg/m³ (18%) in NO_2. Both policy measures contribute similar amounts to the overall reduction. Annual average NO_X concentrations are reduced by 14.5 µg/m³ (12%) at kerbside sites in the first scenario (zero emission TfL buses) compared to a reduction of 12.7 µg/m³ (11%) under the second policy scenario (zero emission taxis). There is minimal (<1 µg/m³) reduction in $PM_{2.5}$ annual average concentrations as a result of the policy scenarios. This is because the non-exhaust component will not significantly reduce under zero-emission technology and cleaner vehicles.

[17] f-NO2 = fraction of NO_X that is NO_2

Scenario	Site Type	NOX	% reduction	NO2	% reduction	PM2.5	% reduction
Total	Monitoring Sites - Kerbside	117.22	-	50.24	-	13.26	-
	Monitoring Sites - Roadside	107.84	-	50.33	-	13.07	-
	Monitoring Sites - Urban Background	57.33	-	34.50	-	10.62	-
	Sensitive Sites - Care Home	53.17	-	33.37	-	10.39	-
	Sensitive Sites - Hospital	83.32	-	46.11	-	11.96	-
	Sensitive Sites - School	63.44	-	37.65	-	10.99	-
Zero emission TfL Buses	Monitoring Sites - Kerbside	102.68	12%	46.21	8%	13.15	1%
	Monitoring Sites - Roadside	98.71	8%	46.51	8%	13.00	1%
	Monitoring Sites - Urban Background	54.80	4%	33.06	4%	10.60	0%
	Sensitive Sites - Care Home	51.04	4%	32.08	4%	10.37	0%
	Sensitive Sites - Hospital	79.54	5%	44.15	4%	11.93	0%
	Sensitive Sites - School	60.39	5%	35.99	4%	10.96	0%
Zero emission Taxis	Monitoring Sites - Kerbside	104.51	11%	45.16	10%	13.08	1%
	Monitoring Sites - Roadside	97.82	9%	46.11	8%	12.93	1%
	Monitoring Sites - Urban Background	54.08	6%	32.64	5%	10.58	0%
	Sensitive Sites - Care Home	50.99	4%	32.05	4%	10.36	0%
	Sensitive Sites - Hospital	73.80	11%	41.39	10%	11.82	1%
	Sensitive Sites - School	58.94	7%	35.23	6%	10.93	1%
Zero emission TfL Buses and zero emission Taxis	Monitoring Sites - Kerbside	89.96	23%	41.13	18%	13.15	1%
	Monitoring Sites - Roadside	88.68	18%	42.29	16%	13.00	1%
	Monitoring Sites - Urban Background	51.54	10%	31.20	10%	10.60	0%
	Sensitive Sites - Care Home	48.86	8%	30.77	8%	10.37	0%
	Sensitive Sites - Hospital	70.01	16%	39.43	15%	11.93	0%
	Sensitive Sites - School	55.89	12%	33.56	11%	10.96	0%

Table 8-6 Table of NO_X, NO_2, $PM_{2.5}$ annual average concentrations (µg/m³) and the corresponding % reduction under 3 policy scenarios, for stations inside the ULEZ

Scenario	Site Type	NOX	% reduction	NO2	% reduction	PM2.5	% reduction
Total	Monitoring Sites – Airport (Heathrow)	39.36	-	26.68	-	9.99	-
	Monitoring Sites - Kerbside	107.35	-	47.13	-	13.00	-
	Monitoring Sites - Roadside	76.92	-	38.96	-	12.02	-
	Monitoring Sites - Urban Background	43.71	-	27.97	-	10.22	-
	Sensitive Sites - Care Home	45.26	-	27.93	-	10.48	-
	Sensitive Sites - Hospital	44.27	-	27.73	-	10.26	-
	Sensitive Sites - School	42.83	-	27.34	-	10.24	-
Zero emission TfL Buses	Monitoring Sites - Airport (Heathrow)	37.30	5%	25.56	4%	9.97	0%
	Monitoring Sites - Kerbside	92.33	14%	41.23	13%	12.89	1%
	Monitoring Sites - Roadside	70.46	8%	35.97	8%	11.98	0%
	Monitoring Sites - Urban Background	41.76	4%	26.87	4%	10.20	0%
	Sensitive Sites - Care Home	43.04	5%	26.69	4%	10.46	0%
	Sensitive Sites - Hospital	41.54	6%	26.29	5%	10.24	0%
	Sensitive Sites - School	40.94	4%	26.23	4%	10.23	0%
Zero emission Taxis	Monitoring Sites - Airport (Heathrow)	38.38	2%	26.17	2%	9.98	0%
	Monitoring Sites - Kerbside	103.44	4%	45.69	3%	12.94	0%
	Monitoring Sites - Roadside	73.10	5%	37.46	4%	11.97	0%
	Monitoring Sites - Urban Background	42.67	2%	27.37	2%	10.20	0%
	Sensitive Sites - Care Home	44.35	2%	27.42	2%	10.47	0%
	Sensitive Sites - Hospital	43.09	3%	27.08	2%	10.24	0%
	Sensitive Sites - School	41.97	2%	26.83	2%	10.23	0%
Zero emission TfL Buses and zero emission Taxis	Monitoring Sites - Airport (Heathrow)	36.32	8%	25.06	6%	9.97	0%
	Monitoring Sites - Kerbside	88.42	18%	39.79	16%	12.89	1%
	Monitoring Sites - Roadside	66.64	13%	34.47	12%	11.98	0%
	Monitoring Sites - Urban Background	40.72	7%	26.27	6%	10.20	0%
	Sensitive Sites - Care Home	42.14	7%	26.18	6%	10.46	0%
	Sensitive Sites - Hospital	40.36	9%	25.64	8%	10.24	0%
	Sensitive Sites - School	40.09	6%	25.72	6%	10.23	0%

Table 8-7 Table of NO_X, NO_2, $PM_{2.5}$ annual average concentrations (µg/m³) and the corresponding % reduction under 3 policy scenarios, for stations outside the ULEZ

9. Summary and discussion

This report presents the modelling and analysis work done by CERC during the second year of the Breathe London project, building on the achievements of the first year of the project. This year the modelling has been updated from 2018 emissions to 2019 emissions, and then further updated to incorporate the findings of the 'Hotspot analysis' (Appendix 9). The resulting annual average maps present the authors' best estimate of NO_2, NO_X, PM_{10}, $PM_{2.5}$, Ozone and CO_2 concentration at 10m resolution across Greater London and out to the M25 Motorway.

The model validation using 107 LAQN sites, 43 AQE sites and 144 AQMesh sites shows good agreement for all pollutants. The 7-day factors introduced in the Hotspot2019 scenario improved the correlation between modelled and measured concentrations for all pollutants; the application of adjustments to non-exhaust PM emissions in the Hotspot2019 scenario helped to obtain better agreement for PM_{10} and $PM_{2.5}$. For NO_2, correlation between modelled and measured values is lower at AQMesh sites than at reference sites, but this is likely to be due to ozone interference causing some AQMesh measurements to be too high; the final version of the AQMesh measured dataset (not used in this work) includes a correction to account for this behaviour.

Innovative inversion techniques have been developed during the course of this project to assimilate measurements with modelled data to improve model predictions; these have been applied to assess the impact of the ULEZ on road traffic emissions (this report), and also to estimate the impact of COVID-19 restrictions on road traffic emissions (Appendix 8A). This is an exciting area of research that is likely to be highly valuable in future, particularly in a post-COVID world of changing traffic patterns.

Source apportionment analysis has been carried out for 23 categories for NO_X and 25 categories for $PM_{2.5}$, including 10 traffic exhaust categories, traffic non-exhaust emissions, 4 fuel usage categories and 11 other non-traffic categories. Traffic sources dominate the NO_X concentrations, with the concentrations at all sites from traffic sources attributable to at least 36% of the total concentrations and reaching a maximum of 77% at Kerbside monitoring sites outside the ULEZ. Of the traffic sources, Diesel Cars, Diesel LGVs and TfL Buses are the highest contributors. Inside the ULEZ, NO_X concentrations are higher across all site types, with a marked increase of 40 $\mu g/m^3$ from Hospital sites outside the ULEZ compared to inside. The percentage contribution of commercial and domestic fuel usage approximately doubles inside the ULEZ, which is largely dominated by gas combustion.

Three policy scenarios have been assessed to estimate the impact on NO_X, NO_2 and $PM_{2.5}$ of: (a) replacing all TfL buses with zero emission buses; (b) making all taxis zero emission taxis; and (c) implementing (a) and (b) at the same time. The largest NO_X reductions are at kerbside sites within the ULEZ when both TfL Buses and Taxis have zero exhaust emissions, with a reduction of 27.3 $\mu g/m^3$ (23%) in NO_X concentrations, and a reduction of 9.1 $\mu g/m^3$ (18%) in NO_2. A larger proportion of the reduction is attributable to the zero emission TfL Buses. There is minimal (<1 $\mu g/m^3$) reduction in $PM_{2.5}$ annual average concentrations, which is because the policy action only targets exhaust emissions, and the bulk of road traffic $PM_{2.5}$ emissions are associated with the non-exhaust component of emissions.