AIR QUALITY ASSESSMENT

Modelling changes to NOx emissions from NRMM in London

Report for: JCB Power Systems Ltd

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EXECUTIVE SUMMARY

JCB are currently developing hydrogen powered non road mobile machinery (NRMM). When compared to equivalent diesel powered plant, these machines have practically net-zero carbon emissions, and would also reduce the local air quality impact of the NRMM sector to negligible levels, if deployed across the fleet.

This report describes an air quality assessment case study to quantify the potential impact of a technology transition to hydrogen powered NRMM. The case study is in an example urban area, Greater London.

The report describes:

- A review of current methods used to quantify NRMM emission in the UK (NAEI) and London (LAEI) emission inventories; and based on the review, a derived method to model the impact of technology changes on emissions from the NRMM fleet.
- Spatially gridded air pollution dispersion simulations for Greater London that compare a series of emission change scenarios against baseline conditions in 2019, specifically for oxides of nitrogen (NOx) expressed as annual mean NO_2 concentrations when dispersed. The emission scenarios tested can be summarised as:
    - Scenario/Test Case 1: 2019 baseline
    - Scenario/Test Case 2: 2019 All NRMM and road traffic comply with the best available NOx emission standards
    - Scenario/Test Case 3: 2019 The impact of hydrogen powered (H2ICE) NRMM is assessed "relative to a hypothetical scenario where no traditionally powered NRMM or ICE powered road traffic are operational within London, whereby:
        - All NRMM with power rating <=19kW is zero emitting
        - All NRMM with power rating >19kW will be hydrogen powered and operate at a NOx emission rate of 0.02 g/kWh.

The outcomes of the air quality modelling assessment can be summarised as follows:

2019 baseline:

- Maximum NOx annual mean concentrations attributable to both Construction and Industry NRMM source sectors are in the central area of London. This reflects the spatial distribution of NRMM activity and associated NOx emissions reported in the 2019 London Atmospheric Emissions Inventory (LAEI2019).
- The maximum modelled contribution to annual mean NOx in 2019 for:
    - Construction NRMM is ~5 $\mu g.m^{-3}$
    - Industrial NRMM is ~1.4 $\mu g.m^{-3}$
    - Construction NRMM + Industrial NRMM is ~5.8 $\mu g.m^{-3}$
- Source apportionment analysis at three locations in Central London; confirms that NRMM contributes a very small proportion of overall NOx when compared with the contribution from road traffic and other source sectors/background in the 2019 baseline scenario.

Test case scenarios results

Intuitively it is clear that we expect to see beneficial impacts i.e. reduction in NOx and NO_2 annual mean for all emission reduction scenarios when compared with the 2019 baseline.

Scenario/Test Case 2: When all NRMM and road traffic are modelled using the best available NOx emission standards:

- Road NOx is reduced by approximately 2/3rd at the locations where source apportionment analysis has been conducted.
- NRMM NOx is reduced by approximately 1/3rd when all plant has Stage V emissions rates applied, calculated using the EMEP Tier 3 methodology.

Scenario/Test Case 3

In Scenario/Test Case 3, the impact of H2ICE NRMM was assessed relative to a hypothetical scenario where no NRMM or ICE road traffic Is operational within London.

The modelled impact of H2ICE NRMM on annual mean NOx concentrations is very small, almost imperceptible. The maximum impact we see is 0.019 µg.m^{-3}. When rounding predicted concentrations to one decimal place as presented in our mapped outputs, the impact of the H2ICE NRMM is rounded out and therefore becomes imperceptible. Assessing this impact using the current UK best practice guidance for assessing air quality impacts for planning purposes; concludes that any impact of less than 0.5% of the air quality objective being assessed is classified as negligible. When assessing NO_2 impacts using this method 0.5% of the 40 µg.m^{-3} objective equals 0.2 µg.m^{-3}; any predicted change less than 0.2 µg.m^{-3} is therefore classified as negligible.

This conclusion could also be considered as robust to significant input variance of the NOx emissions from H2ICE; If H2ICE emissions were doubled, then the impact on annual mean NO_2, at the worst case locations assessed, would still be lower than that required for a “negligible” classification, against either the 40 µg.m^{-3} UK objective, or the more stringent 10 µg.m^{-3} WHO guidance (0.5% of 10 µg.m^{-3} = 0.05 µg.m^{-3}).

The limit of detection for automatic analysers in use in the UK air quality measurement networks range from 0.2 to 1.2 ppb (~0.4 µg.m^{-3} to 2.3 µg.m^{-3}); any change in concentration less than that could therefore be considered beyond the limit of detection using current reference measurement methods.

1. INTRODUCTION

JCB are currently developing hydrogen powered non road mobile machinery (NRMM) which, when compared with equivalent diesel-powered plant, is expected to reduce emissions to air of greenhouse gases and other key atmospheric pollutants.

Ricardo Energy & Environment have been commissioned to quantify the potential impact of this technology transition on ambient air quality in an example urban area, in this case study, the Greater London area.

The main objectives of the project are:

1. Review and understand current methods used to quantify NRMM emissions in the UK and London.
2. The delivery of spatially gridded air pollution dispersion simulations for Greater London that compare a series of emission change scenarios against baseline conditions in 2019. The assessment will consider emissions of oxides of nitrogen (NOx) expressed as annual mean NO_2 concentrations when dispersed.
3. Assess the potential air quality impact of hydrogen powered NRMM on NO_2 concentrations.

1.1 POLICY BACKGROUND AND ASSESSMENT CRITERIA

1.1.1 UK Air Quality Strategy and Objectives

The atmospheric pollutants being assessed in this study are NO_2 and NO_x. Local Authorities are required under the Environment Act 1995 to assess air quality in their areas on an annual basis against air quality objectives set out in the regulations; these pollutants are normally included in such assessments. The current UK air quality objectives for NOx and NO_2 are presented in Table 1-1 which includes the standards in micrograms per cubic metre ($\mu g.m^{-3}$) with the number of short-term exceedances that are permitted where applicable.

Table 1-1: Objectives included in the Air Quality Regulations and subsequent Amendments, for the purpose of Local Air Quality Management

Pollutant	Concentration	Measured as
Nitrogen dioxide for protection of human health	200 $\mu g.m^{-3}$ not to be exceeded more than 18 times a year	1-hour mean
	40 $\mu g.m^{-3}$	annual mean
Long term critical level for Oxides of Nitrogen (NOx) for the protection of vegetation	30 $\mu g.m^{-3}$	annual mean
Short term critical level Oxides of Nitrogen (NOx) for the protection of vegetation	75 $\mu g.m^{-3}$	24hr daily mean

1.1.2 Sensitive locations for protection of human health

The locations where objectives apply are defined in the UK Air Quality Strategy (AQS) as locations outside buildings or other natural or man-made structures above or below ground where members of the public are regularly present and might reasonably be expected to be exposed over the relevant averaging period of the objectives. Typically, these include residential properties, hospitals, and schools for the longer averaging periods (i.e., annual mean) pollutant objectives and the above locations recreational facilities, shopping areas, etc., for short-term (i.e. 1-hour) pollutant objectives. Table 1-2 lists examples of where the AQS objectives should and should not apply.

Table 1-2: Objectives Examples of where the Air Quality Objectives should and should not apply

Averaging Period	Pollutants	Objectives *should* apply at …	Objectives should *not* generally apply at …
Annual mean	NO_2	All locations where members of the public might be regularly exposed. Building façades of residential properties, schools, hospitals, care homes etc.	Building facades of offices or other places of work where members of the public do not have regular access. Hotels, unless people live there as their permanent residence. Gardens of residential properties. Kerbside sites (as opposed to locations at the building façade), or any other location where public exposure is expected to be short term
1-hour mean	NO_2	All locations where the annual mean objective is applied. Kerbside sites (e.g., pavements of busy shopping streets). Those parts of car parks and railway stations etc. which are not fully enclosed. Any outdoor locations to which the public might reasonably be expected to have access.	Kerbside sites where the public would not be expected to have regular access.

1.1.3 World Health Organisation (WHO) recommended air quality guideline levels and interim targets

The World Health Organisation (WHO) periodically issues health-based air quality guidelines to assist governments and civil society to reduce human exposure to air pollution and its adverse effects. The overall objective of the WHO guidelines is to offer quantitative health-based recommendations for air quality management, expressed as long, or short-term concentrations for several key air pollutants. Exceedance of the air quality guideline (AQG) levels is associated with important risks to public health. These guidelines are not legally binding standards; however, they do provide WHO Member States with an evidence-informed tool that they can use to inform legislation and policy[1].

The latest WHO recommended AQG levels and interim targets for NO_2 are duplicated in Table 1-3. Interim targets are included to guide reduction efforts towards the ultimate achievement of the AQG levels in countries that substantially exceed these levels. Although these air quality guidelines and interim targets have not been adopted by the UK government yet; they do provide relevant context regarding the latest available evidence and recommendations from the WHO.

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[1] World Health Organisation (2021) WHO global air quality guidelines; available to download at: https://www.who.int/publications-detail-redirect/9789240034228

Table 1-3: Current WHO recommended AQG levels and interim targets for NO_2

Pollutant	**Averaging time**	**Interim target**				**AQG level**
		1	2	3	4	
NO_2 µg.m^{-3}	Annual mean	40	30	20	-	10
	24-hour mean	120	50	-	-	25

1.1.4 Description of Air Quality Impacts using IAQM/EPUK Planning for air quality guidance

Qualitative impact descriptors are required to assist with determining the significance of the results of the air quality assessment. The approach to determining impact descriptors developed by the IAQM, which has been incorporated into the latest IAQM and Environmental Protection UK (EPUK) guidance document on planning and air quality[2] has been used for this assessment.

In summary, the approach involves quantifying the magnitude of change in annual mean NO_2 concentrations attributable to the proposed development; then expressing the magnitude of incremental change as a proportion of each respective air quality standard. In the context of this project, we can interpret the “development” as the introduction of the hydrogen engines into the NRMM population.

An impact descriptor can then be assigned as ‘Negligible’, ‘Minor’, ‘Moderate’ or ‘Substantial’ adverse or beneficial based on the percentage change in pollutant concentration relative to the air quality objective in context with the long-term average concentration at any specific receptor location.

The matrix used to derive impact descriptors from the latest guidance is duplicated in Figure 1. This approach is widely used throughout the UK and considered as current best practice when assessing air quality impacts for planning and development control purposes. It provides a useful, familiar and well-established basis for assessment of technology interventions that may affect air quality.

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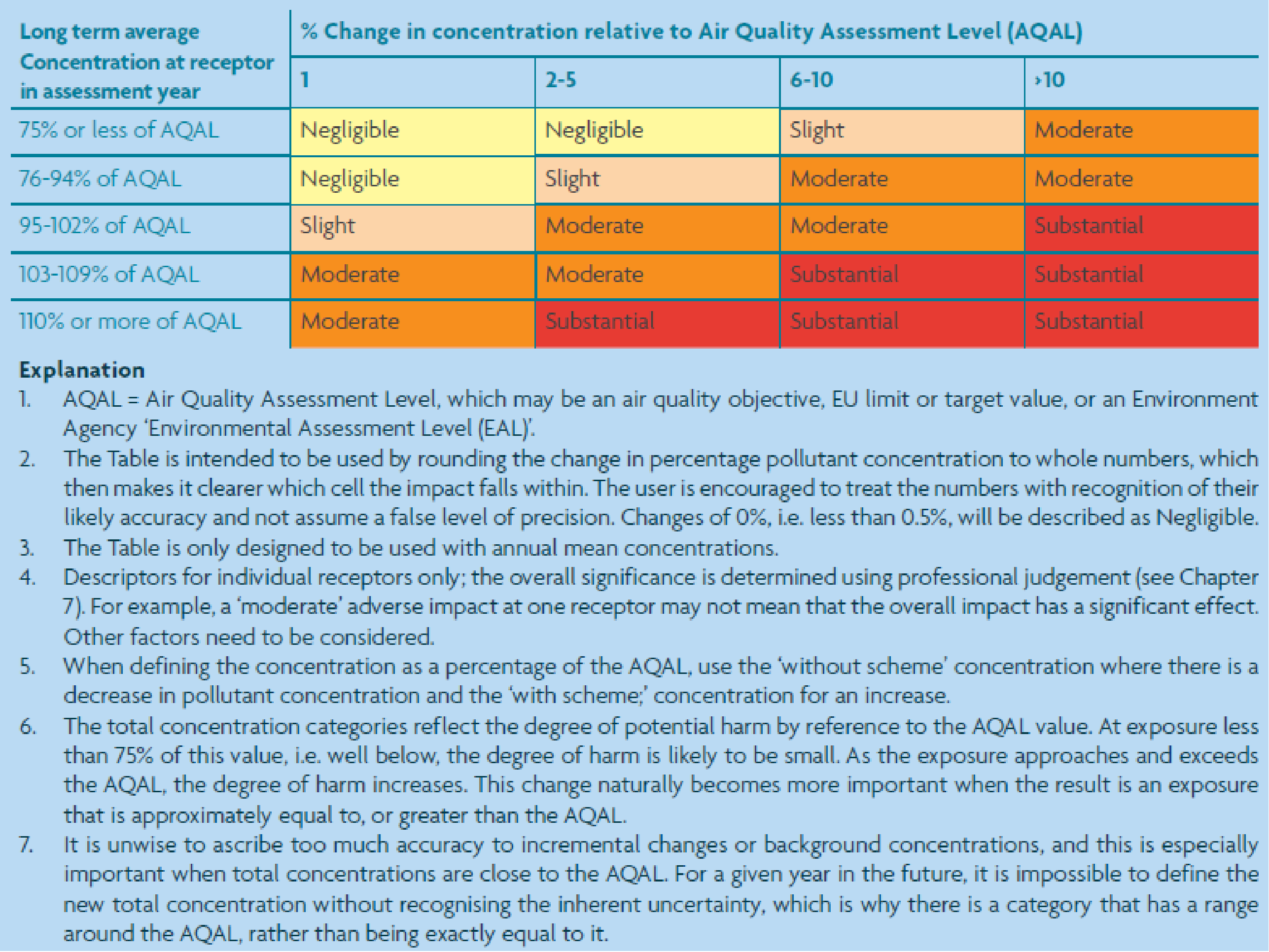
[2] EPUK & IAQM (2017) Land-Use Planning & Development Control: Planning for Air Quality; Guidance from Environmental Protection UK and the Institute of Air Quality Management f or the consideration of air quality within the land-use planning and development control processes; January 2017

Figure 1: IAQM/EPUK Air quality Impact Descriptors[3].



Long term average Concentration at receptor in assessment year	% Change in concentration relative to Air Quality Assessment Level (AQAL)			
	1	2-5	6-10	›10
75% or less of AQAL	Negligible	Negligible	Slight	Moderate
76-94% of AQAL	Negligible	Slight	Moderate	Moderate
95-102% of AQAL	Slight	Moderate	Moderate	Substantial
103-109% of AQAL	Moderate	Moderate	Substantial	Substantial
110% or more of AQAL	Moderate	Substantial	Substantial	Substantial

Explanation

1. AQAL = Air Quality Assessment Level, which may be an air quality objective, EU limit or target value, or an Environment Agency 'Environmental Assessment Level (EAL)'.
2. The Table is intended to be used by rounding the change in percentage pollutant concentration to whole numbers, which then makes it clearer which cell the impact falls within. The user is encouraged to treat the numbers with recognition of their likely accuracy and not assume a false level of precision. Changes of 0%, i.e. less than 0.5%, will be described as Negligible.
3. The Table is only designed to be used with annual mean concentrations.
4. Descriptors for individual receptors only; the overall significance is determined using professional judgement (see Chapter 7). For example, a 'moderate' adverse impact at one receptor may not mean that the overall impact has a significant effect. Other factors need to be considered.
5. When defining the concentration as a percentage of the AQAL, use the 'without scheme' concentration where there is a decrease in pollutant concentration and the 'with scheme;' concentration for an increase.
6. The total concentration categories reflect the degree of potential harm by reference to the AQAL value. At exposure less than 75% of this value, i.e. well below, the degree of harm is likely to be small. As the exposure approaches and exceeds the AQAL, the degree of harm increases. This change naturally becomes more important when the result is an exposure that is approximately equal to, or greater than the AQAL.
7. It is unwise to ascribe too much accuracy to incremental changes or background concentrations, and this is especially important when total concentrations are close to the AQAL. For a given year in the future, it is impossible to define the new total concentration without recognising the inherent uncertainty, which is why there is a category that has a range around the AQAL, rather than being exactly equal to it.

1.2 ASSESSMENT SCENARIOS

The air quality modelling scenarios included in the assessment are:

1. Baseline of 2019 NOx contributions in London, based on the London Atmospheric Emissions Inventory (LAEI) at this time.
2. Repeat of test case 1, 2019 with all internal combustion engine (ICE) NOx contributions modelled to appropriate best available emissions standards (i.e. for NRMM Stage V, For road traffic Euro 6D etc.)
3. The impact of hydrogen powered (H2ICE) NRMM is assessed relative to a hypothetical scenario where no traditionally powered NRMM or ICE powered road traffic are operational within London, whereby:
    - All NRMM with power rating <=19kW is zero emitting
    - All NRMM with power rating >19kW will be hydrogen powered and operate at a NOx emission rate of 0.02 g/kWh.

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[3] Ibid.

2. NRMM EMISSION CALCULATION METHODS

2.1 THE LONDON ATMOSPHERIC EMISSION INVENTORY (LAEI)

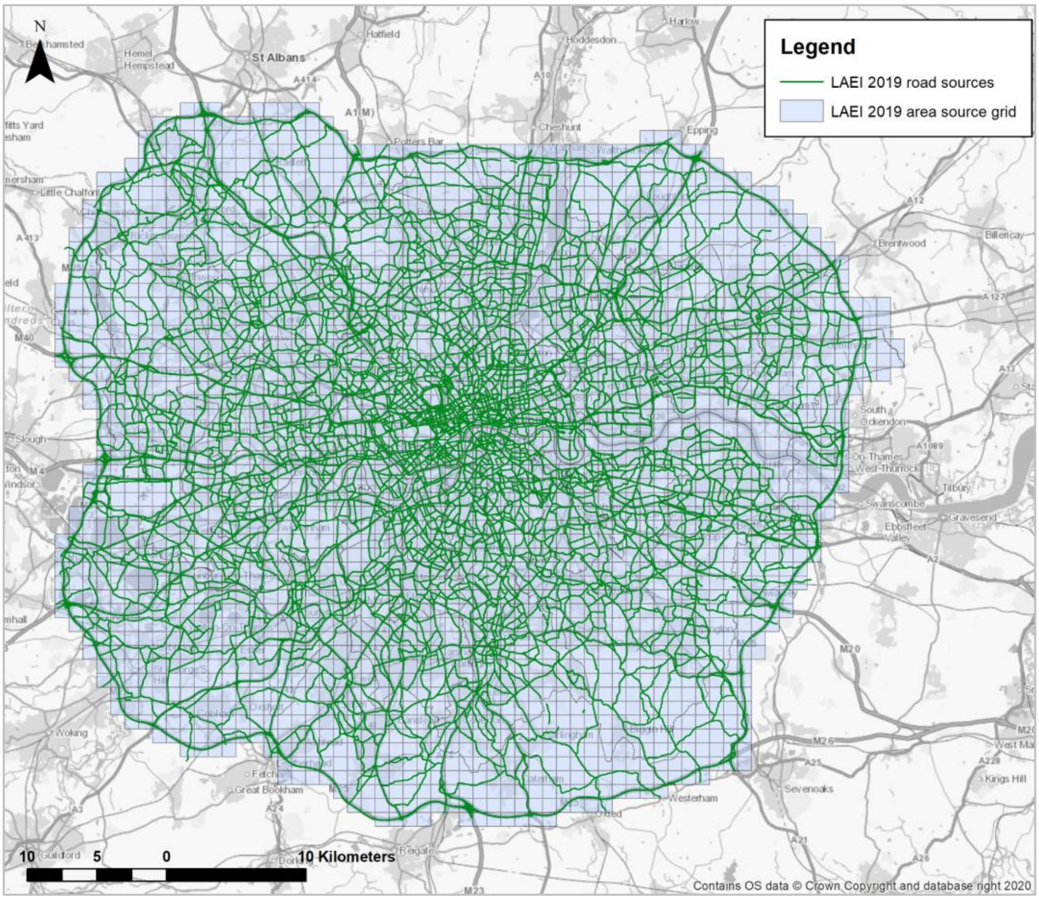
2.1.1 Brief overview of the LAEI

The 2019 London Atmospheric Emissions Inventory (LAEI) is a spatially allocated database of atmospheric pollutant emissions in Greater London. In our early discussions with JCB it was agreed that the LAEI was the most sensible choice of baseline emission data given it is open source and accepted as representative by the GLA and national government. The most recent (2019) version of the LAEI was published in December 2021. The LAEI is produced by the Greater London Authority with input from various other project partners[4] such as Transport for London. Data is publicly available and provides valuable information used for evidence-based air quality policy assessment in London.

Road transport emissions are represented as road link/line sources in the inventory; all other sources are projected on a 1km^2 resolution grid, further split by the boundary of each London borough to allow accurate aggregations of emissions by borough (mapped in Figure 2). Annual emissions are provided for various source sectors and associated sub sectors (Figure 3).

The currently available LAEI methodology document published in 2020, is for the LAEI-2016[5]. In the absence of a more recent report, we have assumed that the methods described for deriving emissions in the LAEI-2016 methodology are also applicable to the LAEI-2019 inventory.

Figure 2: LAEI 2019 area and road source domains



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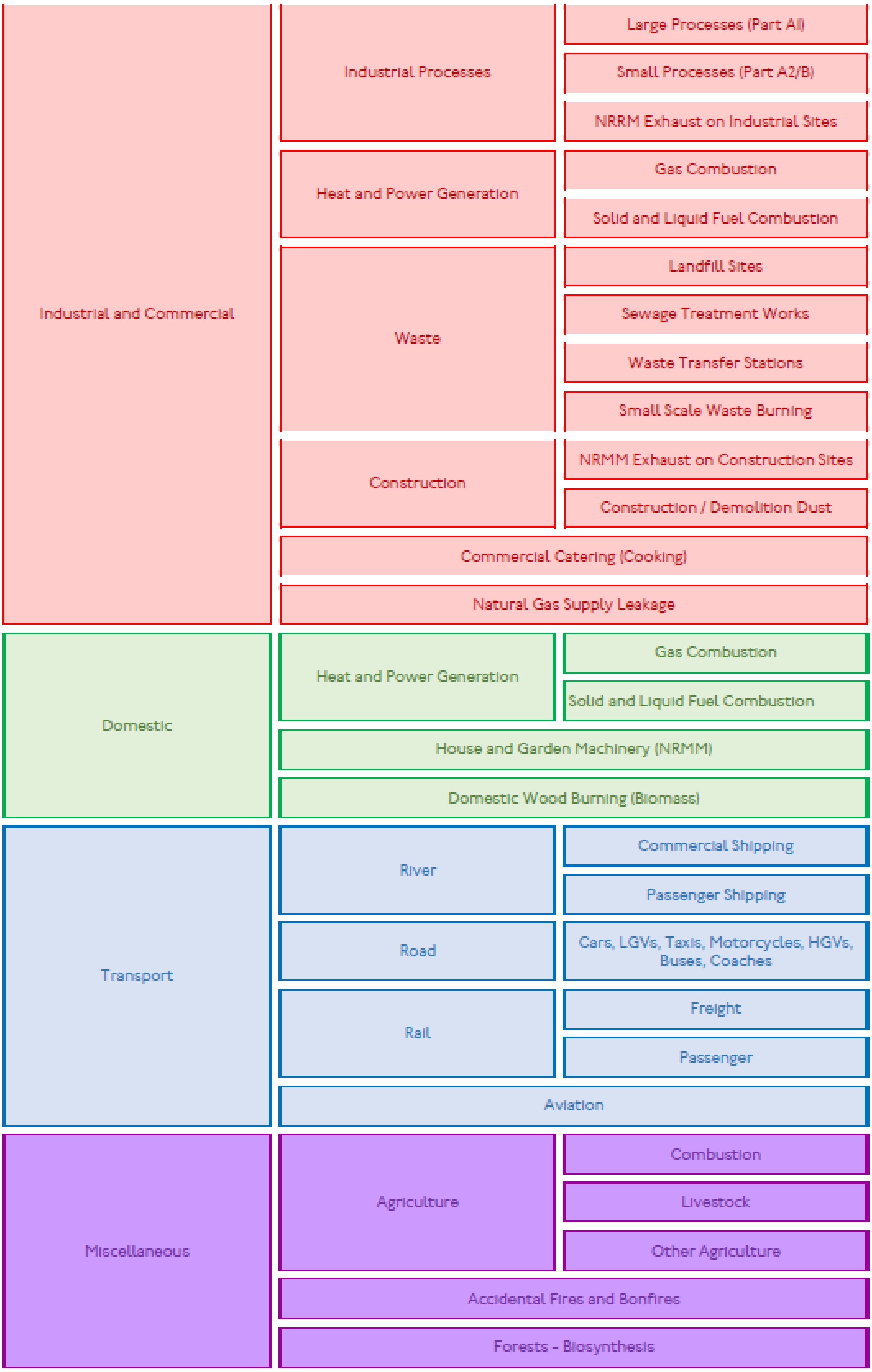
[4] GLA (2021) LAEI 2019 Summary note; available to download at https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2019; accessed Nov 2022

[5] Transport for London (2020) London Atmospheric Emissions Inventory (LAEI) 2016 – Methodology

Figure 3: Emission sources in the LAEI[6]



Industrial and Commercial	Industrial Processes	Large Processes (Part AI)
		Small Processes (Part A2/B)
		NRRM Exhaust on Industrial Sites
	Heat and Power Generation	Gas Combustion
		Solid and Liquid Fuel Combustion
	Waste	Landfill Sites
		Sewage Treatment Works
		Waste Transfer Stations
		Small Scale Waste Burning
	Construction	NRMM Exhaust on Construction Sites
		Construction / Demolition Dust
	Commercial Catering (Cooking)	
	Natural Gas Supply Leakage	
Domestic	Heat and Power Generation	Gas Combustion
		Solid and Liquid Fuel Combustion
	House and Garden Machinery (NRMM)	
	Domestic Wood Burning (Biomass)	
Transport	River	Commercial Shipping
		Passenger Shipping
	Road	Cars, LGVs, Taxis, Motorcycles, HGVs, Buses, Coaches
	Rail	Freight
		Passenger
	Aviation	
Miscellaneous	Agriculture	Combustion
		Livestock
		Other Agriculture
	Accidental Fires and Bonfires	
	Forests - Biosynthesis	

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[6] Transport for London (2020) London Atmospheric Emissions Inventory (LAEI) 2016 – Methodology; May 2020; pp11, Table 1: Emission Sources in the LAEI

2.1.2 NRMM sector emissions in the LAEI

NRMM Emissions in the LAEI 2019 (and previous iterations 2013 and 2016) are accounted for in two of the industrial and commercial sub-sectors which are:

- Construction – NRMM exhaust on construction sites
- Industrial Processes - NRMM exhaust on industrial sites

2.1.2.1 Proportion of total area source emissions attributable to NRMM

When considering the likely significance of changes to NOx emissions from NRMM upon local air quality, it is useful to consider what proportion of total emissions are attributable to these NRMM source sectors in the LAEI. From the map presented in Figure 4 and associated histogram in Figure 5; we can see that, although there are some locations with a relatively high proportion of NRMM emissions, in most locations NRMM contributes up to 25% of non-road source NOx emissions, with the majority of locations having a less than 5% contribution.

This does however demonstrate that NRMM contributions to total NOx emission in the LAEI 2019 inventory can be considered as not negligible at many locations; therefore, testing the air quality impact of NRMM NOx emission reduction measures is worthwhile.

In Figure 6, which shows a smaller area of the gridded inventory, we can see how NRMM as a proportion of other emissions vary by borough as well as by 1km grid square. This map also shows an example where intersection of a borough boundary with the regular grid creates a small segment within a 1km inventory square with a relatively high percentage of emissions attributable to NRMM. Other small intersections of borough boundaries with the 1km grid like this account for the maximum NRMM emission proportions displayed on the map. These relatively high NRMM percentage contributions located in very small segments of the inventory are considered to be an artifact of the emission mapping process. To overcome this when conducting our dispersion modelling study, we have disregarded the borough boundaries within each 1km inventory grid cell by aggregating emissions in each cell, which can then be modelled as uniform 1km square area sources.

Figure 4: LAEI 2019 NRMM emissions as a percentage of total (non-road source) emissions

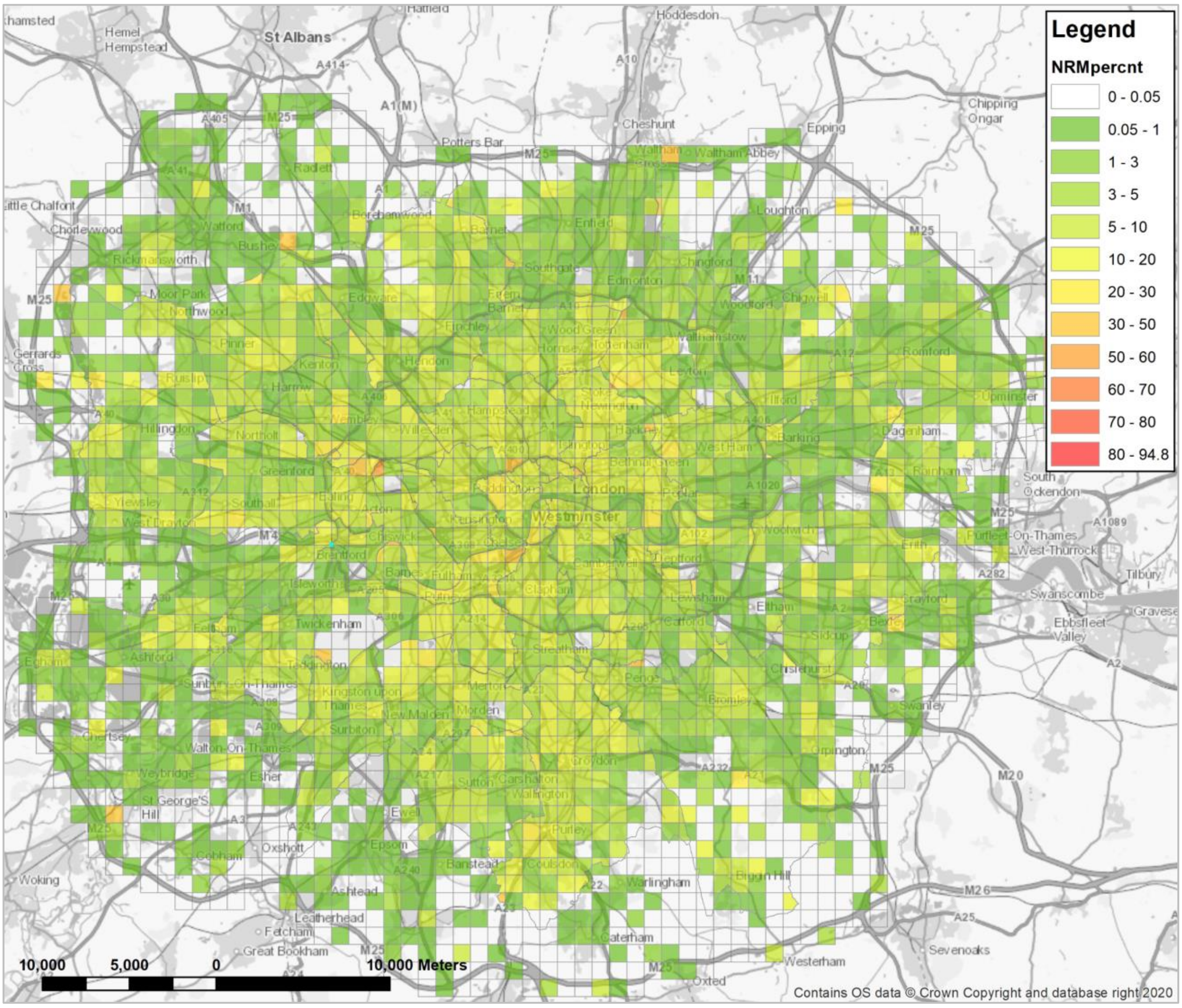


Figure 5: Frequency of LAEI 2019 NRMM emissions as a percentage of total (non-road source) emissions

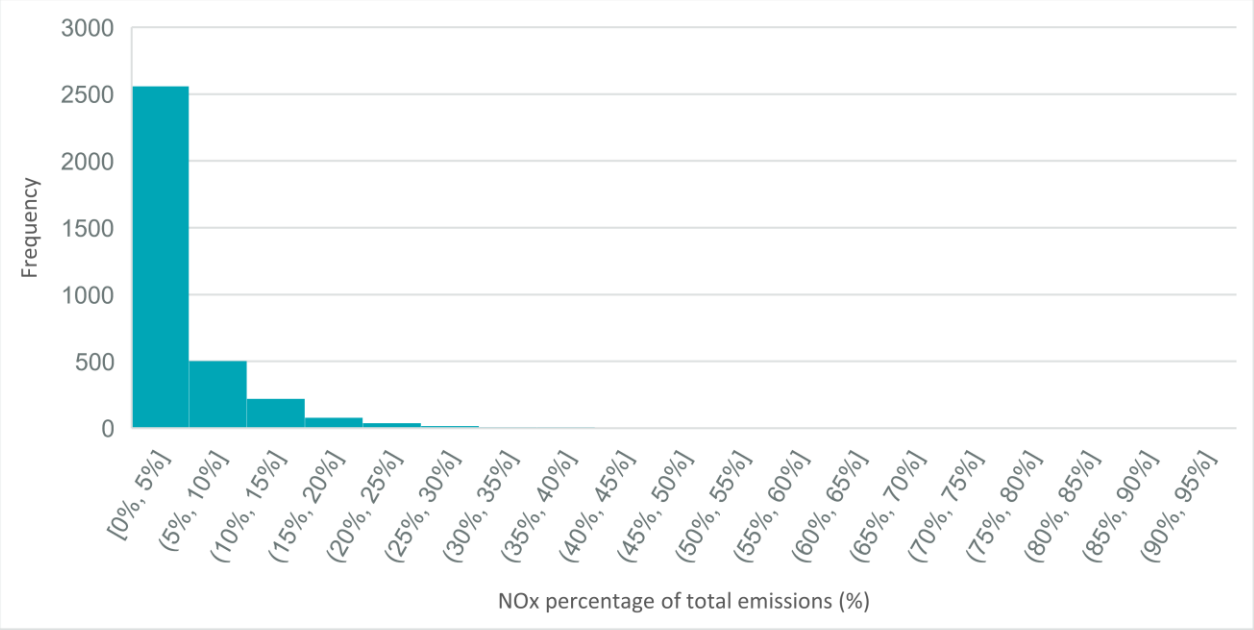
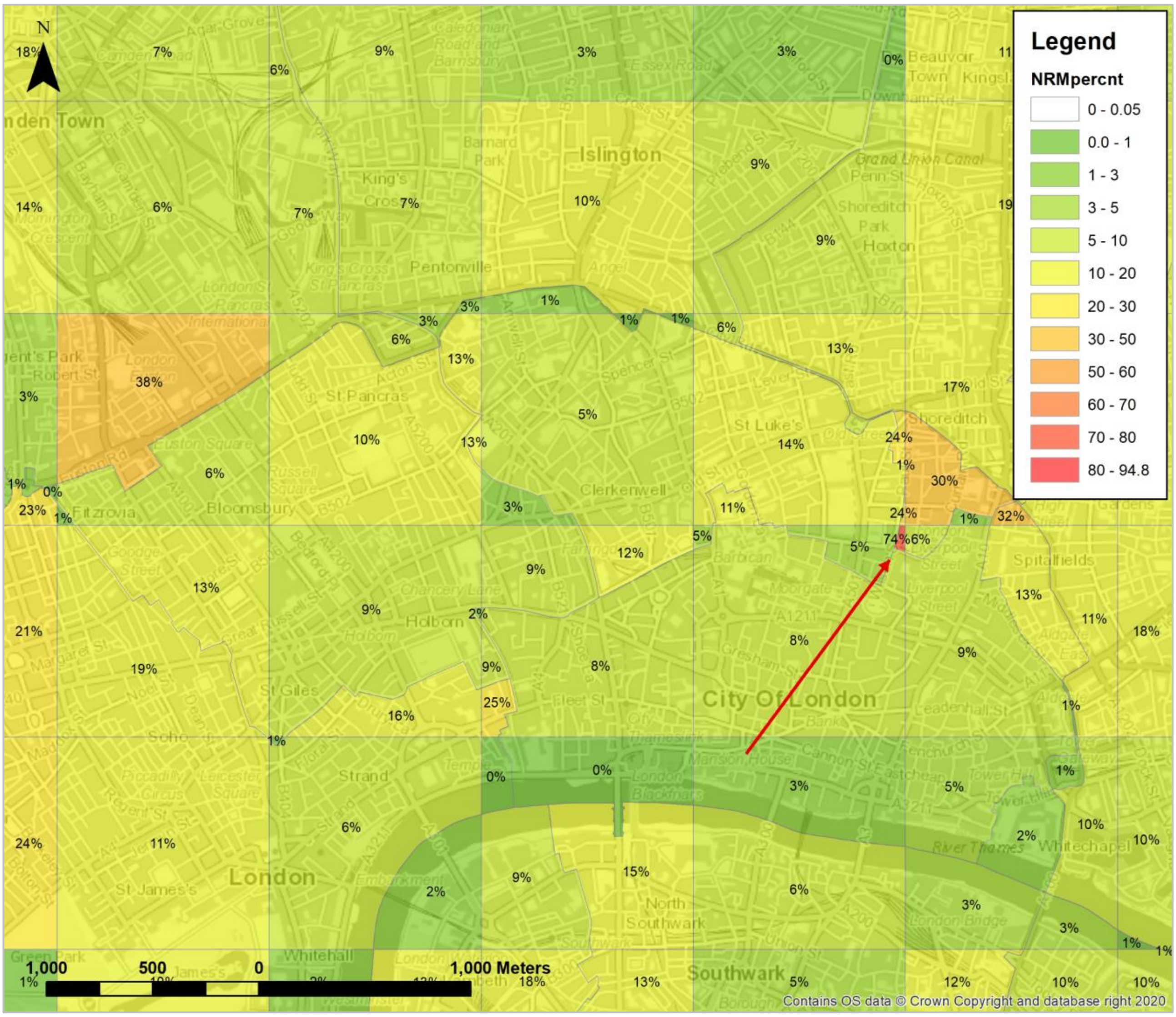


Figure 6: Smaller scale example of NRMM emissions as a percentage of total (non-road source) emissions



2.1.2.2 How NRMM activity and pollutant emission estimates are calculated in the LAEI

The LAEI-2016 methodology report[7] provides brief descriptions of how emissions were derived for both the Industrial Processes NRMM and Construction NRMM sectors; these are duplicated below in Box 1 and Box 2 respectively. The inventory methodology is provided for reference purposes only. Using the output data has been agreed with JCB which in turn means that the methods used to derive it are agreed as being fit for purpose.

In summary:

- For both the industrial and construction sectors, emissions are based on the total UK NRMM emissions reported in the NAEI; which has then been multiplied by a proxy value representing spatial distribution of activity in the respective source sector in London.
- For Industrial processes NRMM – the 1km resolution NAEI CO_2 emissions map is used as a proxy for spatial distribution of industrial activity.
- For construction NRMM

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[7] Transport for London (2020) London Atmospheric Emissions Inventory (LAEI) 2016 – Methodology; May 2020

- Employment data in the construction industry across the UK has been used as a proxy indicator of construction activity in London, allowing a relevant percentage of total UK NRMM emissions to be allocated to London.
- A bottom-up estimation of the spatial distribution of emissions in London was derived using records of active construction sites reported in the London Development Database (LDD)

These emission inventories, although uncertain by nature of the activity data and assumptions used when calculating emissions, do provide the best (and only) available estimate of the likely magnitude and spatial distribution of NRMM emissions from each 'parent' sector.

Box 1: Extract from LAEI methodology report[8] – Industrial Processes NRMM

Emissions and Spatial Distribution

2.1.13 As for the LAEI 2013, NRMM exhaust emissions from industrial sites for 2016 were determined based on a top-down approach, using total NRMM emissions reported in the NAEI for the UK, combined with data from the latest NAEI CO_2 emissions map[9].

2.1.14 NAEI CO_2 emissions reported for the "Combustion in Industry" sector, provided at a 1km^2 resolution across the UK, have been used as a proxy indicator of industrial activity across the UK. This is deemed representative of the spatial distribution of NRMM exhaust emissions on industrial sites.

2.1.15 This enabled us to estimate the fraction of the UK industrial NRMM emissions within the LAEI area (3.7% assumed in 2016), as well as the distribution of these emissions on the LAEI grid.

Box 2: Extract from LAEI methodology report[10] – Construction NRMM

Emissions and Spatial Distribution

2.4.4 As for the LAEI 2013, NRMM exhaust emissions from construction sites for 2016 were determined combining a top-down approach using total NRMM emissions reported in the NAEI for the UK, with a bottom-up estimate of emission spatial distribution using active construction sites reported in the London Development Database (LDD)[11].

2.4.5 Employment data in the construction industry across the UK has been used as a proxy indicator of construction activity. Based on the data for 2016, 14.1% of construction related NRMM emissions reported in the NAEI have been allocated to the LAEI.

2.2 THE NATIONAL ATMOSPHERIC EMISSION INVENTORY (NAEI)

2.2.1 How NRMM activity and pollutant emission estimates are calculated in the National Atmospheric Emission Inventory (NAEI)

The LAEI method uses the National Atmospheric Emission Inventory (NAEI) total UK NRMM emissions to calculate source sector NRMM emissions in London. The next important step in determining how we can model changes to activity-based emission rates, is to understand how NRMM emissions in the NAEI are derived.

As the main objective of this study is to assess emission changes to NRMM with a power rating greater than 19kW (as described for modelling scenario 3 in the introduction above), it is also important that we understand how emissions are calculated for the NAEI based on activity estimates of NRMM plant of varying power ratings. The basic principle of how emissions estimates are calculated for an inventory is presented in Box 3.

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[8] Ibid.

[9] Available at http://naei.beis.gov.uk/data/map-uk-das ()

[10] Transport for London (2020) London Atmospheric Emissions Inventory (LAEI) 2016 – Methodology; May 2020

[11] London Development Database available online at https://www.london.gov.uk/what-we-do/planning/london-plan/london-development-database

Box 3: How emission estimates are calculated[12]

Emission estimates are calculated by applying an emission factor to an appropriate activity statistic:

$$\text{Emission} = \text{Emission Factor} \times \text{Activity Data}$$

An emission factor is defined as the average emission rate of a given pollutant for a given source, relative to units of activity

The Ricardo Energy & Environment NAEI team have advised us of their calculation method. These methods have a high level of provenance, having been devised in full compliance with international emission reporting requirements of the UK Government. They use the following elements to calculate UK wide NRMM activity and associated emissions:

1. UK NRMM population and activity (by NRMM type)
    a. NRMM type and number operating in any given year.
    b. average power rating
    c. average annual operational hours
    d. typical loading factors
    e. NRMM population turnover and growth
2. Emission factors – based on
    a. Power rating
    b. Technology emission standard

UK NRMM population and activity

In 2004 Netcen (National Environmental Technology Centre, a historical division of Ricardo Energy and Environment) produced a report for the Department for Transport (DfT)[13] assessing the 2004 status of the UK population of diesel-engine non-road mobile machinery (NRMM). This included survey results quantifying the size of the UK population of a range of NRMM type and their typical usage rates in hours per year. It also included average power rating (kW), population (number of units), annual usage (hrs/year) and typical loading factors for various types of NRMM. Data from this report is replicated in Table 2-1 below.

The 2004 NRMM population data forms the basis of the NAEI method for describing the NRMM population, which is then factored to later years using population turnover and sales estimates. The NRMM population data and associated power rating and typical loading factors for any (historical, current or projected) inventory year are then used in combination with published European emission factors to calculate UK wide annual NRMM emissions.

For the purpose of this study, we have used 2019 NRMM population as used in the NAEI. This has kindly been provided to us by the UK NAEI team. All annual NRMM population turnover and growth factors applied to the original 2004 dataset and resulting changes to the overall percentage of each type of NRMM assumed to be present within the national population have therefore been included in our calculations for the 2019 baseline.

European emission factors

European emission factors for NRMM are accessed from the EMEP/EEA air pollutant emission inventory guidebook produced by the European Environment Agency (EEA)[14]. The Tier 3 emission factors for diesel

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[12] Ricardo Energy & Environment (2022) UK Spatial Emissions Methodology A report of the National Atmospheric Emission Inventory 2020; ED 11787218/2022 | Issue Number 1 | Date 4 July 2022; available at: https://naei.beis.gov.uk/reports/

[13] NETCEN (2004) - Non-Road Mobile Machinery Usage, Life and Correction Factors Report to the Department for Transport; ref. AEAT/ENV/R/1895; November 2004

[14] https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-4-non-road-1/view

NRMM, based on power rating (kW) and emission standard, provide emission rates in grams per kilowatt hour (g.kWh^{-1}) for various pollutants (replicated in Table 2-2 below).

Emission limits for NRMM have been implemented through various European Directives, whereby gradually more stringent emission standards have been introduced over time. The NAEI calculation method applies a relevant technology stage and associated emission factor for each NRMM type.

NRMM emission standards in London

In London, the 'Control of Dust and Emissions during Construction and Demolition Supplementary Planning Guidance (SPG)'[15] specifies emission standards for non-road mobile machinery (NRMM) which are based upon engine emissions standards set in EU Directive 97/68/EC and its subsequent amendments.

From 1 September 2015 NRMM of net power between 37kW and 560kW used within Greater London was required to meet Stage IIIA of the Directive as a minimum; and NRMM used on any site within the Central Activity Zone or Canary Wharf is required to meet Stage IIIB of the Directive as a minimum.

From 1 September 2020 NRMM within Greater London is required to meet Stage IIIB of the Directive as a minimum. NRMM used on any site within the Central Activity Zone or Canary Wharf is required to meet Stage IV of the Directive as a minimum.

To our knowledge, the emission stages used to calculate NRMM emissions in the UK wide NAEI are not adjusted to account for the emission standards required in London. We are not aware if this is accounted for in the LAEI activity-based calculations.

2.3 HOW WE HAVE CALCULATED AND MODELLED NRMM EMISSIONS

The main objective of this study is to assess the air quality impact of emission changes to NRMM on NOx/NO_2 concentrations. JCB have advised that a NOx emission rate of 0.02 g/kWh is achievable from hydrogen powered NRMM with a power rating greater than 19kW.

As explained in the report sections above. In the NAEI and subsequently derived LAEI, NRMM sector emissions are aggregated into 1km grid squares. Each square represents an estimate of NRMM activity at that location, which has been converted to an annual NOx emission rate based on an understanding of local construction or industrial NRMM activity, typical (UK wide) NRMM fleet makeup and associated NOx emission factors.

To model the impact of changing the NRMM fleet makeup, initially we need to back-calculate how much NRMM activity, by type of NRMM (expressed as energy usage in kWh) is being represented in the LAEI 2019.

We can calculate this by breaking down the total aggregated annual NOx emission rate by each NRMM type, which can then be converted to associated NRMM activity (expressed in kWh) using the EMEP emission factors we know were applied in the NAEI calculations.

The 2019 NRMM population used in the 2019 NAEI, provided sufficient data to calculate what percentage of the total mass emission is allocated to each NRMM type. This percentage can then be applied to the 1km aggregated emissions, and the resulting emission value divided by the respective emission rate to derive the energy used (kWh).

Once we have back calculated annual NRMM activity (kWh) for each plant type, we can then apply revised emission factors for each scenario being modelled e.g. 0.02 g/kWh for relevant NRMM types, and recalculate annual emissions. It is then straightforward to re-aggregate emissions for all NRMM types and calculate the percentage change compared to the baseline or any other scenario being modelled.

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[15] Mayor of London (2014) THE CONTROL OF DUST AND EMISSIONS DURING CONSTRUCTION AND DEMOLITION SUPPLEMENTARY PLANNING GUIDANCE; July 2014.

Table 2-1: Netcen 2004 - Best Estimates of NRMM population parameters for industry, construction, agriculture, and mobile refrigeration units; and loading factors

NRMM Type	**NAEI category**	**Dft priority class**	**Average Power rating (kW)**	**Population (units)**	**Annual usage hours/year**	**Useful Lifetime (years)**	**Loading factors (%)**		
Industry and construction							**Best**	**Low**	**High**
Portable Generators 5-100kW	Construction	1	49	99802	844	6	50%	35%	65%
Portable Generators 100-1000kW	Construction	1	194	21941	844	6	50%	35%	65%
Forklift (non-RTF)	Industry	2	35	64006	844	6	30%	21%	39%
Rough Terrain Forklifts (RTF)	Construction	2	56.25	6125	850	6.3	30%	21%	39%
Telescopic Handlers		2	75	25200	1050	6.3	27.50%	19.25%	35.75%
Backhoe Loaders	Construction	2	67.5	19950	1000	7.7	32.50%	22.75%	42.25%
Mini Excavators	Construction	2	18.75	31500	1100	4.6	40%	28%	52%
Excavators									
Wheeled excavators	Construction	3	100	2100	875	6.3	30%	21%	39%
Crawler excavators	Construction	3	75	2975	1000	6.3	33%	23%	42%
Access Platforms		3	17	1779	1400	5	30%	21%	39%
Welding Equipment	Industry	3	ND	ND	ND	4			
Air Compressors	Industry	3	30	12600	875	4.2	60%	42%	78%
Wheeled Loaders	Construction	3	112.5	6475	1100	8.4	30%	21%	39%
Industrial Tractors	Industry	4	ND	ND	ND	ND			
Gas Compressors	Industry	4	30	6300	875	4.2	60%	42%	78%
Off Highway Trucks									

NRMM Type	NAEI category	Dft priority class	Average Power rating (kW)	Population (units)	Annual usage hours/year	Useful Lifetime (years)	Loading factors (%)		
Rigid dump trucks	Construction	4	712.5	945	1250	8.3	30%	21%	39%
Articulated dump trucks	Construction	4	168.75	3640	875	7.7	30%	21%	39%
Cranes	Construction	4	225	4690	1000	10.5	20%	14%	26%
Bulldozers	Construction	4	135	1339	375	7.7	38%	26%	49%
Concrete Pavers	Construction	5	ND	ND	ND	ND			
Surfacing Equipment	Construction	5	ND	ND	ND	ND			
Concrete Saws	Construction	5	ND	ND	ND	5			
Crawler Tractors	Construction	5	ND	ND	ND	4			
Asphalt Pavers	Construction	5	90	998	750	3.9	35%	25%	46%
Paving Equipment	Construction	5	22.5	18900	500	8.8	70%	49%	91%
Bore/drill rigs	Quarrying	5	ND	ND	ND	ND			
Skid-Steer Loaders	Construction	5	33.75	6300	1000	4.2	25%	18%	33%
Crushing/Processing Equipment	Quarrying	5	182.5	700	1350	ND			
Tracked Loaders	Construction	5	120	367	500	9.5	35%	25%	46%
Graders	Construction	6	150	123	375	12.3	34%	25%	46%
Scrapers	Construction	6	341.25	88	500	14	30%	21%	39%

ND: No data

Table 2-2: EMEP/EEA air pollutant emission inventory guidebook 2019 - Baseline emission factors and fuel consumption (FC) for diesel NRMM [g/kWh][16]

Engine Power (kW)	Technology Level	NOx	VOC	CH_4	CO	N_2O	NH3	PM	PM_{10}	$PM_{2.5}$	BC	FC
P<8	<1981	12	5	0.12	7	0.035	0.002	2.8	2.8	2.8	1.54	300
P<8	1981-1990	11.5	3.8	0.091	6	0.035	0.002	2.3	2.3	2.3	1.265	285
P<8	1991-Stage I	11.2	2.5	0.06	5	0.035	0.002	1.6	1.6	1.6	0.88	270
P<8	Stage V	6.08	0.68	0.016	4.8	0.035	0.002	0.4	0.4	0.4	0.32	270
8<=P<19	<1981	12	5	0.12	7	0.035	0.002	2.8	2.8	2.8	1.54	300
8<=P<19	1981-1990	11.5	3.8	0.091	6	0.035	0.002	2.3	2.3	2.3	1.265	285
8<=P<19	1991-Stage I	11.2	2.5	0.06	5	0.035	0.002	1.6	1.6	1.6	0.88	270
8<=P<19	Stage V	6.08	0.68	0.016	3.96	0.035	0.002	0.4	0.4	0.4	0.32	270
19<=P<37	<1981	18	2.5	0.06	6.5	0.035	0.002	2	2	2	1.1	300
19<=P<37	1981-1990	18	2.2	0.053	5.5	0.035	0.002	1.4	1.4	1.4	0.77	281
19<=P<37	1991-Stage I	9.8	1.8	0.043	4.5	0.035	0.002	1.4	1.4	1.4	0.77	262
19<=P<37	Stage II	6.5	0.6	0.014	2.2	0.035	0.002	0.4	0.4	0.4	0.32	262
19<=P<37	Stage IIIA	6.08	0.6	0.014	2.2	0.035	0.002	0.4	0.4	0.4	0.32	262
19<=P<37	Stage V	3.81	0.42	0.01	2.2	0.035	0.002	0.015	0.015	0.015	0.002	262
37<=P<56	<1981	7.7	2.4	0.058	6	0.035	0.002	1.8	1.8	1.8	0.99	290
37<=P<56	1981-1990	8.6	2	0.048	5.3	0.035	0.002	1.2	1.2	1.2	0.66	275
37<=P<56	1991-Stage I	11.5	1.5	0.036	4.5	0.035	0.002	0.8	0.8	0.8	0.44	260
37<=P<56	Stage I	7.7	0.6	0.014	2.2	0.035	0.002	0.4	0.4	0.4	0.32	260
37<=P<56	Stage II	5.5	0.4	0.01	2.2	0.035	0.002	0.2	0.2	0.2	0.16	260
37<=P<56	Stage IIIA	3.81	0.4	0.01	2.2	0.035	0.002	0.2	0.2	0.2	0.16	260
37<=P<56	Stage IIIB	3.81	0.28	0.007	2.2	0.035	0.002	0.025	0.025	0.025	0.02	260
37<=P<56	Stage V	3.81	0.28	0.007	2.2	0.035	0.002	0.015	0.015	0.015	0.002	260
56<=P<75	<1981	7.7	2.4	0.058	6	0.035	0.002	1.8	1.8	1.8	0.99	290
56<=P<75	1981-1990	8.6	2	0.048	5.3	0.035	0.002	1.2	1.2	1.2	0.66	275
56<=P<75	1991-Stage I	11.5	1.5	0.036	4.5	0.035	0.002	0.8	0.8	0.8	0.44	260
56<=P<75	Stage I	7.7	0.6	0.014	2.2	0.035	0.002	0.4	0.4	0.4	0.32	260
56<=P<75	Stage II	5.5	0.4	0.01	2.2	0.035	0.002	0.2	0.2	0.2	0.16	260
56<=P<75	Stage IIIA	3.81	0.4	0.01	2.2	0.035	0.002	0.2	0.2	0.2	0.16	260
56<=P<75	Stage IIIB	2.97	0.28	0.007	2.2	0.035	0.002	0.025	0.025	0.025	0.02	260
56<=P<75	Stage IV	0.4	0.28	0.007	2.2	0.035	0.002	0.025	0.025	0.025	0.02	260
56<=P<75	Stage V	0.4	0.13	0.003	2.2	0.035	0.002	0.015	0.015	0.015	0.002	260
75<=P<130	<1981	10.5	2	0.048	5	0.035	0.002	1.4	1.4	1.4	0.77	280
75<=P<130	1981-1990	11.8	1.6	0.038	4.3	0.035	0.002	1	1	1	0.55	268
75<=P<130	1991-Stage I	13.3	1.2	0.029	3.5	0.035	0.002	0.4	0.4	0.4	0.22	255
75<=P<130	Stage I	8.1	0.4	0.01	1.5	0.035	0.002	0.2	0.2	0.2	0.16	255
75<=P<130	Stage II	5.2	0.3	0.007	1.5	0.035	0.002	0.2	0.2	0.2	0.16	255
75<=P<130	Stage IIIA	3.24	0.3	0.007	1.5	0.035	0.002	0.2	0.2	0.2	0.16	255
75<=P<130	Stage IIIB	2.97	0.13	0.003	1.5	0.035	0.002	0.025	0.025	0.025	0.02	255

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[16] EEA(2019) EMEP/EEA air pollutant emission inventory guidebook 2019; 1.A.2.g vii; 1.A.4.a.ii, 1.A.4.b ii; 1.A.4.c ii; 1.A.4.c iii; 1.A.5.b Non-road mobile sources and machinery;

pp37 Tier 3 emission factors; Table 3-6 Baseline emission factors and fuel consumption (FC) for diesel NRMM [g/kWh]; available at https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-4-non-road-1/view

Engine Power (kW)	Technology Level	NOx	VOC	CH_4	CO	N_2O	NH3	PM	PM_{10}	$PM_{2.5}$	BC	FC
75<=P<130	Stage IV	0.4	0.13	0.003	1.5	0.035	0.002	0.025	0.025	0.025	0.02	255
75<=P<130	Stage V	0.4	0.13	0.003	1.5	0.035	0.002	0.015	0.015	0.015	0.002	255
130<=P<560	<1981	17.8	1.5	0.036	2.5	0.035	0.002	0.9	0.9	0.9	0.45	270
130<=P<560	1981-1990	12.4	1	0.024	2.5	0.035	0.002	0.8	0.8	0.8	0.4	260
130<=P<560	1991-Stage I	11.2	0.5	0.012	2.5	0.035	0.002	0.4	0.4	0.4	0.2	250
130<=P<560	Stage I	7.6	0.3	0.007	1.5	0.035	0.002	0.2	0.2	0.2	0.14	250
130<=P<560	Stage II	5.2	0.3	0.007	1.5	0.035	0.002	0.1	0.1	0.1	0.07	250
130<=P<560	Stage IIIA	3.24	0.3	0.007	1.5	0.035	0.002	0.1	0.1	0.1	0.07	250
130<=P<560	Stage IIIB	1.8	0.13	0.003	1.5	0.035	0.002	0.025	0.025	0.025	0.018	250
130<=P<560	Stage IV	0.4	0.13	0.003	1.5	0.035	0.002	0.025	0.025	0.025	0.018	250
130<=P<560	Stage V	0.4	0.13	0.003	1.5	0.035	0.002	0.015	0.015	0.015	0.002	250
P>560	Stage V	3.5	0.13	0.003	1.5	0.035	0.002	0.045	0.045	0.045	0.002	250

3. DISPERSION MODELLING METHOD AND SUPPORTING INFORMATION

3.1 CORE ASPECTS OF THE MODELLING APPROACH

The assessment considers emissions of oxides of nitrogen (NOx) expressed as annual mean NOx and NO_2 concentrations when dispersed. Dispersion simulations for baseline conditions in 2019, and a series of emission change scenarios have been modelled. The model domain covers the extent of the Greater London area included in the LAEI (mapped above in Figure 2)

Three main NOx source sector categories have been included in the dispersion modelling:

1. **NRMM emissions for the construction and industry sectors.**
   The LAEI 1km resolution NOx emission grid for the ‘Industry NRMM’ and ‘Construction NRMM’ sector have been modelled with Ricardo’s RapidAir® air dispersion model in “Area source mode”. This was parameterised to provide 10m resolution NOx annual mean concentration grids that can be combined with model outputs from other emission source categories.

2. **Road traffic emissions**
   Road traffic emissions have been modelled with Ricardo’s RapidAir® air dispersion model in “Road source mode”. The LAEI provides high resolution road traffic activity data allocated to spatially accurate mapping of major road links in the London Road network. Pollutant emission rates for road links have been calculated using this traffic activity data and London specific vehicle fleet composition estimates (further details on road traffic activity and emission calculations are provided in Section 3.5 below). Dispersion of road traffic NOx emissions has been modelled at a spatial resolution of 3m.
3. **All other sector emissions and rural background concentrations**
   Contributions to NOx annual mean concentrations from all other source sectors and rural background NOx have been accessed from the Defra UK background maps[17]; which are 1km resolution outputs from the UK national scale Pollution Climate Mapping (PCM) model (described further in 3.6 below)

3.2 RAPIDAIR® DISPERSION MODELLING SYSTEM

Ricardo’s RapidAir® modelling system has been used to model dispersion of NOx emissions from road traffic and NRMM across the Greater London citywide domain. RapidAir® is Ricardo Energy & Environment’s proprietary modelling system developed for urban air pollution assessment.

The RapidAir® model produces high resolution concentration fields at the city scale (1 to 3m scale) so is ideal for spatially detailed air quality modelling and assessment. A validation study has been conducted in London using the same datasets as the 2011 Defra inter-comparison study[18]. Modelling road traffic emissions derived from the LAEI 2008 traffic activity data, the results compared with the corresponding 2008 air quality measurements demonstrated that model performance was consistent (and across some metrics performed better) than other modelling solutions currently in use in the UK. The results of this study have been published in the peer reviewed journal ‘Environmental Modelling and Software’[19].

The model is based on convolution of an emissions grid with dispersion kernels derived from the USEPA AERMOD[20] model. The physical parameterisation (release height, initial plume depth and area source configuration) closely follows guidance provided by the USEPA in their statutory road transport dispersion modelling guidance[21]. AERMOD provides the algorithms which govern the dispersion of the emissions and is

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[17] Defra (2023) https://laqm.defra.gov.uk/air-quality/air-quality-assessment/background-maps/

[18] https://uk-air.defra.gov.uk/research/air-quality-modelling?view=intercomparison

[19] Masey, Nicola, Scott Hamilton, and Iain J. Beverland. "Development and evaluation of the RapidAir® dispersion model, including the use of geospatial surrogates to represent street canyon effects." *Environmental Modelling & Software* (2018). DOI: https://doi.org/10.1016/j.envsoft.2018.05.014

[20] https://www3.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod

[21] https://www.epa.gov/state-and-local-transportation/project-level-conformity-and-hot-spot-analyses

an accepted international model for air quality assessment (it is one of only two mandated models in the US and is widely used overseas for this application).

3.3 METEOROLOGICAL DATA

Modelling was conducted using the 2019 annual surface meteorological dataset measured at Heathrow Airport. The dataset was downloaded and processed in house using RapidAIR's built-in meteorological data processing system. We use freely available overseas meteorological databases which hold the same observations as supplied by UK meteorological data vendors. The RapidAir meteorological processor also takes account of 'upper air' observation data which profiles the vertical structure of the atmosphere (wind speed, direction, temperature and pressure). The data is then used to determine the height of the planetary boundary layer at noon and contributes to the calculation of turbulent mixing in the lower atmosphere.

The upper air data was obtained from the closest radiosonde site and process with the surface data in RapidAIR's automated controller for the USEPA AERMET model. RapidAIR utilises data filling where necessary following USEPA guidance which sets out the preferred hierarchy of routines to account for small gaps of a few hours (persistence, interpolation, substitution). RapidAIR's processing ensures that all aspects of the meteorological data handling is conducted following the USEPA guidance. To account for differences between the meteorological site and the dispersion site, surface parameters at the met site were included as recommended in the guidance and the urban option specified for the dispersion site; land use parameters are automatically handled in RapidAIR, the source data for which is derived from the CORINE land cover datasets[22].

A wind rose for the 2019 Heathrow airport met dataset is presented in Appendix A.

3.4 NRMM EMISSIONS

NOx emissions from the 'Industry NRMM' and 'Construction NRMM' sectors at 1km resolution have been calculated for each assessment scenario, then converted to emission rates expressed in grams per $10m^2$ to provide 10m resolution emission grids inputs for the RapidAir® model (in 'Area Source mode'). A 10m resolution dispersion kernel modelled at an emission height of 5m was created for use in the RapidAir convolution routines. The NRMM emission calculation method is described earlier in this report (Section 2.3).

3.5 ROAD TRAFFIC ACTIVITY DATA

3.5.1 Average flow, speed and fleet split

The LAEI provides spatially accurate GIS polyline shapefiles representing the major road network in London; this provides road traffic activity data for ~79,500 separate road link sections.

For each individual link the following activity data provided was used in the link emission calculations:

- Annual average daily traffic (AADT) for each vehicle type category – Car, Taxi, LGV, HGV Rigid, HGV Artic, Bus, Coach and motorcycle.
- Average speed (kph)
- Road type (London outer, inner and centre (ULEZ))

3.5.2 Time varying traffic activity profiles and congestion

Congestion occurs during peak traffic periods at busy locations on the road network. During congested periods, average vehicle speeds reduce when compared to the daily average; the combination of slower average vehicle speeds and more vehicles lead to higher pollutant emissions during peak hours; it's therefore important to account for this when modelling vehicle emissions to estimate pollutant concentrations.

The LAQM.TG(16) guidance states that the preferred approach to representing the increase in vehicle emissions during peak periods is to calculate the emission rate for the affected roads for each hour of the day

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[22] EEA (2018) https://www.eea.europa.eu/publications/COR0-landcover

or week, using average speeds and traffic flow observations for each hour of the day. The hourly specific emission rates can then be used to calculate a 24-hour diurnal emission profile which can be applied to that section of road.

In this case hourly resolution average speed data was not available to calculate a 24-hour diurnal emission profile; we were however able to calculate an average diurnal traffic flow profile using national traffic statistics describing typical variation in daily traffic flow TRA0307[23].

3.5.3 Vehicle emission factors

The latest version of the Emissions Factor Toolkit[24] (EFT V11.0(Nov 2021)) was used in this assessment to calculate pollutant emission rates for each road link modelled.

Parameters such as road type traffic volume, speed and fleet composition are entered into the EFT, and an emissions factor in grams of pollutants/kilometre/second is generated for input into the dispersion model. Version 11.0 the latest version of the EFT uses the latest COPERT 5.3 NOx and PM emissions factors. These emission factors are widely used for the purpose of calculating emissions from road traffic in Europe. Defra recognises these as the current official emission factors for road traffic sources when conducting local, regional and national scale dispersion modelling assessments.

The EFT utilises bespoke vehicle fleet information and projections for London, provided by Transport for London (TfL) - Fleet composition data in London for motorways, central, inner and outer areas. This includes fleet makeup information specific to the London LEZ and ULEZ areas of the city. The London datasets are inclusive of the impact from 2019 onwards of the Ultra-Low Emissions Zone (ULEZ) in central London, the TfL bus fleet meeting the ULEZ requirements London-wide in 2020 and all new taxis registered from 2018 onwards being Zero Emissions Capable (ZEC)[25].

The EFT also includes a ‘user euro’ option whereby the proportion of vehicle age/euro classification can be amended to bespoke values for any vehicle type. In this study we have used this option to set all vehicle types to the latest and best available emission standard (typically Euro 6 for heavy vehicles and Euro 6d for light vehicles) for Scenario/Test case 2.

3.6 OTHER SECTOR EMISSIONS AND RURAL BACKGROUND CONCENTRATIONS

The Pollution Climate Mapping (PCM) model is a collection of models designed to fulfil part of the UK's EU Directive (2008/50/EC) requirements to report on the concentrations of particular pollutants in the atmosphere. These models are run by Ricardo Energy & Environment on behalf of Defra and model various source sectors and roadside concentrations for the UK.

The PCM Model is used to produce pollutant background maps covering the UK at 1km resolution. The background maps provide estimates of annual mean background concentrations of key pollutants from a base year of 2018 and can be projected forward to future years up to 2030.

The maps are calculated by summing contributions from the following national scale model outputs[26]:

- Large point sources – modelled using the air dispersion model ADMS and emissions estimates from the UK National Atmospheric Emissions Inventory 2018 (NAEI 2018).
- Small point sources – modelled using the small points model and emissions estimates from the NAEI 2018.

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[23] https://www.gov.uk/government/statistical-data-sets/road-traffic-statistics-tra

[24] https://laqm.defra.gov.uk/review-and-assessment/tools/emissions-factors-toolkit.html

[25] Defra(2021) Emissions Factors Toolkit v11.0 User Guide November 2021

[26] Ricardo Energy & Environment (2021) Technical report on UK supplementary assessment under The Air Quality Directive (2008/50/EC), The Air Quality Framework Directive (96/62/EC) and Fourth Daughter Directive (2004/10 for 2019; Report for The Department for Environment, Food and Rural Affairs, The Welsh Government, The Scottish Government and The Department of the Environment for Northern Ireland; Ricardo Energy & Environment/R/3472 ED 12633 | Issue Number 1 Date 12/02/2021

- EU Emissions Trading Scheme (ETS) point sources – those above the large point source modelling threshold or with emission release characteristics are modelled as large point sources those below the modelling threshold are modelled using the small points model and emissions estimates from the NAEI 2018.
- Distant sources – characterised by the rural background concentration.
- Area sources related to domestic combustion – modelled using a time varying dispersion kernel and emissions estimates from the NAEI 2018.
- Area sources related to combustion in industry – modelled using the small points model and emissions estimates from the NAEI 2018.
- Area sources related to road traffic – modelled using a dispersion kernel using time varying emissions and emissions estimates from the NAEI 2018.
- Other area sources – modelled using a dispersion kernel and annual emissions estimates from the NAEI 2018 – **Note: NRMM emissions are included in this 'Other' area sources sector.**

For total oxides of nitrogen (NOx), PM_{10} and $PM_{2.5}$ the maps are provided as both total annual mean and disaggregated into contributions from the various emission source sectors. This allows the contribution of sources being modelled explicitly to be removed to avoid double counting of e.g. road traffic emissions.

For this assessment the contribution from all road source sectors that were modelled explicitly were subtracted from the background maps to avoid double counting. Equally, for NRMM, the contribution was discounted from the 'Other' sector contribution in the background maps.

3.7 NOx TO NO_2 CHEMISTRY

It is necessary to convert the modelled NO_x concentrations to NO_2 for comparison with the relevant air quality objectives. The latest version of the Defra NO_x/NO_2 calculator[27] (a Microsoft excel spreadsheet tool) was used to calculate NO_2 for comparison from the modelled NO_x concentrations. The model requires input of the background NO_x, the modelled road (and in this case NRMM) contribution and accounts for an estimated regional proportion of NO_x released as primary NO_2. NOx emissions from NRMM internal combustion engines will react and convert to NO_2 in a comparable way to road traffic emissions.

To convert NOx to NO_2 for mapping model outputs for large model domains, use of the spreadsheet tool is not practical because the calculator is limited to a maximum of 64.6K lines. When domain wide NO_2 concentration maps are required, outputs from the NOx to NO_2 calculator can be used to define a statistical relationship between NO_2 concentrations and the various input parameters. In this case the statistical relationship was derived using an ordinary least squares (OLS) regression model. The OLS model was derived by defining background NOx, road + NRMM NOx, and primary NO_2 as the independent variables, and total NO_2 as the dependent variable.

3.8 MODEL VERIFICATION

Verification of the model involves comparison of the modelled results with any local pollutant measurements; this assesses how the model is performing. The predicted results from a dispersion model may differ from measured concentrations for many reasons such as:

- Estimates of background concentrations.
- Meteorological data uncertainties.
- Uncertainties in source activity data and emissions factors.
- Model input parameters such as roughness length, minimum Monin-Obukhov; and overall model limitations; and
- Uncertainties associated with monitoring data, including locations.

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[27] Defra(2020) NOx to NO_2 Calculator v8.1; available to download at https://laqm.defra.gov.uk/air-quality/air-quality-assessment/nox-to-no2-calculator/

The verification process also involves checking and refining the model input data to try and reduce uncertainties and produce model outputs that are in acceptable agreement with measurements. This can be followed by adjustment of the model results if required to gain good agreement.

The model verification method described in the LAQM.TG(16) guidance is focused on modelling of road traffic emissions. The guidance recommends making the adjustment to the road component of the pollutant only and not the background concentration these are combined with i.e. it is considered best practice to verify and compare the modelled non-background component at measurement sites.

In this case we are assessing the impact of NRMM emissions, and hence model performance with respect to the predicted NRMM NOx component. As such, NRMM NOx has been included with Road NOx as the modelled non-background component. This approach aims to produce a worst-case assessment of NRMM emissions as any adjustment to the non-background component will be applied equally to the road and NRMM NOx component.

As the focus of this assessment is the impact of technology changes to NRMM on NOx emissions, and not policies relating to road traffic emissions, we have compared modelled versus measured NOx at non-roadside measurement sites.

It is appropriate to verify the performance of the RapidAir model in terms of primary pollutant emissions of nitrogen oxides (NOx = NO + NO_2). To verify the model, the predicted annual mean Road + NRMM NOx concentrations were compared with concentrations measured at the various monitoring sites during 2019. An estimate of measured Road+NRMM NOx at each site was back calculated using measured NO_2 and the background NOx in the NOx to NO_2 calculator. Using this approach means that the same NOx to NO_2 chemistry scheme is being applied throughout the modelling process.

The gradient of the best fit line for the modelled Road+NRMM NOx vs. measured Road+NRMM NOx was then determined using linear regression and used as a global/domain wide Road NOx adjustment factor. This factor was then applied to the modelled Road NOx concentration at each discretely modelled receptor point to provide adjusted modelled Road NOx concentrations. A linear regression plot comparing modelled and monitored Road NOx concentrations before and after adjustment is presented in Figure 7. A primary NOx adjustment factor (PAdj) of **1.6159** based on citywide/global model verification excluding outliers was applied to all modelled Road+NRMM NOx data. Annual mean NO_2 concentrations were then determined using the NOx/NO_2 calculator to combine background and adjusted Road+NRMM NOx contribution concentrations.

A plot comparing modelled and monitored NO_2 concentrations before and after adjustment during 2019 is presented in Figure A2.

Model uncertainty was evaluated by calculating the root mean square error (RMSE) of the modelled vs measured annual mean NO_2 concentrations. The LAQM.TG(16) guidance suggests that an RMSE value of less than 10% of the objective being assessed indicates acceptable model performance. The calculated RMSE of the modelled vs measured annual mean NO_2 concentrations was just over 4 $\mu g.m^{-3}$ after adjustment, which is the suggested value (10% of the objective being assessed). The model has therefore performed reasonably well for use within this type of assessment.

Figure 7: Comparison of modelled Road + NRMM NOx Vs Measured before and after adjustment

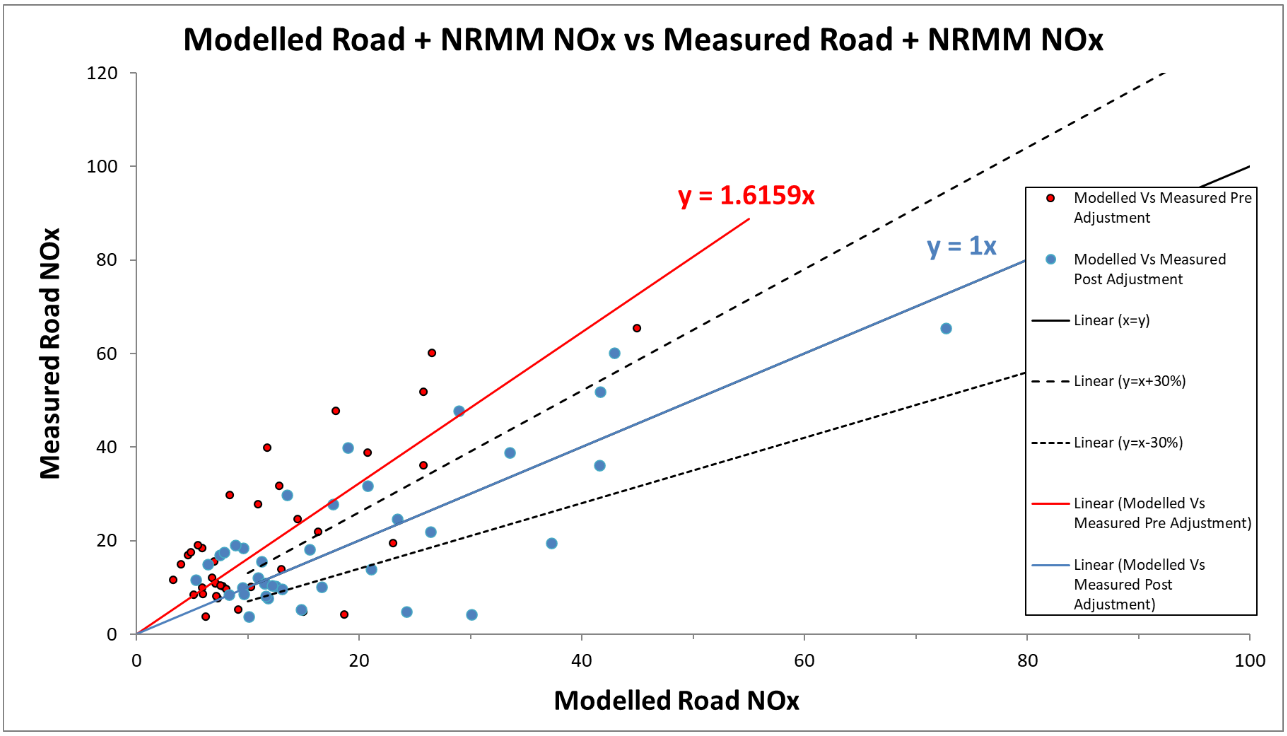


Figure 8: Modelled vs. measured NO_2 annual mean 2019 at urban background and industrial measurement sites.

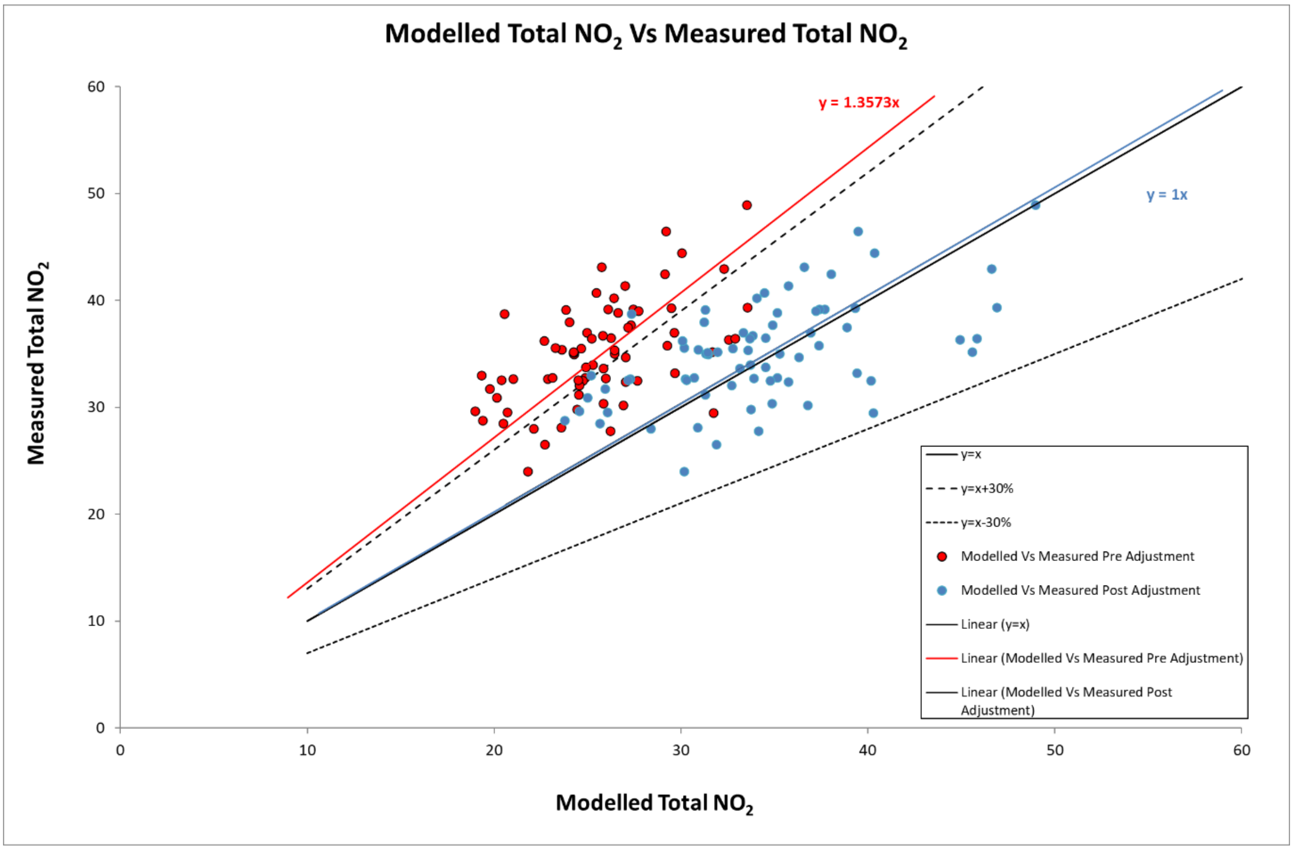


Table 3-1: Measured vs modelled NO_2 post adjustment

Measurement site	Measured NO_2 ($\mu g.m^{-3}$)	Modelled NO_2 ($\mu g.m^{-3}$)
London Bexley	22.7	18.4
London Bloomsbury	31.5	42.8
London Eltham	17.3	19.3
London Haringey Priory Park South	21.9	21.7
London Harlington	30.7	30.2
London Hillingdon	44.7	38.1
London N. Kensington	27.3	30.3
London Westminster	33.7	33.2
Tower Hamlets - Millwall Park	23.6	24.1
Tower Hamlets - Victoria Park	24.0	25.1
Waltham Forest Dawlish Rd	24.1	24.4
Waltham Forest Leyton	31.6	27.0
Barnet Chalgrove School	24.9	23.7
Hillingdon Harmondsworth	23.7	26.8
Heathrow LHR2	42.5	46.5
Hillingdon Sipson	29.7	30.0
Hounslow Cranford	25.6	27.3
Hounslow Chiswick	40.1	32.4
Hounslow Hatton Cross	27.0	28.6
Hounslow Feltham	27.2	29.2
Newham Wren Close	26.4	29.7
Bexley - Belvedere West	20.9	17.8
City of London - The Aldgate School	33.2	41.6
Ealing - Acton Vale	26.5	24.4
Enfield - Bush Hill Park	22.4	17.8
Enfield - Prince of Wales School	22.6	17.7
Harrow - Stanmore	20.3	16.1
Islington - Arsenal	24.8	25.6
Lambeth - Bondway Interchange	47.5	50.0
Lambeth - Streatham Green	32.0	34.3
Lewisham - Catford	33.2	31.0
Lewisham - Honor Oak Park	24.1	19.4
Redbridge - Ley street	29.8	22.4
Richmond Upon Thames - Barnes Wetlands	21.1	21.1
Southwark - Elephant and Castle	30.4	38.0
Sutton - Beddington Lane north	29.4	24.5
Wandsworth - Putney	35.3	26.2
Wandsworth - Wandsworth Town Hall	40.6	36.5
	RMSE	**4.46**

4. MODEL RESULTS

As described in the report introduction (Section 0), the following scenarios/test cases have been modelled.

1. Scenario/Test Case 1: 2019 baseline
2. Scenario/Test Case 2: 2019 All NRMM and road traffic comply with the best available NOx emission standards
3. Scenario/Test Case 3: 2019 The impact of hydrogen powered (H2ICE) NRMM is assessed “relative to a hypothetical scenario where no NRMM or ICE powered road traffic are operational within London, whereby:
    - All NRMM with power rating <=19kW is zero emitting
    - All NRMM with power rating >19kW will be hydrogen powered and operate at a NOx emission rate of 0.02 g/kWh.

Intuitively it is clear that we expect to see beneficial impacts i.e. reduction in NOx and NO_2 annual mean for all three emission reduction scenarios when compared with the 2019 baseline. The results of Scenario 3 (Hydrogen ICE powered NRMM > 19kW) are presented versus a hypothetical scenario where no NRMM or ICE powered road traffic are operational within London. This approach aims to provide an assessment of the potential adverse impact of hydrogen powered NRMM when compared to a emissions removed scenario, as opposed to quantifying the beneficial impact when compared with the existing baseline.

For all pollutants assessed, modelled annual mean concentrations have been presented using:

- Contours plot mapping representing the modelled spatial variation in modelled NOx concentrations; and show hotspot locations.
- Source apportionment bar charts at a selection of worst-case receptor locations, to show the relative contribution of NRMM, road traffic, and other source sectors to the total modelled NOx annual mean.
- Tabulated numerical NO_2 annual mean at receptor points where there is an air quality measurement site or a location with relevant human exposure e.g. façade of a residential building; these results can be compared with the air quality objectives.

The pollutant contours and receptor locations have been modelled at 1.5m above ground level to represent human exposure at head height. Results for each scenario are presented in turn below.

4.1 MAPPED RESULTS

4.1.1 Scenario/test case 1: 2019 Baseline

The air quality assessment is primarily aimed at understanding the likely impact of changes to NOx emissions from NRMM on ambient NOx and hence NO_2 concentrations. To provide some context in terms of the relative impact of NRMM on baseline air quality, it is useful to understand the magnitude and range of modelled NOx concentrations attributable to NRMM emissions only; compared with the contribution from all other source sectors modelled.

Maps showing total modelled annual mean NOx attributable to estimated ‘Construction NRMM’ and ‘Industrial NRMM’ activity in 2019 are presented in Figure 9 and Figure 10 respectively, with the summed outputs representing total NRMM in Figure 11.

These plots show that:

- Maximum NOx annual mean concentrations attributable to both Construction and Industry NRMM source sectors are in the central area of London.
- The maximum modelled contribution to annual mean NOx in 2019 for:
    - Construction NRMM is ~5 $\mu g.m^{-3}$
    - Industrial NRMM is ~1.4 $\mu g.m^{-3}$
    - Construction NRMM + Industrial NRMM is ~5.8 $\mu g.m^{-3}$

Figure 9: 2019 Baseline NOx annual mean (µg.m^{-3}) – Construction NRMM

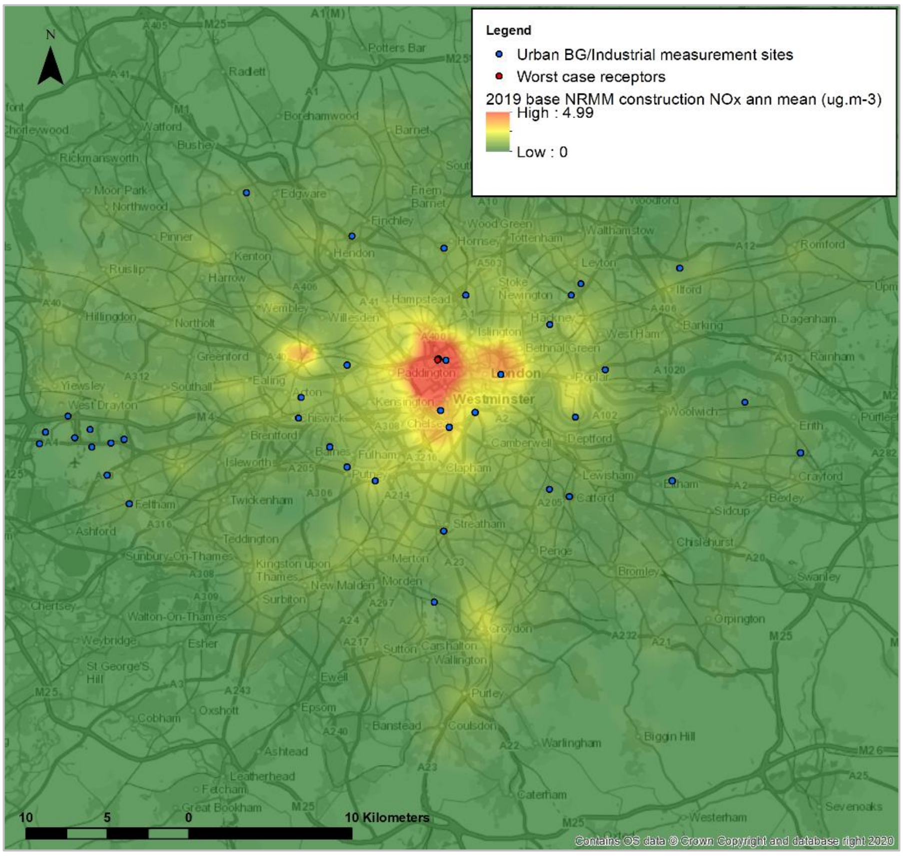


Figure 10:2019 Baseline NOx annual mean (µg.m^{-3}) – Industry NRMM

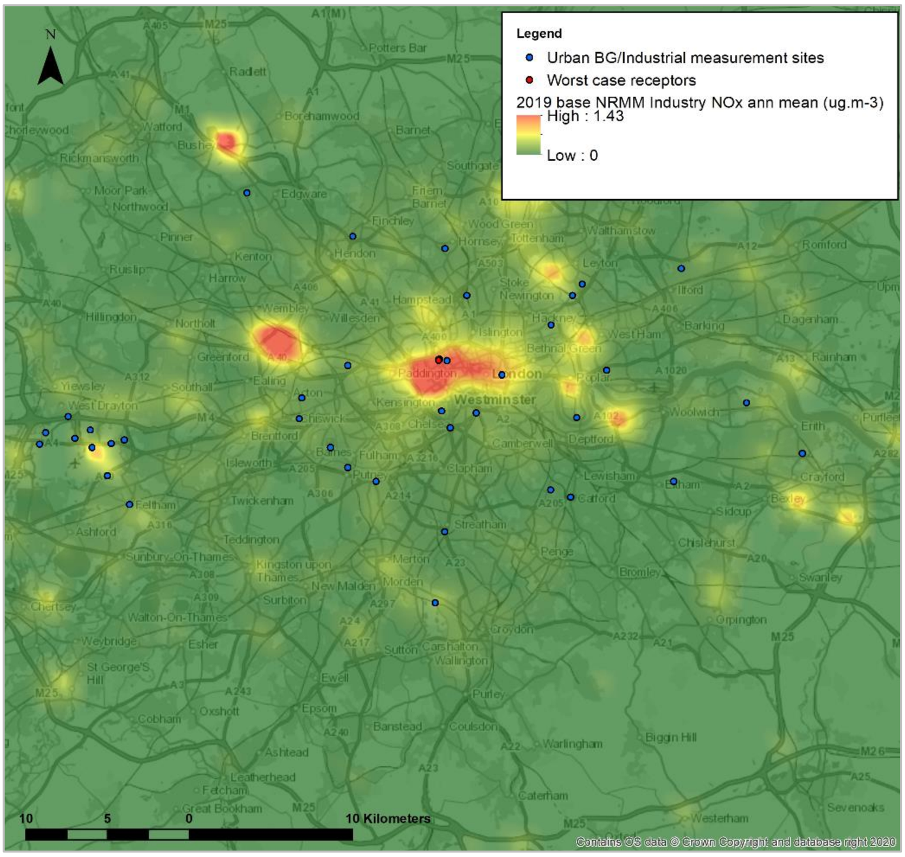
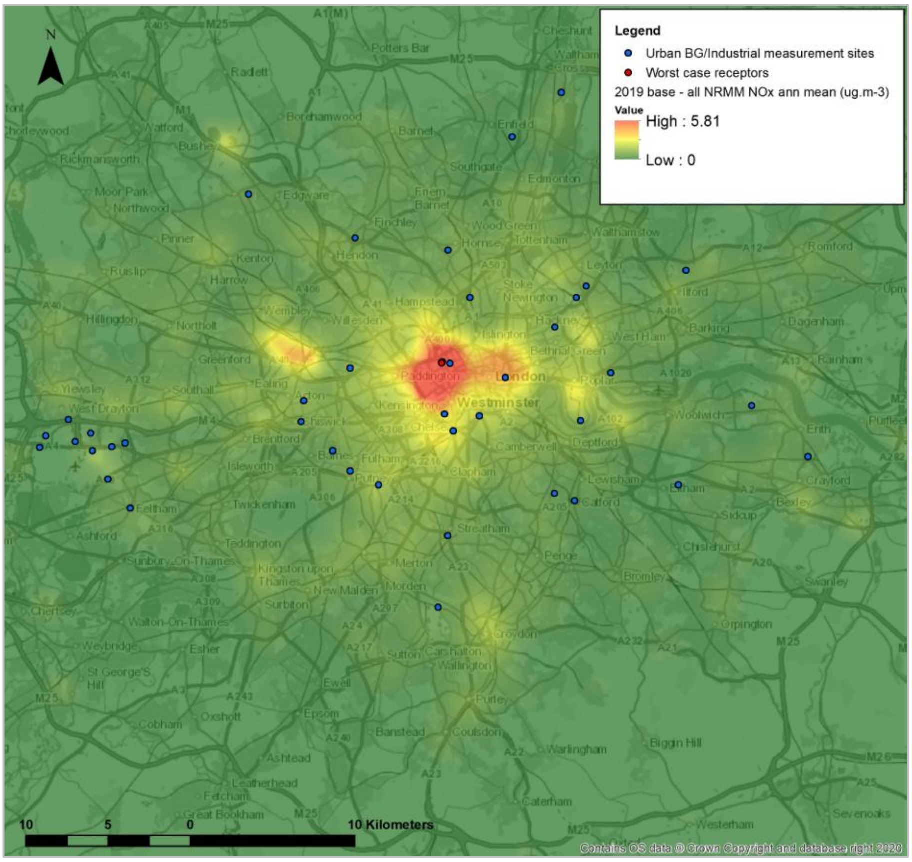


Figure 11: 2019 Baseline NOx annual mean (µg.m^{-3}) – Construction NRMM + Industry NRMM



Maps showing NOx from all NRMM combined with road traffic and all other sectors/background sources are presented in Figure 12 (whole city) and Figure 13. (Central London). **We can see from these model outputs that:**

- **The maximum modelled NOx annual means are at roadside locations, road traffic is clearly a dominant source of NOx in London. The maximum annual mean of ~255 µg.m^{-3} (likely located in busy road carriageway) is approximately 51 times greater than the max NRMM contribution.**
- **The influence of Heathrow airport and density of traffic and other source sector activity in central London is apparent in the mapped 2019 baseline NOx annual mean.**
- **NOx annual mean contribution from NRMM emissions are no longer easy to distinguish when mixed with NOx from the much more dominant road traffic and other sector/background sources in these mapped model outputs.**

To help demonstrate the proportion of NOx that NRMM is contributing; we have included a simple source apportionment analysis at a small selection of receptor locations. The receptors are all within the Central London area where the maximum NRMM NOx concentrations have been modelled. Receptors include two urban background measurement stations – London Westminster and London Bloomsbury; and a worst-case receptor (in terms of predicted NRMM NOx) representing potential human exposure at a building façade at Mallett Street.

Source apportionment is the process whereby the contribution of different pollutant sources to annual mean concentrations are quantified. This aims to provide information about which sources are most significant and is generally used when considering measures to improve air quality.

Bar charts showing source apportionment at each location for the 2019 baseline scenario are presented on Figure 14. At all locations NRMM contributes a small proportion of overall NOx when compared with the contribution from road traffic and other source sectors/background.

Figure 12: 2019 Baseline NOx annual mean (µg.m^{-3}) – all NRMM + Road traffic + all other sectors - Citywide

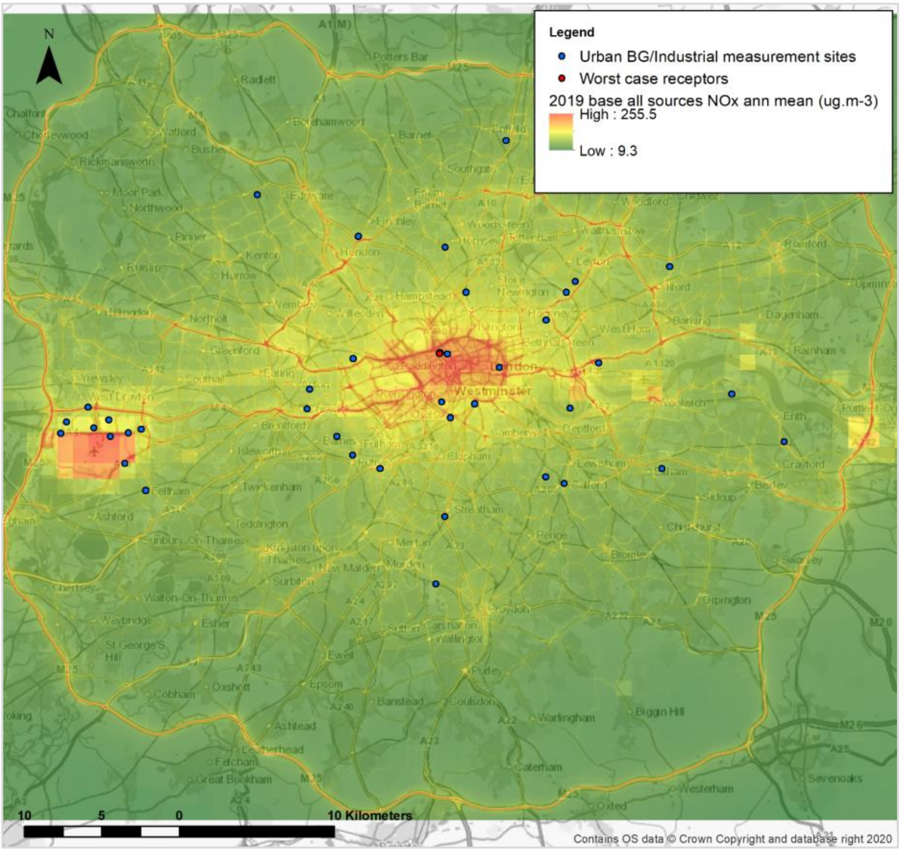


Figure 13: 2019 Baseline NOx annual mean– all NRMM + Road traffic + all other sectors - Central London

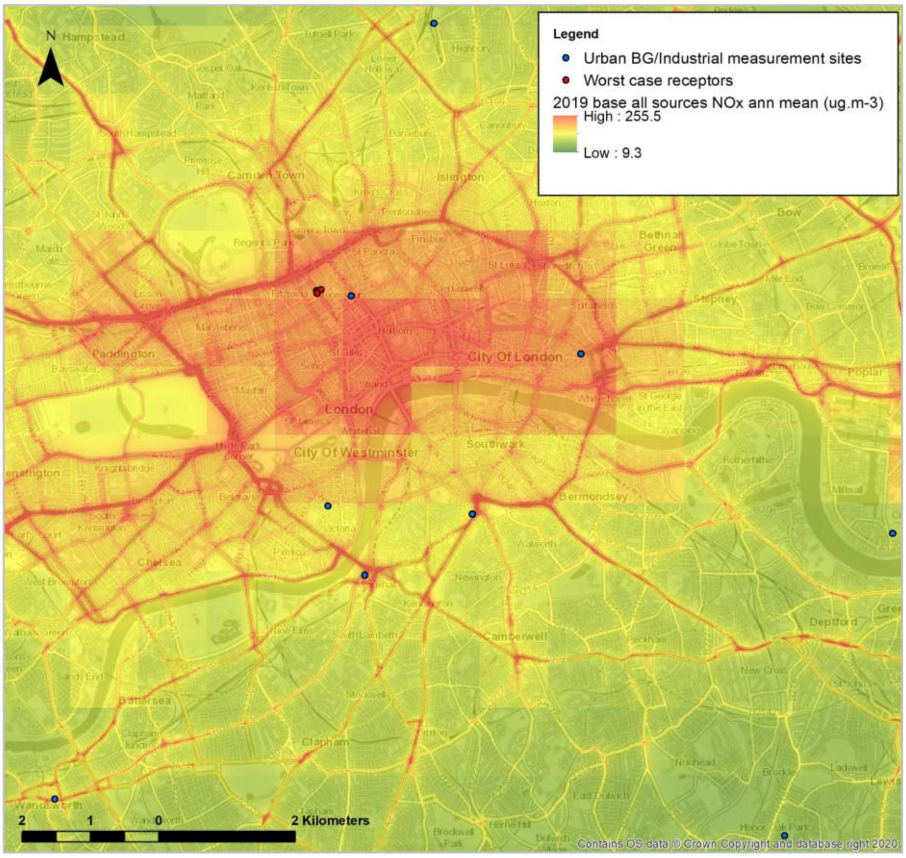
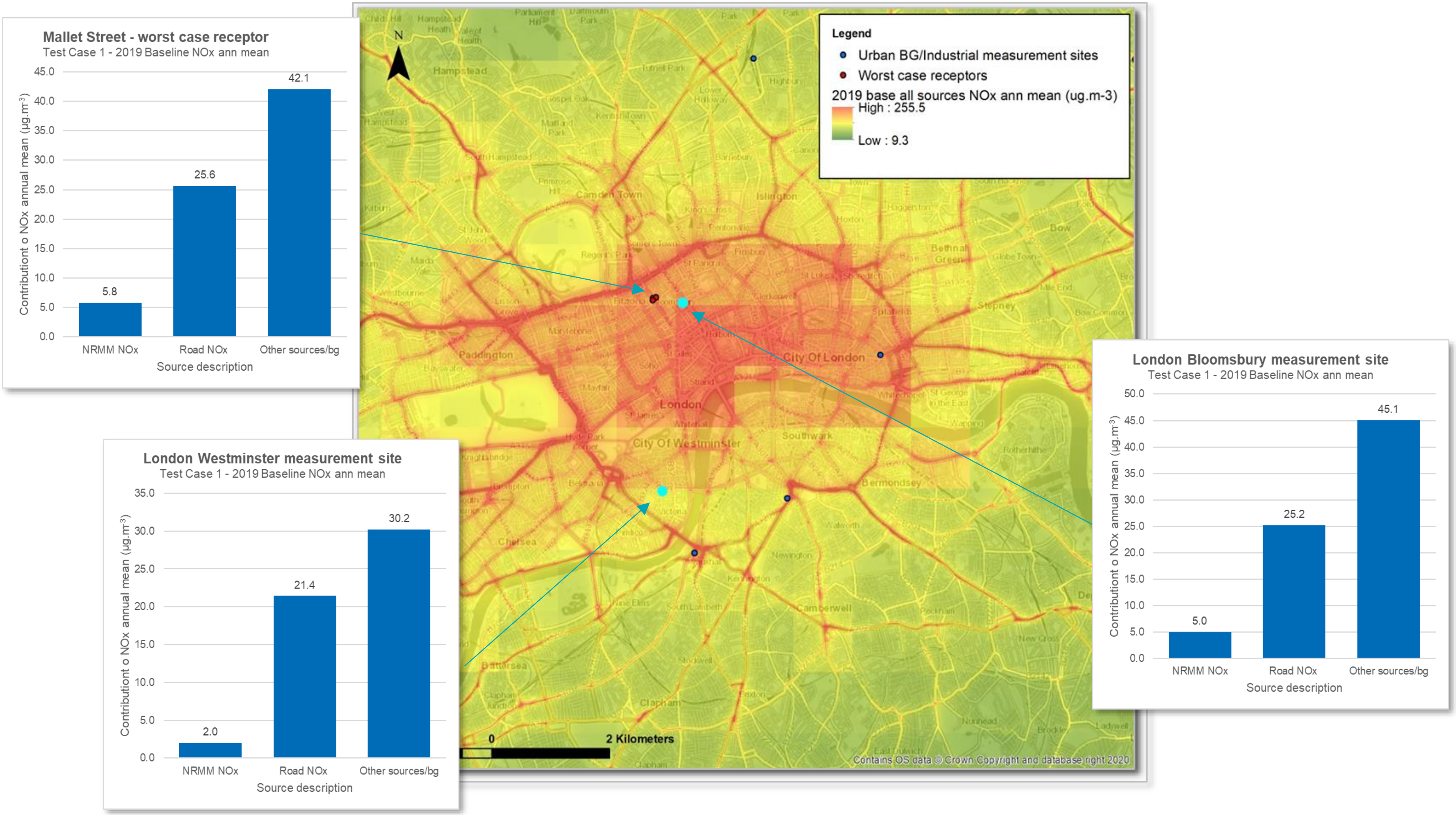


Figure 14: 2019 Baseline NOx annual mean mapped model results and source apportionment at three locations



4.1.2 Scenario/Test Case 2

Scenario/Test Case 2 simulates all internal combustion engine (ICE) NOx emission rates corresponding with the best available emissions standards. For NRMM this is the equivalent of EMEP Tier 3 Stage V, and for road traffic is Euro 6D or the newest available emission standard for each vehicle type.

Mapped results and source apportionment charts for this test case are shown in Figure 15. In this case, the source apportionment also includes NRMM power rating sub-categories for plant with power ratings either side of 56kW rating, above which SCR[28] exhaust NOx abatement is typically used on NRMM.

The Test case 2 results show:

- **The maximum NOx annual mean across the model domain reduces by ~58 μg.m^{-3}; this maximum is likely to be at a road carriageway location.**
- **Road NOx is reduced by approximately 2/3rd at our worst-case receptor locations.**
- **NRMM NOx is reduced by approximately 1/3rd when all plant has Stage V emissions rates applied, calculated using the EMEP Tier 3 methodology**

4.1.3 Scenario/Test Case 3

Scenario/Test Case 3 models the impact of hydrogen powered (H2ICE) NRMM is assessed relative to a hypothetical scenario where no NRMM or ICE powered road traffic are operational within London.

The underlying method to calculate NRMM NOx emissions for this scenario can be summarised as:

- All NRMM with power rating <=19kW is zero emitting
- All NRMM with power rating >19kW will be hydrogen powered and operate at a NOx emission rate of 0.02 g/kWh.

Mapped results and source apportionment charts for this test case are shown below in Figure 16.

The modelled impact of H2ICE NRMM on annual mean NOx concentrations is very small, almost imperceptible. The maximum impact we see at the Mallet Street receptor is 0.019 μg.m^{-3}. When rounding predicted concentrations to one decimal place as presented in our mapped outputs, the impact of the H2ICE NRMM is rounded out and therefore becomes imperceptible.

In the next section we present a comparison of tabulated numerical model results and associated impact descriptors.

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[28] Selective Catalytic Reduction (SCR)

Figure 15: Test Case 2 NOx annual mean mapped model results and source apportionment at three locations

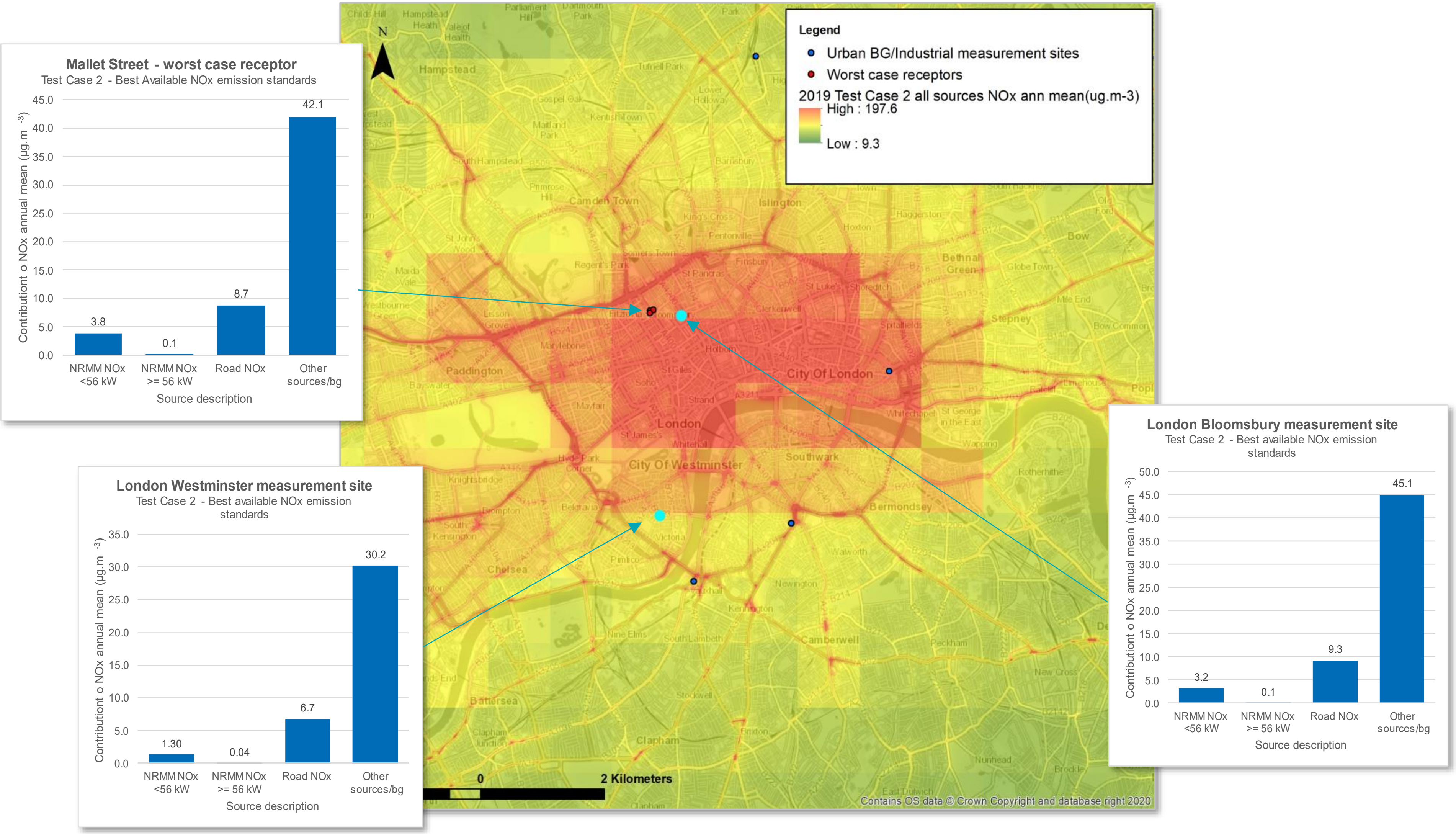
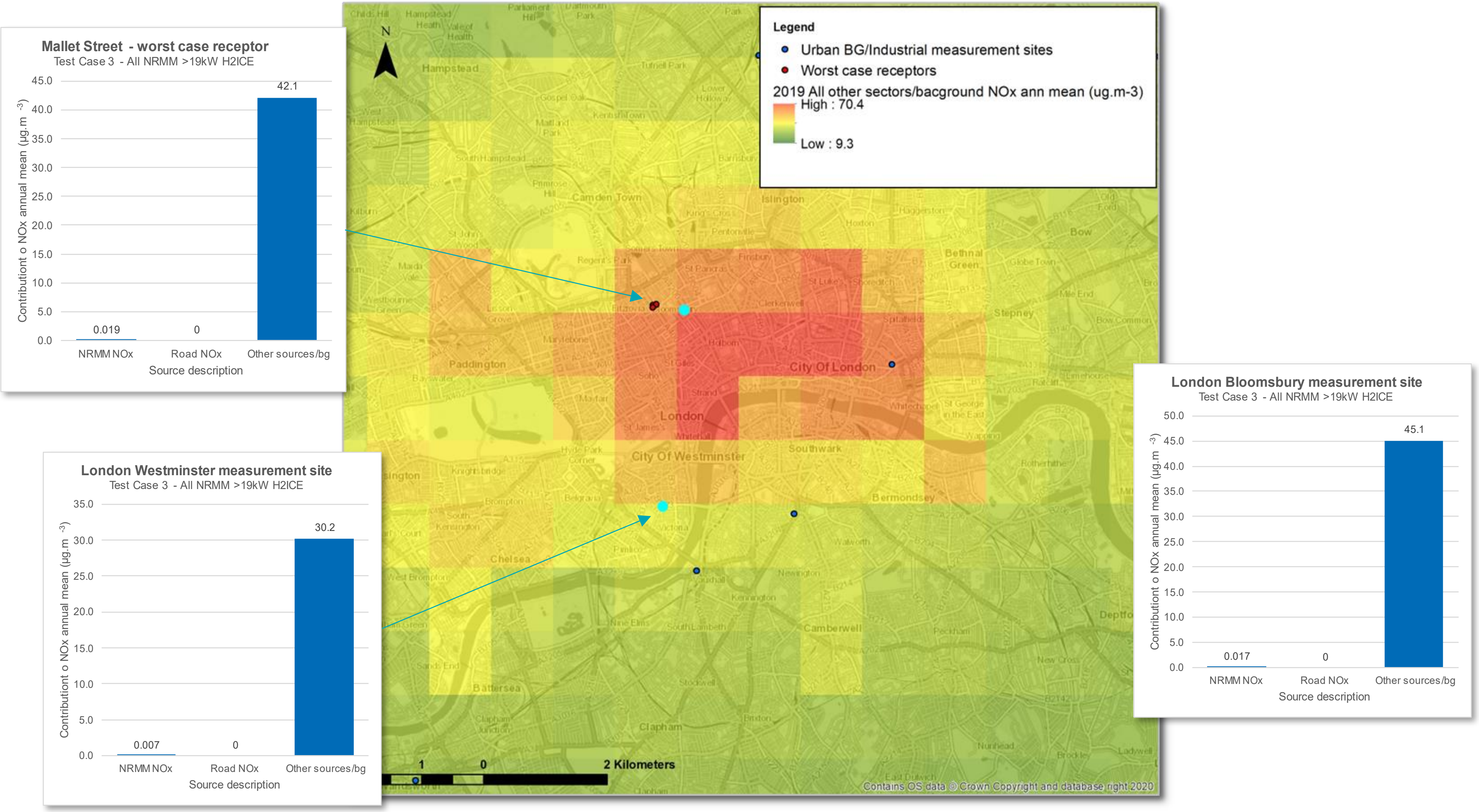


Figure 16: Test Case 3 – No road traffic, All NRMM <= 19kW zero emitting, all NRMM >19kW hydrogen powered (NOx emission rate of 0.02 g/kWh)



4.2 TABULATED RESULTS AND IMPACT ASSESSMENT

Tabulated numerical NO_2 annual mean at receptor points where there is an air quality measurement site or a location with relevant human exposure e.g. façade of a residential building are presented in Table 4-1.

The results include IAQM/EPUK impact descriptors for the Hydrogen NRMM (Scenario/Test Case 3 - when H2ICE powered NRMM is assessed against a hypothetical scenario where no traditionally powered NRMM or ICE powered road traffic are operational within London). At all receptors the magnitude of increase in NOx, and hence NO_2 concentrations is so small that there is no perceptible change in modelled NO_2 annual mean.

The IAQM/EPUK method recommends rounding the magnitude of change (expressed as a percentage of the objective being assessed) to the nearest 1%, anything less than 0.5% will be described as negligible. When assessing NO_2 impacts using this method 0.5% of the 40 $\mu g.m^{-3}$ objective equals 0.2 $\mu g.m^{-3}$; any predicted change less than 0.2 $\mu g.m^{-3}$ is therefore classified as negligible.

The modelled magnitude of change in NOx/NO_2 concentrations can also be considered in context with the measurement limit of detection. This varies depending on the measurement method, type of analyser used and is usually expressed in parts per billion (ppb). The limit of detection for automatic analysers in use in the UK AURN air quality measurement network range from 0.2 to 1.2 ppb (~0.4 $\mu g.m^{-3}$ to 2.3 $\mu g.m^{-3}$)[29]; any change in concentration less than that could therefore be considered beyond the limit of detection using current reference measurement methods.

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[29] TUV Rheinland Immissionsschutz und Energiesysteme GMBH (2007) Translation of the report on the suitability test of the ambient air measuring system M200E of the company Teledyne Advanced Pollution Instrumentation for the measurement of NO, NO_2 and NOx; TUV Report 936/21205926/A2 Cologne, 22.06.2007

Table 4-1: Modelled NO_2 annual mean ($\mu g.m^{-3}$) at measurement sites and receptor locations

Receptor name	Type	2019 Baseline	Test Case 2	Hypothetical baseline (no ICE NRMM or road traffic)	Test Case 3	IAQM/EPUK Impact descriptor Test Case 3 vs Hypothetical baseline
London Bexley	Suburban	18.4	14.9	13.6	13.6	Negligible
London Bloomsbury	Urban background	42.8	35.3	29.5	29.5	Negligible
London Eltham	Suburban	19.3	15.1	13.4	13.4	Negligible
London Haringey Priory Park South	Urban background	21.7	18.4	17.0	17.0	Negligible
London Harlington	Industrial	30.2	26.5	25.0	25.0	Negligible
London Hillingdon	Urban background	38.1	24.5	18.7	18.7	Negligible
London N. Kensington	Urban background	30.3	24.8	22.4	22.4	Negligible
London Westminster	Urban background	33.2	26.2	22.3	22.3	Negligible
Tower Hamlets - Millwall Park	Urban background	24.1	20.8	19.4	19.4	Negligible
Tower Hamlets - Victoria Park	Urban background	25.1	20.9	19.0	19.0	Negligible
Waltham Forest Dawlish Rd	Urban background	24.4	20.5	18.8	18.8	Negligible
Waltham Forest Leyton	Urban background	27.0	21.1	18.5	18.5	Negligible
Barnet Chalgrove School	Urban background	23.7	18.3	16.0	16.0	Negligible
Hillingdon Oxford Avenue	Urban background	43.3	37.6	35.3	35.3	Negligible
Hillingdon Harmondsworth	Urban background	26.8	23.2	21.9	21.9	Negligible
Heathrow LHR2	Industrial	46.5	42.2	40.2	40.2	Negligible
Hillingdon Sipson	Urban background	30.0	26.1	24.5	24.5	Negligible
Heathrow Green Gates	Industrial	40.8	36.4	34.8	34.8	Negligible
Hounslow Cranford	Suburban	27.3	23.3	21.6	21.6	Negligible
Hounslow Chiswick	Urban background	32.4	22.9	18.8	18.8	Negligible
Hounslow Hatton Cross	Urban background	28.6	24.3	22.4	22.4	Negligible
Hounslow Feltham	Urban background	29.2	20.4	16.6	16.6	Negligible
Newham Wren Close	Urban background	29.7	22.9	19.7	19.7	Negligible

Receptor name	Type	2019 Baseline	Test Case 2	Hypothetical baseline (no ICE NRMM or road traffic)	Test Case 3	IAQM/EPUK Impact descriptor Test Case 3 vs Hypothetical baseline
Bexley - Belvedere West	Urban background	17.8	15.8	15.1	15.1	Negligible
City of London - The Aldgate School	Urban background	41.6	35.4	30.9	30.9	Negligible
Ealing - Acton Vale	Urban background	24.4	20.7	18.9	18.9	Negligible
Enfield - Bush Hill Park	Suburban	17.8	15.1	14.0	14.0	Negligible
Enfield - Prince of Wales School	Urban background	17.7	14.4	13.2	13.2	Negligible
Harrow - Stanmore	Urban background	16.1	13.8	12.8	12.8	Negligible
Islington - Arsenal	Urban background	25.6	21.5	19.7	19.7	Negligible
Lambeth - Bondway Interchange	Industrial	50.0	29.4	19.8	19.8	Negligible
Lambeth - Streatham Green	Urban background	34.3	20.7	15.1	15.1	Negligible
Lewisham - Catford	Urban background	31.0	19.7	15.1	15.1	Negligible
Lewisham - Honor Oak Park	Urban background	19.4	16.7	15.5	15.5	Negligible
Redbridge - Ley street	Urban background	22.4	17.8	15.7	15.7	Negligible
Richmond Upon Thames - Barnes Wetlands	Suburban	21.1	18.2	16.9	16.9	Negligible
Southwark - Elephant and Castle	Urban background	38.0	27.5	21.2	21.2	Negligible
Sutton - Beddington Lane north	Industrial	24.5	17.3	14.3	14.3	Negligible
Wandsworth - Putney	Urban background	26.2	19.7	17.0	17.0	Negligible
Wandsworth - Wandsworth Town Hall	Urban background	36.5	23.2	17.6	17.6	Negligible
Gower Street 1	Human exposure	45.7	35.6	28.1	28.1	Negligible
Mallet Street 1	Human exposure	42.0	33.9	28.1	28.1	Negligible
Gower Street 2	Human exposure	43.6	34.7	28.1	28.1	Negligible

5. SUMMARY AND CONCLUSIONS

This report describes an air quality assessment case study to quantify the potential impact of a technology transition to hydrogen powered NRMM. The case study is in an example urban area, Greater London.

The report describes:

- A review of current methods used to quantify NRMM emission in the UK (NAEI) and London (LAEI) emission inventories; and based on the review, a derived method to model the impact of technology changes on emissions from the NRMM fleet.
- Spatially gridded air pollution dispersion simulations for Greater London that compare a series of emission change scenarios against baseline conditions in 2019. Including emissions of oxides of nitrogen (NOx) expressed as annual mean NO_2 concentrations when dispersed. The emission scenarios tested can be summarised as:
  1. Baseline of 2019 NOx contributions in London, based on the London Atmospheric Emissions Inventory (LAEI) at this time.
  2. Repeat of test case 1, 2019 with all internal combustion engine (ICE) NOx contributions modelled to appropriate best available emissions standards (i.e. for NRMM Stage V, For road traffic Euro 6D etc.)
  3. The impact of hydrogen powered (H2ICE) NRMM is assessed relative to a hypothetical scenario where no traditionally powered NRMM or ICE powered road traffic are operational within London, whereby:
     - All NRMM with power rating <=19kW is zero emitting
     - All NRMM with power rating >19kW will be hydrogen powered and operate at a NOx emission rate of 0.02 g/kWh.

The outcomes of the air quality modelling assessment can be summarised as follows:

2019 baseline:

- Maximum NOx annual mean concentrations attributable to both Construction and Industry NRMM source sectors are in the central area of London. This reflects the spatial distribution of NRMM activity and associated NOx emissions reported in the LAEI2019.
- The maximum modelled contribution to annual mean NOx in 2019 for:
  - Construction NRMM is ~5 $\mu g.m^{-3}$
  - Industrial NRMM is ~1.4 $\mu g.m^{-3}$
  - Construction NRMM + Industrial NRMM is ~5.8 $\mu g.m^{-3}$
- When combined with NOx from other sources in the mapped modelled outputs; the contributions from NRMM emissions are no longer easy to distinguish as they are subsumed by the more dominant road traffic and other sector/background sources.
- Source apportionment analysis at three locations in Central London; confirms that NRMM contributes a very small proportion of overall NOx when compared with the contribution from road traffic and other source sectors/background in the 2019 baseline scenario.

Intuitively it is clear that we expect to see beneficial impacts i.e. reduction in NOx and NO_2 annual mean for all three emission reduction scenarios when compared with the 2019 baseline.

Scenario/Test Case 2: When all NRMM and road traffic are modelled using the best available NOx emission standards:

- Road NOx is reduced by approximately 2/3rd at the locations where source apportionment analysis has been conducted.
- NRMM NOx is reduced by approximately 1/3rd when all plant has Stage V emissions rates applied, calculated using the EMEP Tier 3 methodology.

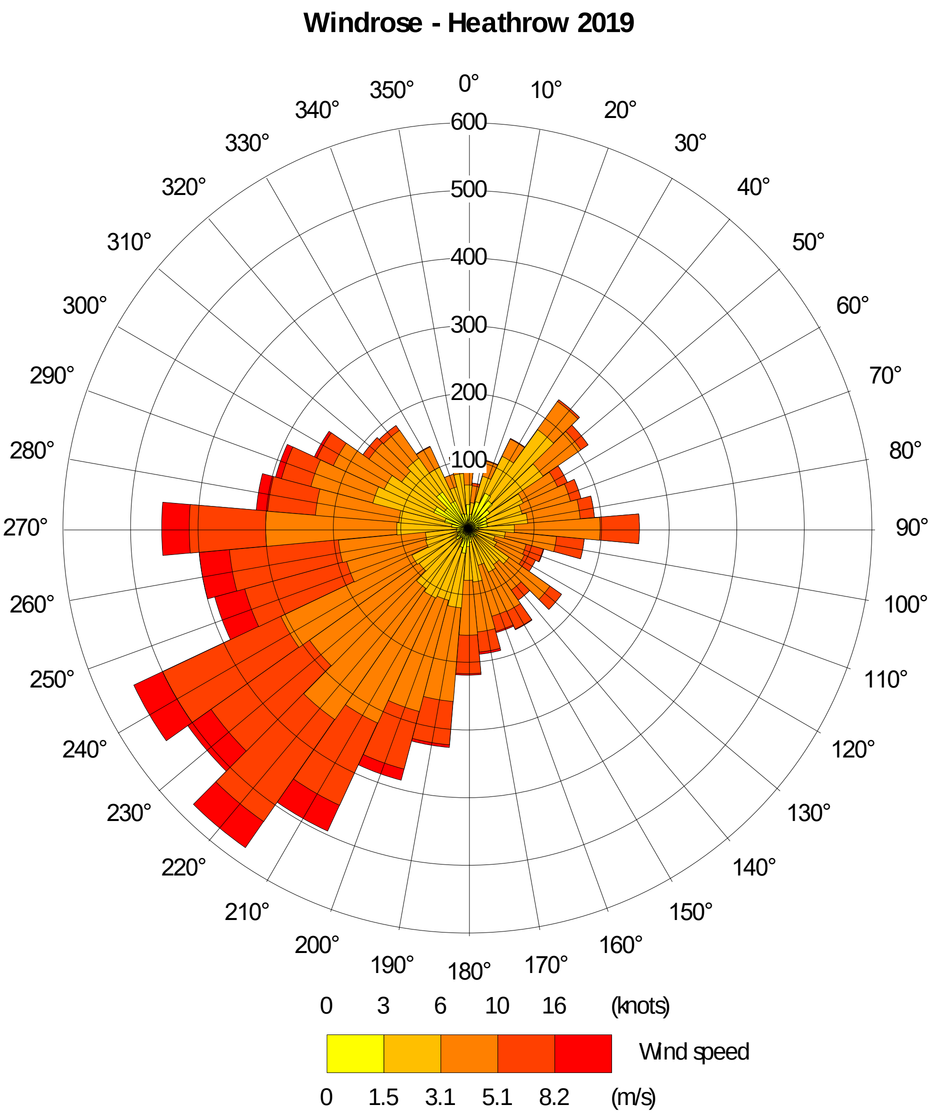
Scenario/Test Case 3: The modelled impact of H2ICE NRMM on annual mean NOx concentrations is very small, almost imperceptible. The maximum impact we see at the Mallet Street receptor is 0.019 µg.m^{-3}. When rounding predicted concentrations to one decimal place as presented in our mapped outputs, the impact of the H2ICE NRMM is rounded out and therefore becomes imperceptible. Assessing this impact using the current UK best practice guidance for assessing air quality impacts for planning purposes; concludes that any impact of less than 0.5% of the air quality objective being assessed is classified as negligible. When assessing NO_2 impacts using this method 0.5% of the 40 µg.m^{-3} objective equals 0.2 µg.m^{-3}; any predicted change less than 0.2 µg.m^{-3} is therefore classified as negligible.

This conclusion could also be considered as robust to significant input variance of the NOx emissions from H2ICE; If H2ICE emissions were doubled, then the impact on annual mean NO_2, at the worst case locations assessed, would still be lower than that required for a “negligible” classification, against either the 40 µg.m^{-3} UK objective, or the more stringent 10 µg.m^{-3} WHO guidance (0.5% of 10 µg.m^{-3} = 0.05 µg.m^{-3}).

The limit of detection for automatic analysers in use in the UK air quality measurement networks range from 0.2 to 1.2 ppb (~0.4 µg.m^{-3} to 2.3 µg.m^{-3}); any change in concentration less than that could therefore be considered beyond the limit of detection using current reference measurement methods.

APPENDICES

APPENDIX 1: METEOROLOGICAL DATASET WINDROSE



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