Cardiff Clean Air Zone – Air Quality Modelling Methodology Report

Report for City of Cardiff Council

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Contact:

Guy Hitchcock

Ricardo Energy & Environment

Gemini Building, Harwell, Didcot, OX11 0QR, United Kingdom

t: +44 (0) 1235 75 3327
e: guy.hitchcock@ricardo.com

Ricardo-AEA Ltd is certificated to ISO9001 and ISO14001

Authors:

Guy Hitchcock, Scott Hamilton, Robert Benney

Approved By:

Guy Hitchcock

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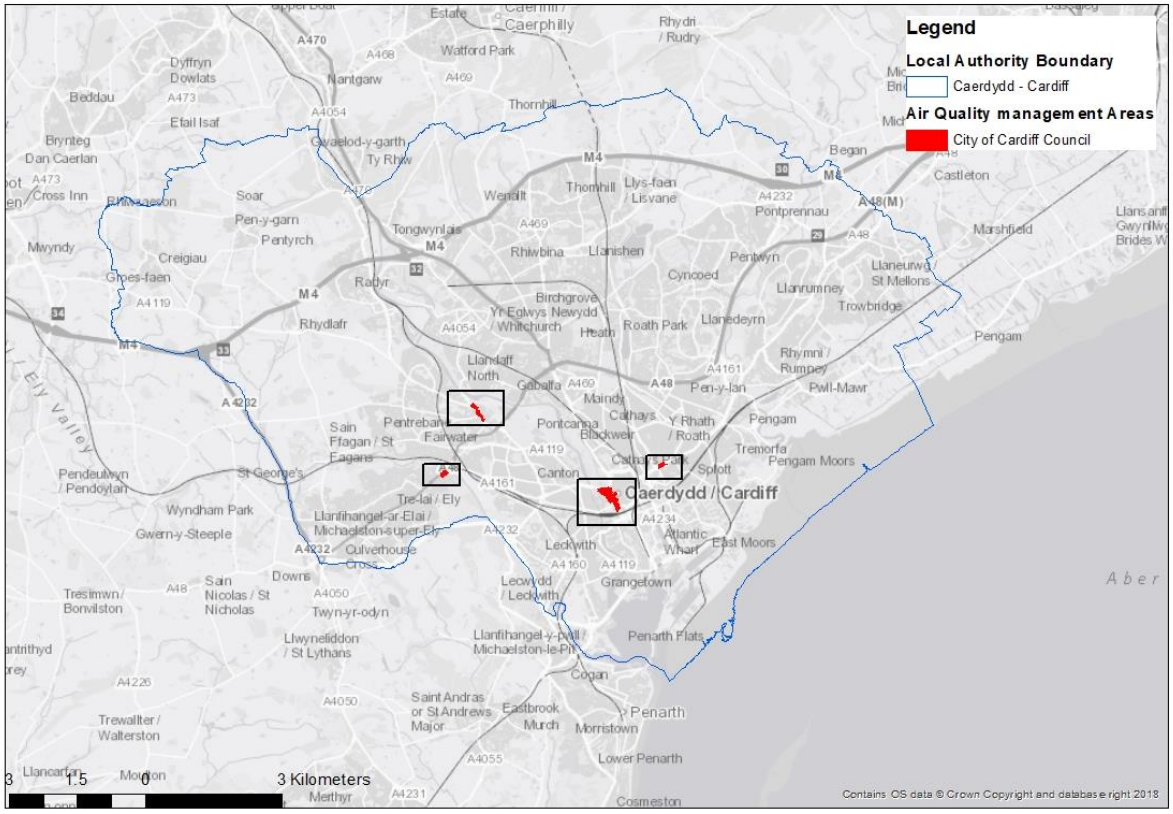
1 Introduction and outline modelling scope

City of Cardiff Council (CCC) has been directed by the Welsh Government to carry out a Nitrogen Dioxide Feasibility Study for non-compliance with the NO_2 limit values. This report sets out the Air Quality modelling methodology used for this study.

1.1 Background

Cardiff like many other urban areas, has elevated levels of Nitrogen Dioxide (NO_2) due mainly to road transport emissions. As such CCC has designated 4 Air Quality Management Areas (AQMA) across the City where concentrations of NO_2 breach Government, health-based air quality objectives as shown in Figure 1.

Figure 1 Cardiff Air Quality Management Areas (AQMA)



At the national level the EU has commenced infraction proceedings against the UK Government and Devolved Administrations for their failure to meet the EU Limit Value for NO_2. In 2015, the Supreme Court ordered the Government to consult on new air pollution plans that had to be submitted to the European Commission no later than 31 December 2015. In 2017 the UK government released a plan to tackle air quality, 'UK plan for tackling roadside nitrogen dioxide concentrations 2017'. Following a judicial review of this plan by Welsh ministers a Welsh Government Interim Supplemental Plan (WGSP) was published, identifying additional technical work to support measure development.

In WGSP, the areas of the pollution climate mapping (PCM) model which identify areas of exceedance in the Cardiff Urban Area are summarised as 'A4161','A4232', 'A4234', 'A470' and 'A48'. Additional areas identified as having poor air quality are established through the Local Air Quality Management (LAQM) regime. Yearly reviews in the form of annual status reports (ASR) review air quality within existing AQMAs. After reviewing Cardiff's latest ASR published in August 2018, Cardiff's

AQMAs cover the city centre, Ely bridge, Stephenson Court and Llandaff. Cardiff have been proactive in managing air quality prior to this NO_2 feasibility study and have proposed measures to improve air quality in these areas and more widely across the city in the Form of a Clean Air Strategy. Cardiff have also bid for funding for Ultra low emission buses/zero emission buses which will introduce electric buses within Cardiff's AQMAs and those areas identified within WGSP, such as the city centre AQMA, Stephenson Court AQMA and the A470 corridor.

Subsequent work by Defra updated its air quality plan using more recent information on the expected real-world emission performance of vehicles. This latest analysis is suggesting that emission from vehicles will be higher than previously estimated and so breaches of the air quality limits are likely to persist for longer and over a wider area.

The current study has carried out a fully updated assessment of air quality in and around Cardiff in relation to European limit values for NO_2 using the latest data on emission factors and traffic activity. This assessment has been used to establish the extent of any air quality compliance issues in Cardiff and to assess the options needed to solve these compliance problems.

1.2 Outline scheme options

Cardiff's Clean Air Strategy Action Plan (CASAP) developed a package of measures to reduce emissions covering all key transport modes in the city: cars, freight, buses and taxis. This introduces a series of measures in three unique CASAP phases. This has been considered as an alternative to a charging clean air zone for achieving compliance with the NO_2 annual mean air quality directive in the shortest time possible. Two variations of charging clean air zones were also considered in this study, CAZ 1 where charges apply to private cars and CAZ 2 where charges apply to light goods vehicles (LGVs) and heavy goods vehicles (HGVs).

The measures included in air quality modelling of these options has been presented within Table 1. The measures which have been reflected in the transport modelling are noted in Table 1, the transport modelling methodology report[1] should be referenced for further information. As a general rule, certain measures can only be reflected in a traffic model which is why the detail of these measures are not included in air quality modelling. The effect of measures in the traffic model are demonstrated through emission calculations related to changes to traffic flow, composition and speed. The exception to this is CAZ 1 and 2, where the change in fleet mix, for example split between petrol/diesel vehicles were developed by the air quality team. Whereas the change in compliant and non-compliant traffic[2] flows associated with the CAZ is established by the traffic model.

Table 1 Outline of measures included in the traffic and air quality modelling exercises

Scenario	Measures reflected in air quality modelling	Measures reflected in traffic modelling
CASAP 1	1. Taxi Licensing, Euro 6 for new licensees and upgrade incentives; 2. Electric Buses on service routes 27, 49/50 and 44/45.	1. Active Travel Package; 2. Cycling Programme to end of 2020; and 3. 50 mph on A4232.
CASAP 2	1. All CASAP 1 measures.	1. All CASAP 1 measures plus

[1] 367590 Air Quality Transport Modelling Technical Note CASAP CAZ.pdf

[2] Compliant vehicles are those that meet the CAZ standard and non-compliant vehicles are those that do not. The CAZ standard is Euro VI for heavy duty vehicles and Euro 6 (diesel and Euro 4 (petrol) for light duty vehicles.

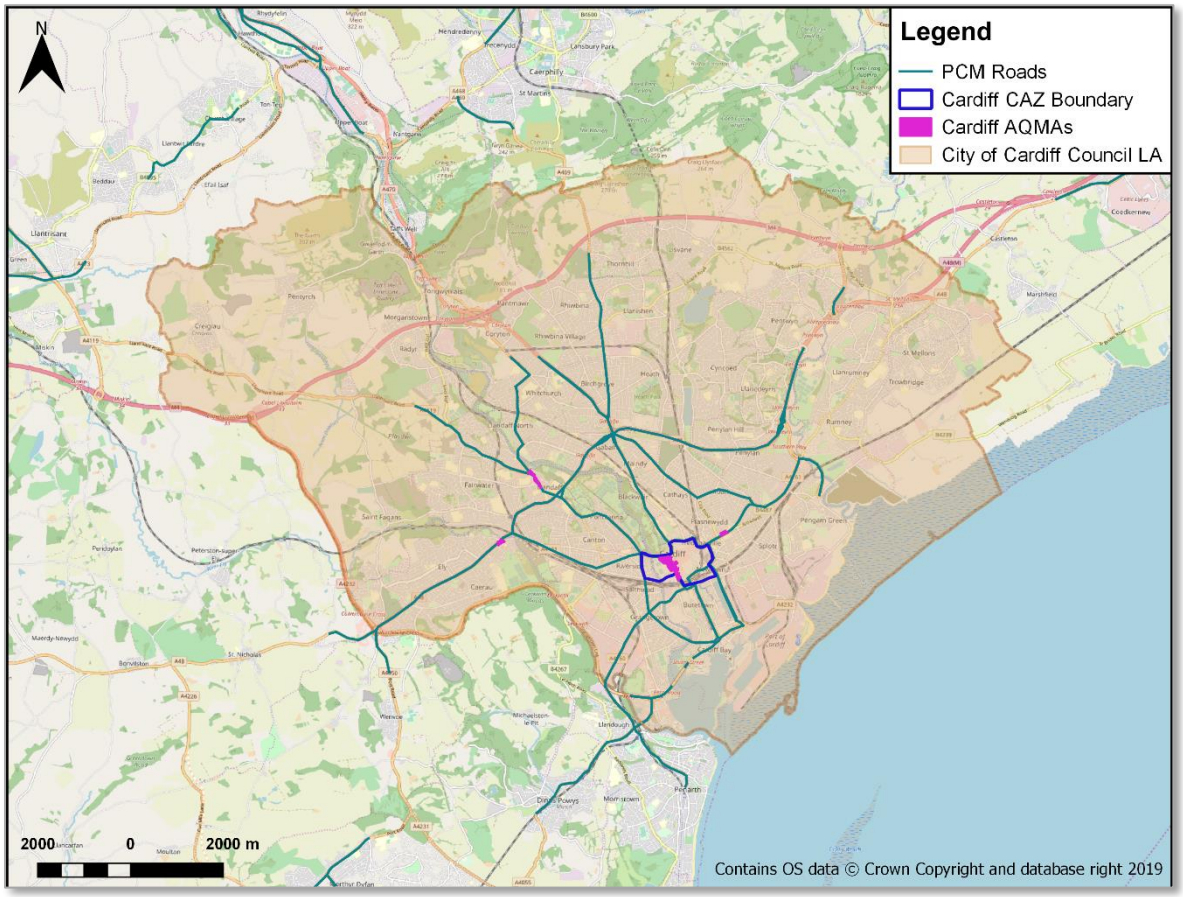
		2. Westgate Street Scheme; 3. East Side Scheme; 4. A48 Park and Ride; 5. J33 Park and Ride; and 6. Parking charges and controls.
CASAP 3	1. All CASAP 1 measures plus; 2. Complete upgrade of Cardiff Bus's fleet to Euro VI.	1. All CASAP 1 and 2 measures plus; 2. A470 additional southbound traffic lane; and 3. Nantgarw bus Park and Ride.
CAZ 1	1. **No** CASAP measures included; 2. £10 charge for private cars entering city centre charging clean air zone.	1. **No** CASAP measures included; and 2. £10 charge for private cars entering charging city centre charging clean air zone.
CAZ 2	1. **No** CASAP or CAZ 1 measures included; 2. £10 charge for light duty vehicles entering charging clean air zone; and 3. £50 charge for heavy duty vehicles entering charging clean air zone.	1. **No** CASAP or CAZ 1 measures included; 2. £10 charge for private cars entering charging clean air zone; 3. £50 charge for heavy duty vehicles entering charging clean air zone.

1.3 Modelling domain and years

Modelling measure options and associated air quality impacts requires a model domain that covers the scheme options, relevant AQMAs and potential diversion routes. Therefore, the model domain shown in Figure 2 has been used to cover the following:

- All the AQMAs in Cardiff including the main areas of concern from the national modelling assessment along the A470 and A48;
- The wider transport network out to and including the M4 which will cover all the likely key diversion routes should vehicles seek to avoid any Clean Air Zone
- The study area includes roads within 2km from the City of Cardiff's local authority boundary, thereby capturing the majority of roads outside Cardiff's jurisdiction which contribute towards local air quality within Cardiff.

Figure 2 Model domain



Two key model years are used in the modelling work: a 2015 base year and a target implementation year for the CAZ of 2021. The base year is taken as 2015 as this is the base year for the most recently validated transport model covering the area. To compliment this, the 2015 air quality data has been used to validate the air quality model. In addition, we have interpolated interim years between 2015 and 2020.

Table 2 Model years

Year	Description
2015	**Base year** – using latest available data on air quality and transport.
2016-2020	**Interim years** – interpolated between the base and implementation year.
2021	**Implementation year** – latest date when CAZ scheme is due to be in place.

1.4 Background modelling

The primary cause of air pollution problems in Cardiff is related to traffic activity and the impact of the any measures will target this traffic activity. As such the focus of the modelling is the transport emissions. Background pollutant concentrations can be taken from Defra's background maps which includes contributions from the majority of potential emissions sources e.g. other road traffic, industrial combustion and domestic emissions. With increasing distance from these emission sources Defra's background maps represent these emission sources relatively well. However, within close proximity to these emission sources Defra's Background maps can under-represent emissions.

To ensure a realistic representation of background pollutant concentrations, Part A(2) and B emissions to air processes permitted through the environmental permitting regime were reviewed. The outcome of this review is that the distance of industrial sources is such that they will be satisfactorily represented within Defra's background maps. Further information is provided in section 4.4.

Defra's background maps are based upon the same methodology as the PCM model[3]. These are based upon simplifications of emission sources from various sectors such as industry, the meteorological conditions and dispersion environment which cause pollutant concentrations. As Defra's guidance note on background concentrations states, these are estimates, to gauge how accurately these estimates represent background concentrations a comparison can be made against background monitoring locations. There is one background continuous analysers and two diffusion tube locations which can be compared against the estimated background concentrations, this comparison can be seen in Table 3. This shows that Defra's background estimates are actually higher than measured concentrations and use of these are slightly conservative.

Table 3 Comparison of Defra's modelled background concentration with measured

ID	Site Type	2015 Measured NO2 (µg/m3)	2015 Measured NO2 Data Capture %	2015 Defra Background modelled NO2 (µg/m3)	% difference between measured and monitoring
CA_1	Urban Centre	27	80	27.4	1%
169	Urban Background	16.3	100	18.4	13%
160	Urban Centre	27	92	27.4	1%

2 Details of the Modelling Domain

The core air quality model domain encompasses an area within 2km of the City of Cardiff's local authority boundary, based upon the district boundary from Ordnance Survey mapping products[4]. There is no significant displacement of traffic flows outside this domain due to the implementation of either charging CAZ – with a maximum increase of 70 AADT occurring on the A4160 (Penarth Road) with CAZ 1, in a maximum of a 170 AADT increase outside of Cardiff for CAZ 2 and so no material impacts are expected to occur beyond the proposed model domain.

A map showing the extent of the air quality domain relative to the initial CAZ zones and the associated traffic model network is presented in Figure 3. A map showing the model domain relative to roads included in the national Pollution Climate Mapping (PCM) model is presented in Figure 4. All road links in the PCM model pertinent to Cardiff are included in the model domain specification.

CCC has declared 4 AQMA's across the city to date, all of which are within the proposed model domain. A map showing the locations of the AQMA's relative to the model domain is presented in Figure 5. All of CCC's 2015 NO_2 roadside measurements have been used in the air quality modelling assessment to verify the model outputs, assuming data capture and QA/QC are satisfactory for the 2015 baseline year. A map showing the sites at which NO_2 concentrations are measured by CCC is presented in Figure 6.

[3] https://laqm.defra.gov.uk/documents/2015-based-background-maps-user-guide-v1.0.pdf

[4] https://www.ordnancesurvey.co.uk/opendatadownload/products.html

Figure 3: CAZ study domain and relationship to Mott Macdonald's sub-regional transport model links

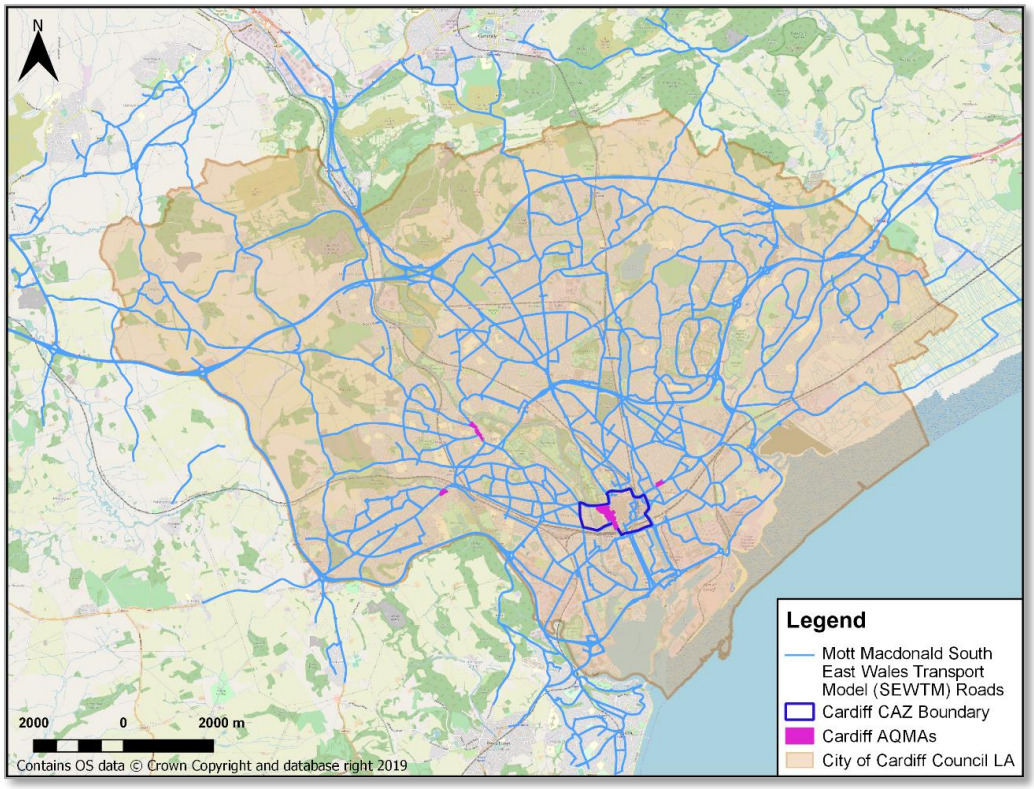


Figure 4: PCM model road links within the CAZ study domain 2015

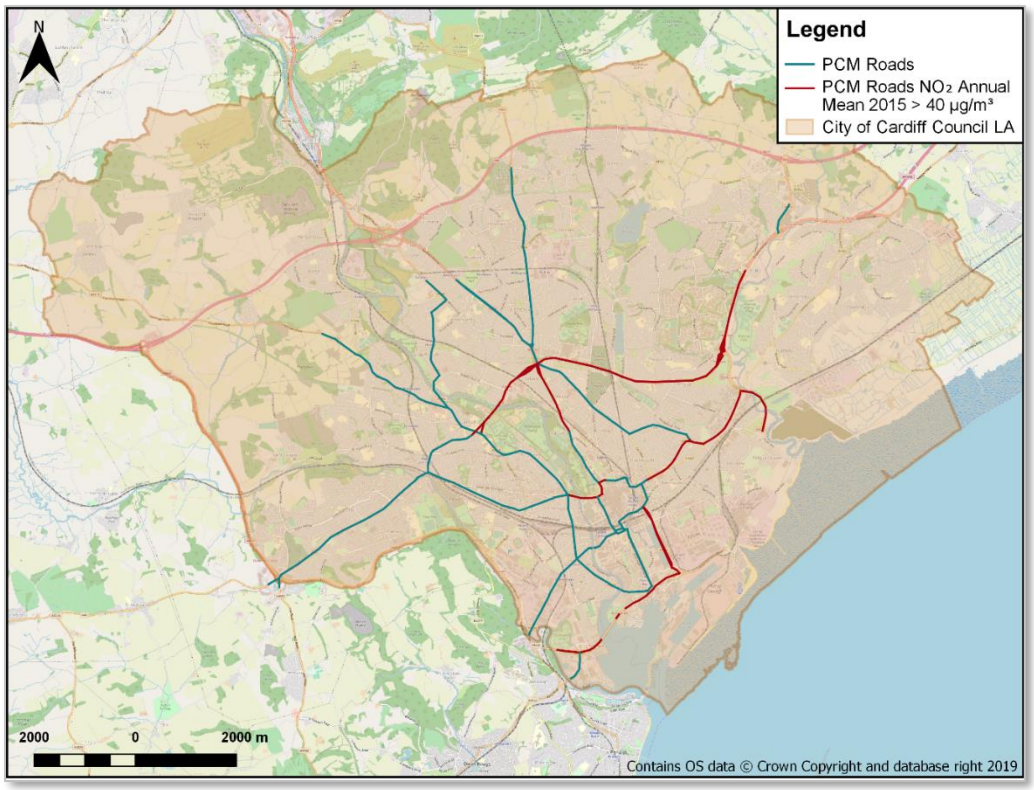


Figure 5: City of Cardiff Council's AQMA locations

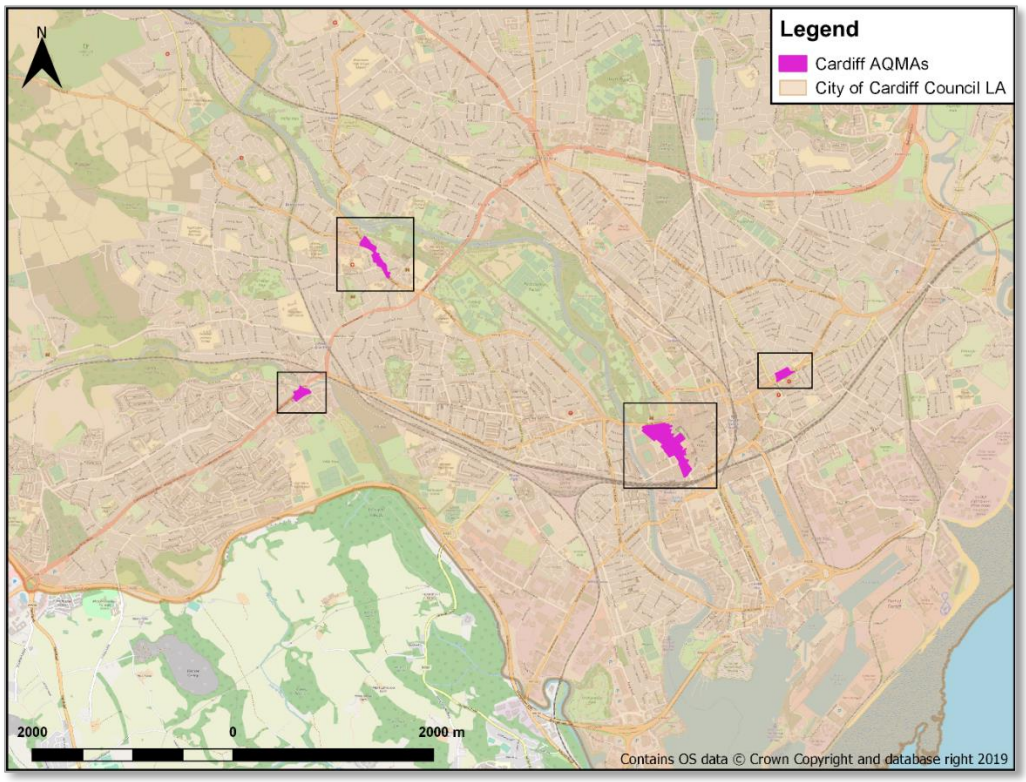
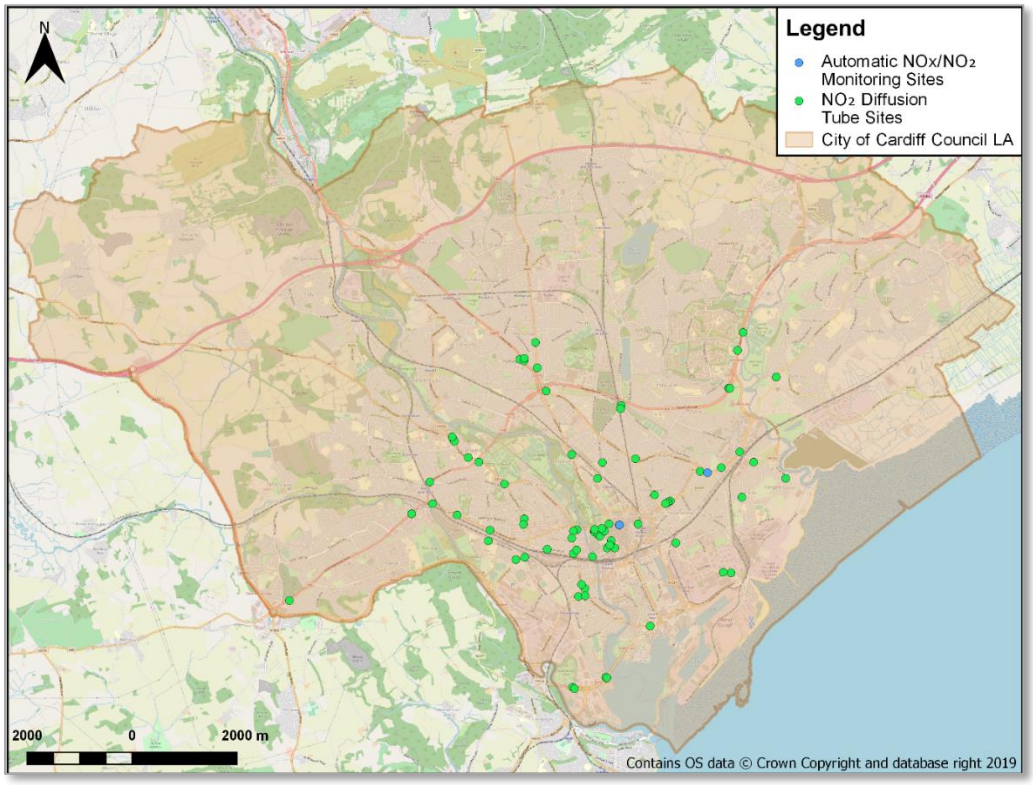


Figure 6 City of Cardiff Council's NO_2 monitoring sites



3 Model and receptor location selection

3.1 Dispersion model

We have used the RapidAir modelling system for the study. This is Ricardo Energy & Environment's proprietary modelling system developed for urban air pollution assessment and the model that was used in other Clean Air Zone feasibility studies such as Derby, London and Southampton.

The model is based on convolution of an emissions grid with dispersion kernels derived from the USEPA AERMOD[5] 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[6]. AERMOD provides the algorithms which govern the dispersion of the emissions and is an accepted international model for road traffic studies (it is one of only two mandated models in the US and is widely used overseas for this application). The combination of an internationally recognised model code and careful parameterisation matching international best practice makes RapidAir demonstrably fit for purpose for this study.

The USEPA have very strict guidelines on use of dispersion models and in fact the use of AERMOD is written into federal law in 'Appendix W' of the Guideline on Air Quality Models[7]. The RapidAir model uses AERMOD at its core and is evidently therefore based on sound principles given the pedigree of the core model.

The model produces high resolution concentration fields at the city scale (1 to 3m scale) so is ideal for spatially detailed compliance modelling. A validation study has been conducted in London using the same datasets as the 2011 Defra inter-comparison study[8]. Using the LAEI 2008 data and the measurements for the same time period the model performance is consistent (and across some metrics performs better) than other modelling solutions currently in use in the UK. The results of this study have been published in Environmental Modelling and Software[9].

3.2 Core aspects of the modelling

3.2.1 Chemistry, meteorology and topology

NOx to NO_2 chemistry was modelled using the Defra NOx/NO_2 calculator. Modelled annual mean road NOx concentrations were combined with background NOx and a receptor specific (i.e. at each receptor) fNO_2 fraction to calculate NO_2 annual mean concentrations. The receptor specific fNO_2 fraction was calculated by dividing the modelled road NOx by modelled road NO_2 at each receptor.

3.2.2 Meteorology

Modelling was conducted using the 2015 annual surface meteorological dataset measured at Cardiff City Centre. The dataset was processed in house using our own meteorological data gathering and processing system. We use freely available overseas meteorological databases which hold the same observations as supplied by UK meteorological data vendors. Our RapidAir model also takes account of upper air data which is used to determine the strength of turbulent mixing in the lower atmosphere;

[5] https://www3.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod
[6] https://www.epa.gov/state-and-local-transportation/project-level-conformity-and-hot-spot-analyses
[7] 40 CFR Part 51 Revision to the Guideline on Air Quality Models: Adoption of a Preferred General Purpose (Flat and Complex Terrain) Dispersion Model and Other Revisions; Final Rule, Environmental Protection Agency, 2005
[8] https://uk-air.defra.gov.uk/research/air-quality-modelling?view=intercomparison
[9] 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

this was obtained from the closest radiosonde site and process with the surface data in the USEPA AERMET model. We have utilised data filling where necessary following USEPA guidance which sets out the preferred hierarchy of routines to account for gaps (persistence, interpolation, substitution). AERMET processing was conducted following the USEPA guidance. To account for difference 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 were accessed from the CORINE land cover datasets[10].

A uniform surface roughness value of 1.0 m was modelled to represent a typical city/urban environment.

3.2.3 Canyon modelling

The platform includes two very well-known street canyon algorithms with significant pedigree in the UK and overseas. The first replicates the functionality of the USEPA 'STREET' model. The code was developed by the Office of Mobile Source Air Pollution Control at the USEPA and published in a series of technical articles aimed at operational dispersion modellers in the regulatory community[11,12]. The STREET model has been used for many years and has been adopted in dispersion modelling software such as AirViro. The USEPA canyon model algorithms are essentially the same as those recommended by the European Environment Agency for modelling canyons in compliance assessment[13].

The RapidAir model also includes the AEOLIUS model which was developed by the UK Met Office in the 1990s. The AEOLIUS model was originally developed as a nomogram procedure[14]. The scientific basis for the model is presented in a series of papers by the Met Office[15,16,17,18,19.] The model formulation shares a high level of commonality with the Operational Street Pollution Model[2021] (OSPM) which in turn forms the basis of the basic street canyon model included in the ADMS-Roads software. Therefore, the AEOLIUS based canyon suite in RapidAir aligns well with industry standards for modelling dispersion of air pollutants in street canyons.

Using available information on building heights and road widths, candidate locations for street canyons were identified. These locations were then checked using Google Street View to confirm the presence of a street canyon. For roads assigned as street canyons, the required information for the AEOLIUS street canyon model was populated – this includes building height, emissions and number of vehicles per hour. The canyon model is only turned on if the wind is blowing parallel across the canyon (± 5 degrees) i.e. the wind must be between 40 and 50 degrees from the orientation of the canyon. For each hour in the meteorological data (same as that described in 3.2.2) with wind direction matching the criteria to turn the street canyon on, the leeward, windward and parallel street canyon concentrations were calculated. To provide annual street canyon concentrations, the sum of the data contained within each of leeward, windward and parallel was calculated.

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[10] EEA (2018) https://www.eea.europa.eu/publications/COR0-landcover
[11] Ingalls., M. M., 1981. Estimating mobile source pollutants in microscale exposure situations. US Environmental Protection Agency. EPA-460/3-81-021
[12] USEPA Office of Air Quality Planning and Standards., 1978. Guidelines for air quality maintenance planning and analysis, Volume 9: Evaluating indirect sources. EPA-450/4-78-001
[13] http://www.eea.europa.eu/publications/TEC11a/page014.html
[14] Buckland AT and Middleton DR, 1999, Nomograms for calculating pollution within street canyons, Atmospheric Environment, 33, 1017-1036.
[15] Middleton DR, 1998, Dispersion Modelling: A Guide for Local Authorities (Met Office Turbulence and Diffusion Note no 241: ISBN 0 86180 348 5), (The Meteorological Office, Bracknell, Berks).
[16] Buckland AT, 1998, Validation of a street canyon model in two cities, Environmental Monitoring and Assessment, 52, 255-267.
[17] Middleton DR, 1998, A new box model to forecast urban air quality, Environmental Monitoring and Assessment, 52, 315-335.
[18] Manning AJ, Nicholson KJ, Middleton DR and Rafferty SC, 1999, Field study of wind and traffic to test a street canyon pollution model, Environmental Monitoring and Assessment, 60(2), 283-313.
[19] Middleton DR, 1999, Development of AEOLIUS for street canyon screening, Clean Air, 29(6), 155-161, (Nat. Soc for Clean Air, Brighton, UK).
[20] Hertel O and Berkowicz R, 1989, Modelling pollution from traffic in a street canyon: evaluation of data and model development (Report DMU LUFT A129), (National Environmental Research Institute, Roskilde, Denmark).
[21] Berkowicz R, Hertel O, Larsen SE, Sørensen NN and Nielsen M, 1997, Modelling traffic pollution in streets, (Ministry of Environment and Energy, National Environmental Research Institute, Roskilde, Denmark).

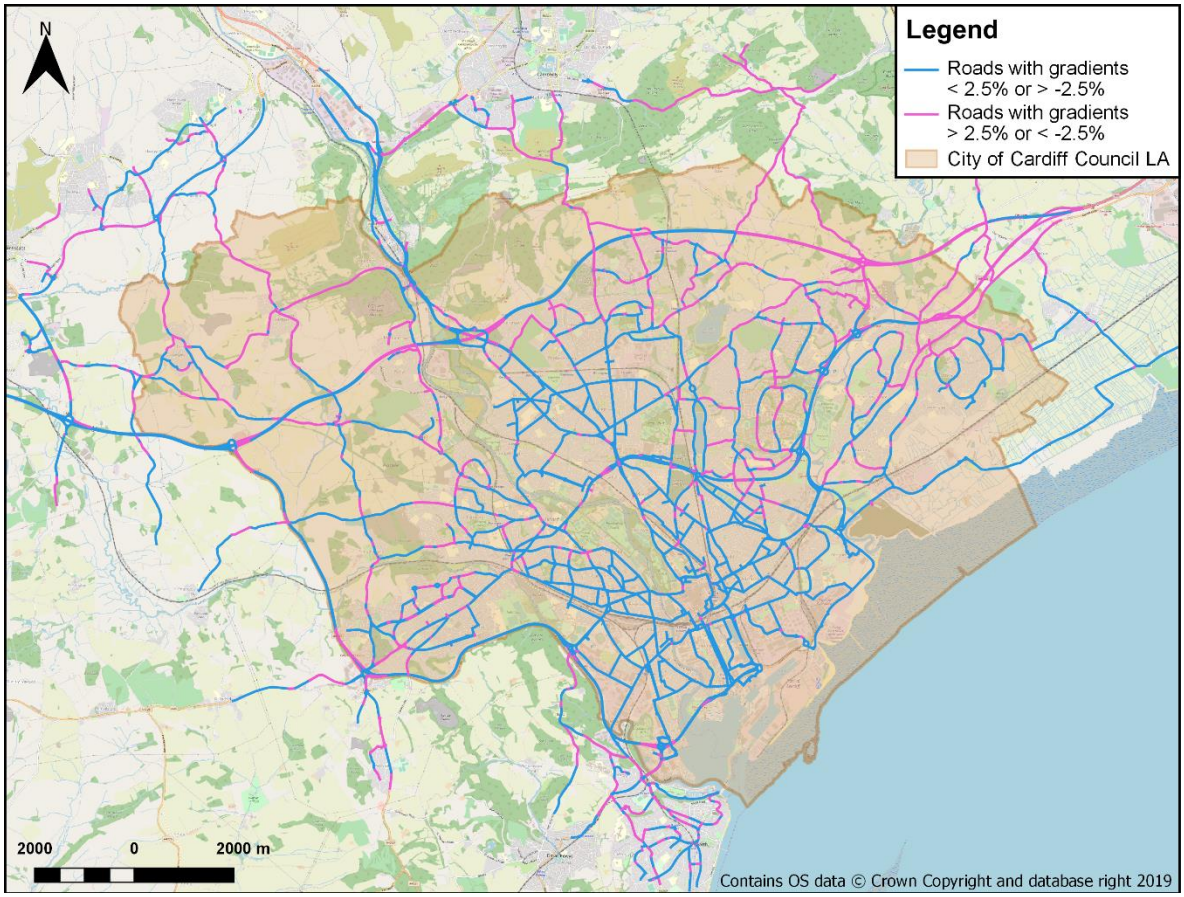
The results from the street canyon module were combined with the concentrations modelled in the dispersion step of RapidAir. The annual leeward and annual windward concentrations were added together, then this was added to the dispersion modelled road NO_x. The concentrations from the parallel contribution of the street canyon model were not included as including this would result in double counting of the road NOx when combined with the dispersion NO_x.

3.2.4 Gradient, tunnels and flyovers

Gradient effects have been included for relevant road links during emissions calculations. LIDAR Composite Digital Terrain Model (DTM) datasets at 1m and 2m resolution are available over the proposed model domain[22]. Link gradients across the model domain can be calculated using GIS spatial analysis of LIDAR DTM datasets.

The method described in TG(16) provides a method of adjusting road link emission rates for gradients greater than 2.5%; it is applicable to broad vehicle categories for heavy vehicles only. Defra's Joint Air Quality Unit (JAQU) have instructed dispersion modelling of English CAZs to gradient adjust all pre-Euro VI HDVs, this has been undertaken for Cardiff. Figure 7 shows the roads where gradient effects were included during emissions calculations.

Figure 7: Locations where gradient effects have been included during emission calculations



No modelling of tunnels or flyovers was included as the RapidAir kernel approach applies the same source height across the model domain. All roads provided by the traffic modellers within CCC

[22] http://environment.data.gov.uk/ds/survey/#/survey

boundary were modelled at ground level, this includes both flyovers and tunnels. For example, in Figure 7 it can seen that the A4232, Cardiff Bay Link Road, flyover and tunnel have been included. If modelling of flyovers was considered to be beneficial for this assessment, we could have modelled road link at a higher elevation using a dispersion kernel created with a different source height in AERMOD. It was not however considered beneficial to do this for this assessment.

3.3 Receptor locations

Cardiff has a wide network of monitoring locations comprising a mix of passive and active sampling. All available monitoring locations for 2015 will be treated as receptors in the model as the 2015 NO_2 annual mean measurements will be used for model verification and producing model performance statistics. A map of these monitoring locations is shown above in Figure 6 in relation to the modelling domain.

The RapidAir model can deal with about 1.2 billion gridded locations which provides for over 30,000 cells in the 'x' and 'y' axes. We can therefore model 40km x 30km, which is roughly the size of the Cardiff modelling domain, down to a 1m resolution. Therefore, we have used this 1m resolution for our work in Cardiff. The canyon model is set to the same resolution as the grid model so that they align perfectly spatially.

As RapidAir produces concentration grids (in raster format), modelled NO_2 concentrations can be extracted at receptor locations anywhere on the 1m resolution model output grid. For comparison with PCM model results, annual mean concentrations at a distance of 4m from the kerb have been extracted from the RapidAir data and presented as a separate model output file. This will allow the selected locations to be assessed according to the Air Quality Directive (AQD) requirements Annex III A, B, and C3.

Cardiff has four AQMAs all of which contain numerous sensitive receptors. RapidAir, by virtue of its very high-resolution outputs, can produce discrete estimates at every single residential property in Cardiff (every 1m 'square' in actual fact); any location where there is a risk of the objective being exceeded can therefore be included in the modelling and outlined during post processing.

To aid interpretation of the outcomes of the study when considering compliance with the air quality directive (AQD), annual mean concentrations at the roadside exceedance locations identified in the PCM model will be extracted from the RapidAir dispersion model results and presented as a separate model output file. Roadside receptor locations in the PCM model are at a distance of 4m from the kerb and at 2m height. A subset of the OS Mastermap GIS dataset provided spatially accurate polygons representing the road carriageway, receptor locations were then placed at 10m intervals along relevant road links using a 4m buffer around the carriageway polygons. For Cardiff's modelling exercise concentrations were sampled at 4m from the kerbside and at a height of 1.5 metres.

This resulted in a total of 20,142 discrete sampling points. Geospatial analysis permitted point allocation to the closest Census IDs used within the PCM model. The maximum estimated concentration at discrete receptors representative of Census IDs were used for this localised dispersion modelling study. Consequently, the worst-case modelled concentrations are being used in comparison with those from the PCM model.

It should be noted that relevant exposure to the annual mean NO_2 EU limit value could be within less than 4 metres from the kerb. The highest concentrations in the whole model domain are predicted along census link 30665. According to the definitions of relevant exposure within LAQM.TG(16) there are no areas with relevant exposure at 4 metres or less at a height of 1.5 metres. Modelling receptors at a distance of 4m has not resulted in any potential areas of exceedance from being excluded from this modelling exercise.

Annex III of the AQD specifies that macroscale siting of sampling points should be representative of air quality for a street segment of no less than 100 m length at traffic-orientated sites. To provide

results relevant to this requirement, for roadside locations where there is public access and the Directive applies; road links with exceedances of the NO_2 annual mean objective stretching over link lengths of 100m or greater can be presented as a separate GIS layer of model results.

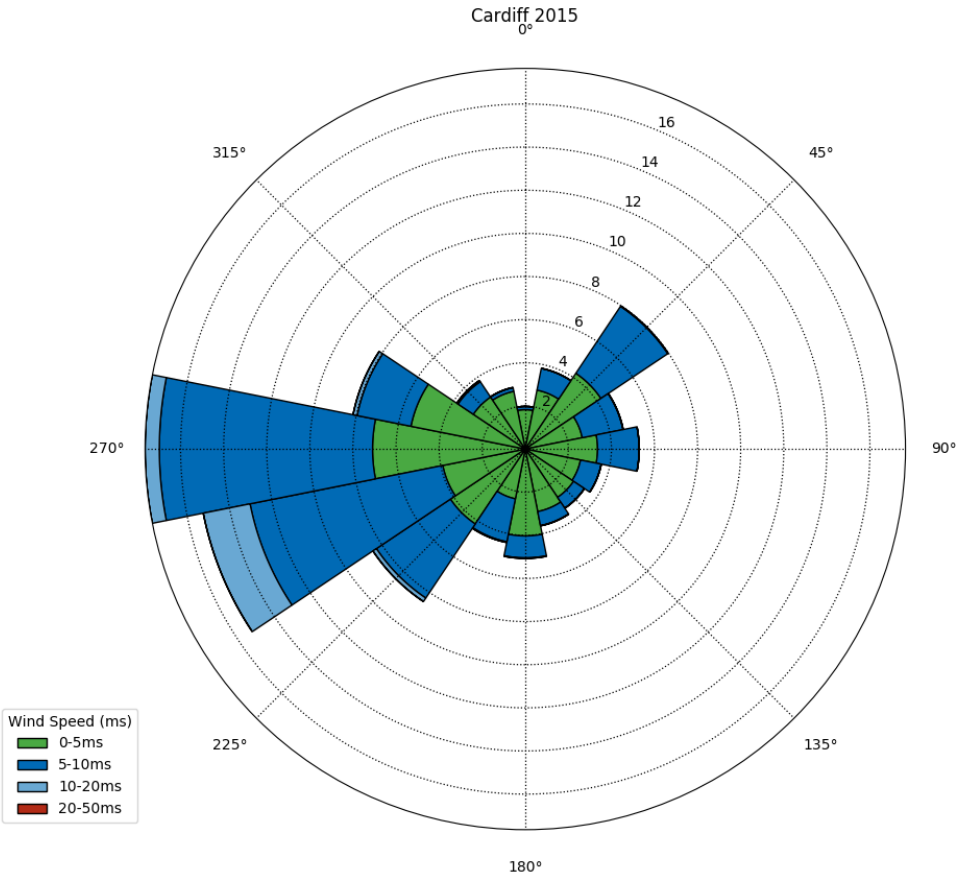
Annex III of the AQD also specifies that microscale sampling should be at least 25 m from the edge of major junctions. When reporting model results relevant to compliance with the AQD, locations up to 25m from the edge of major junctions in the model domain have also been excluded.

4 Base year modelling

4.1 Base year and meteorological dataset

As described in section 1.3 we have modelled a baseline year of 2015. We have used the 2015 annual surface meteorological dataset measured at Cardiff City Centre which has been processed in house using our own meteorological data gathering and processing system. We use open overseas meteorological databases which hold the same observations as supplied by UK meteorological data vendors. Our RapidAir model also takes account of upper air data which is used to determine the strength of turbulent mixing in the lower atmosphere; we have derived this from the closest radiosonde site and process with the surface data in the USEPA AERMET model. Where necessary we have utilised data filling following USEPA guidance which sets out the preferred hierarchy of routines to account for gaps (persistence, interpolation, substitution). A wind rose for the 2015 Cardiff City Centre met dataset is presented in Figure 8.

Figure 8: Windrose

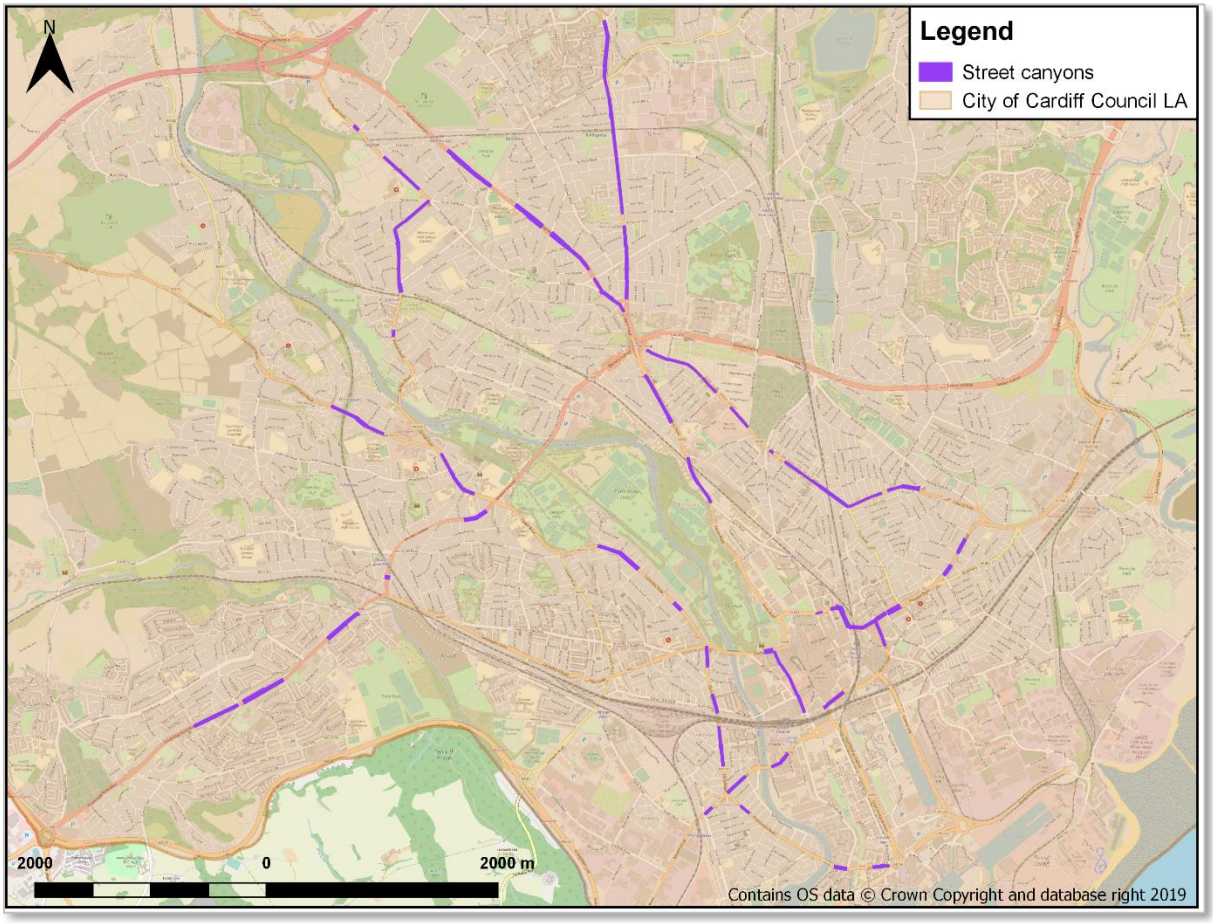


4.2 Representation of road locations and canyons

A realistic representation of road locations has been modelled by assigning emissions to the road links represented in the Ordnance Survey ITN Roads GIS dataset; it contains spatially accurate road centreline locations for various road categories e.g. Motorway, A-road, B-road, minor road, local street etc. Link gradients across the model domain were calculated using LIDAR DTM datasets.

A map showing the locations where canyon effects were modelled is presented in Figure 9.

Figure 9: Location of street canyons modelled



4.3 Road traffic modelling

4.3.1 Average daily vehicle flow and speeds

Baseline and future year annual average daily traffic (AADT) link flows for each model link were provided by Mott Macdonald using outputs from the South East Wales Transport Model (SEWTM) that covers the areas of Cardiff, Newport, Caerphilly and east of Swansea. Traffic flows were provided for the following vehicles types; Cars, light goods vehicles (LGV), heavy goods vehicles (HGV) and buses. It should be noted that the bus traffic flows only include service operators. This means that modelled buses do not include coaches or mini-buses and will be under-estimation of bus movements.

Speeds were provided for four modelled period: AM (peak hour 07:45-08:45), Inter-Peak (average of period 09:30-15:30), PM (peak hour 16:30-17:30) and Off-peak (average between 18:00-07:00). Ricardo calculated the AADT equivalent speeds with a weighted average. This involves summing the multiplication of each peak hour speed by the corresponding period traffic flow and dividing by AADT, see equation below.

$$AADT\ speed = \frac{(AM\ phs\ \times\ AM\ ptf) + (IP\ aps\ \times\ IP\ ptf) + (PM\ phs\ \times\ PM\ ptf) + (OP\ aps\ \times\ OP\ ptf)}{AADT}$$

Where: *phs = peak hour speed*
ptf = period traffic flow
aps = average period speed

In traffic modelling there is an area of detailed modelling (AODM) and rest of area (ROF), the former denotes areas where the traffic modellers have greater accuracy in traffic forecasts and the latter less accuracy. It has been confirmed all roads links included in the dispersion modelling exercise are within the AODM. Further information on how the baseline 2015, 2021 and other scenarios have been represented within the SEWTM model can be found within the traffic modelling chapter[23].

An extensive 2015 Automatic Traffic Count (ATC) survey was undertaken in support of the SEWTM model. An ATC survey provides total number of vehicles across a number of vehicle categories for a 15 minute period over the duration of the survey. This survey provides data required to establish the proportion of traffic that is contributed to a daily total from up to a resolution of 15 minutes. Thereby enabling the development of a diurnal profile which establishes the proportion each hour contributes to a 24-hour period total. Only ATC locations across Cardiff, which were considered representative of the model domain were used in the development of this diurnal profile. One diurnal profile was developed for all vehicle types and applied as time varying emissions in AERMOD when creating the RapidAir dispersion kernel.

4.3.2 Vehicle fleet composition

The 4 core vehicle fleet types are; cars, LGVs, HGVs and buses. The subcategories of these vehicles types with emission rates are;

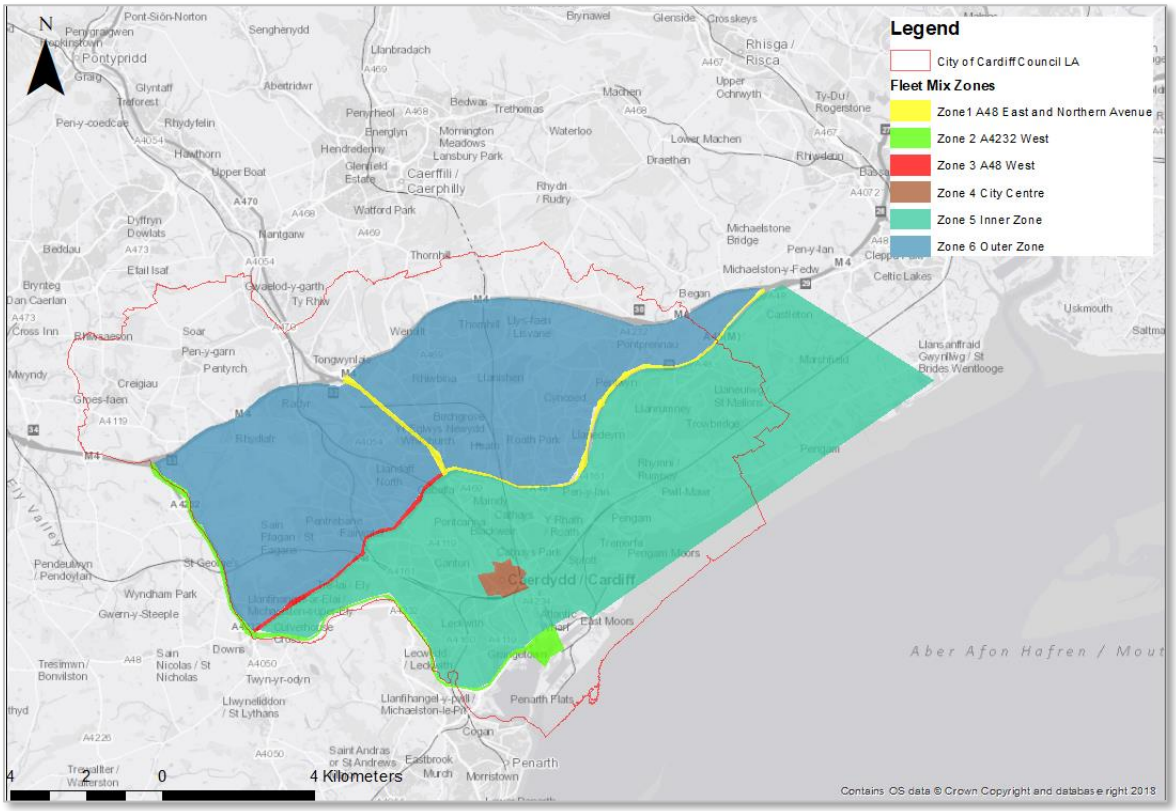
- **Cars:** are split into passenger/private, private hire taxis and hackney taxis;
- **LGVs**: there is no split for LGVs;
- **HGVs**: are split into articulated HGVs and rigid HGVs; and
- **Buses:** there is no split for buses.

These can be calculated using the latest COPERT v5 NOx emission functions.

The traffic model provided vehicle flows for four highway user classes which are: Car, HGV, LGV and Buses. HGVs were further broken down into rigid and articulated and cars were divided into private hire and Hackney taxis subcategories, this was undertaken using Automatic Number Plate Recognition (ANPR) data. ANPR locations were selected if they were in an area of key concern for air quality. This includes AQMAs and non-compliance links in the PCM model. ANPR cameras were setup at 12 locations, recording various directions of traffic resulting in 21 unique records. To ensure that fleet mixes most accurately represented these key air quality areas 7 unique zones were created, as per Figure 10. Zone 7 is an average fleet mix derived from all the ANPR cameras across Cardiff. This has been applied to roads which are outside zones 1-6.

[23] 367590 Air Quality Transport Modelling Technical Note CASAP CAZ.pdf

Figure 10 Cardiff Fleet Mix Zones



The ANPR survey lasted for a week over a traffic neutral period i.e. during term time and is representative of a years' typical weekly traffic. The ANPR survey enables emission rates from road traffic to be represented in the greatest detail possible within COPERT V, which includes:

1. Cars, split between Petrol and Diesel from pre-euro standards up to Euro 6 and alternative technologies such as electric and plug in hybrids;
2. Light Goods Vehicles (LGV) (<3.5 tonnes), split between Petrol and Diesel from pre-euro standards through to Euro 6; LGVs consist of Vans and People Carriers e.g. large passenger cars and mini-buses.
3. Rigid and Artic Heavy-Goods Vehicles (HGV), from pre-euro standards through to Euro 6.
4. Bus and Coach, from pre-euro standards through to EURO VI.
5. Motorcycles are an option within COPERT, however, the NAEI defaults for 2015 and 2021 have been used.

Emission calculations for each vehicle category will be based on vehicle fuel type and Euro classification. Information on the local fuel type mix and Euro standard distribution has been collected from the ANPR surveys conducted over one week from the 12th to 19th May 2018. The scenarios included in dispersion modelling are baseline 2015, baseline 2021, CASAP1, CASAP2, CASAP 3 and the City Centre Clean Air Zone 1 and 2. From this, there are 2 unique years which should be considered in the calculation of the fleet mix, 2015 and 2021. As the ANPR survey was undertaken in 2018, National Atmospheric Emission Inventory's (NAEI) fleet mix projections were used to back-cast to 2015 and forecast to 2021. The distribution of fuel type and Euro classification from the 2018 local data average across all the ANPR locations is shown in Figure 11 to Figure 16 below compared to the 2018 national average data taken from the (NAEI).

Representing Fleet Mixes with ANPR data

There were approximately 2.6 million ANPR records, which have been matched to the DVLA database. Each individual vehicle which has been captured and matched to the DVLA database has

had a vehicle type assigned by TRACSIS. TRACSIS are the traffic survey specialist which provided the ANPR data. Further detail provided includes the vehicle type associated with each vehicle captured e.g. Car, Private Hire Vehicle (PHV), Hackney, PSV (buses and coaches), OGV1 (Rigid HGV) and OGV2 (Artic HGV). As mentioned above, there are euro standards for each of the vehicle types, as such these have been associated and used within the COPERT V emission calculations. This assumes that TRACSIS have correctly linked each vehicle type to each category.

Using Euro standards for PSVs, as defined by ANPR data, for exclusively buses will mean that coaches will result in a slight misrepresentation of Euro standards. This is the case for buses in emission calculations, as only buses from service operators within Cardiff have been included in the bus traffic flows from the traffic model. When comparing bus Euro standards from only Cardiff Bus's fleet to those within the ANPR data, Cardiff bus have a much more polluting fleet with 82.5% being pre-Euro VI. Whereas the % of pre-Euro VI standard PSVs within the ANPR data is only 61.7%. Which will mean that emission contribution from buses are being under-represented, however these discrepancies have been offset during the model validation process. This compares modelled NO_x against measured NO_x taking a regression result across all validation locations to adjust modelled results.

Figure 11 Car fuel type split

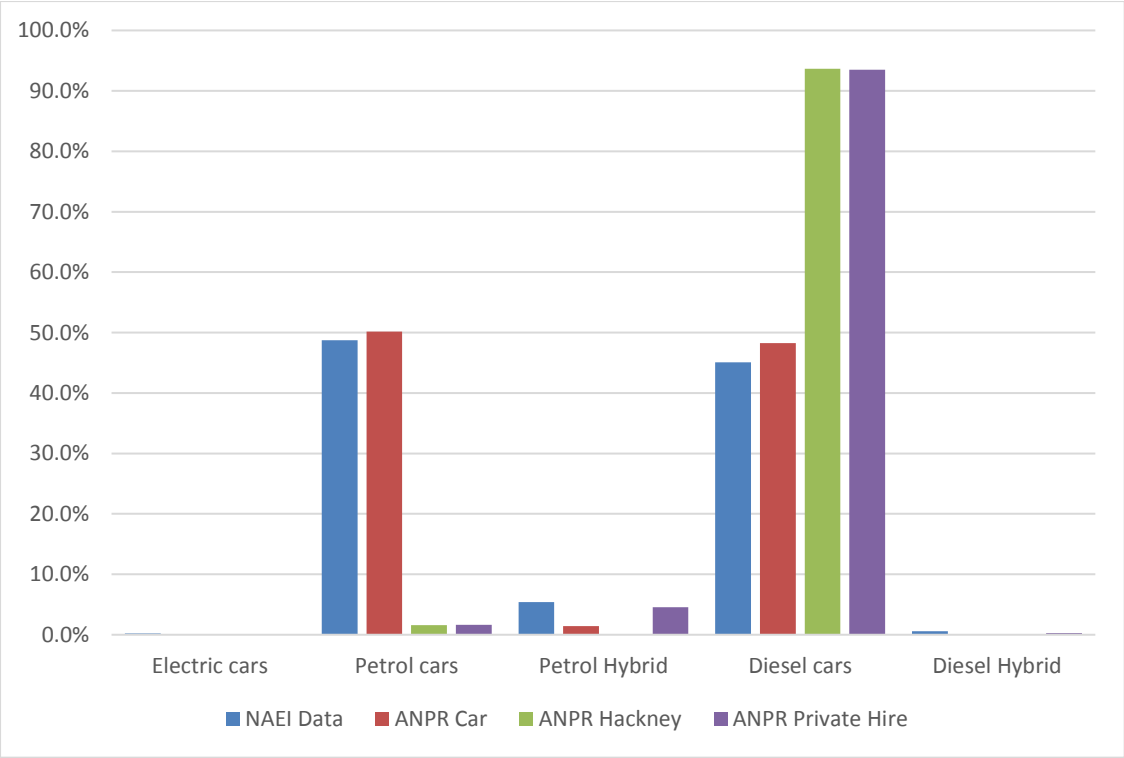


Figure 12 Diesel car Euro classification distribution

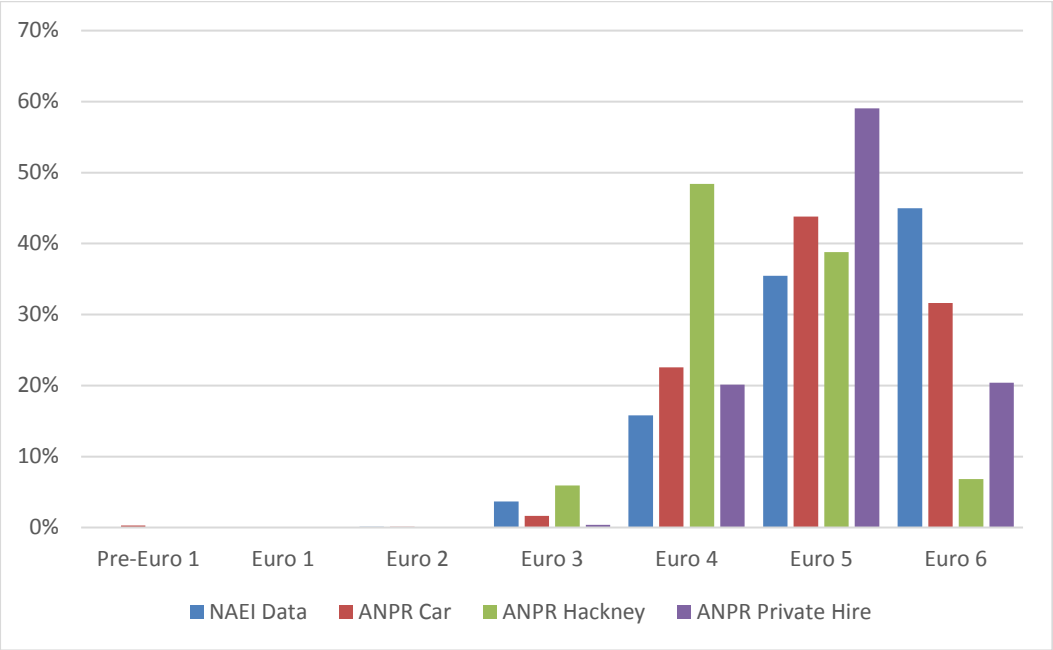


Figure 13 Petrol car Euro classification distribution

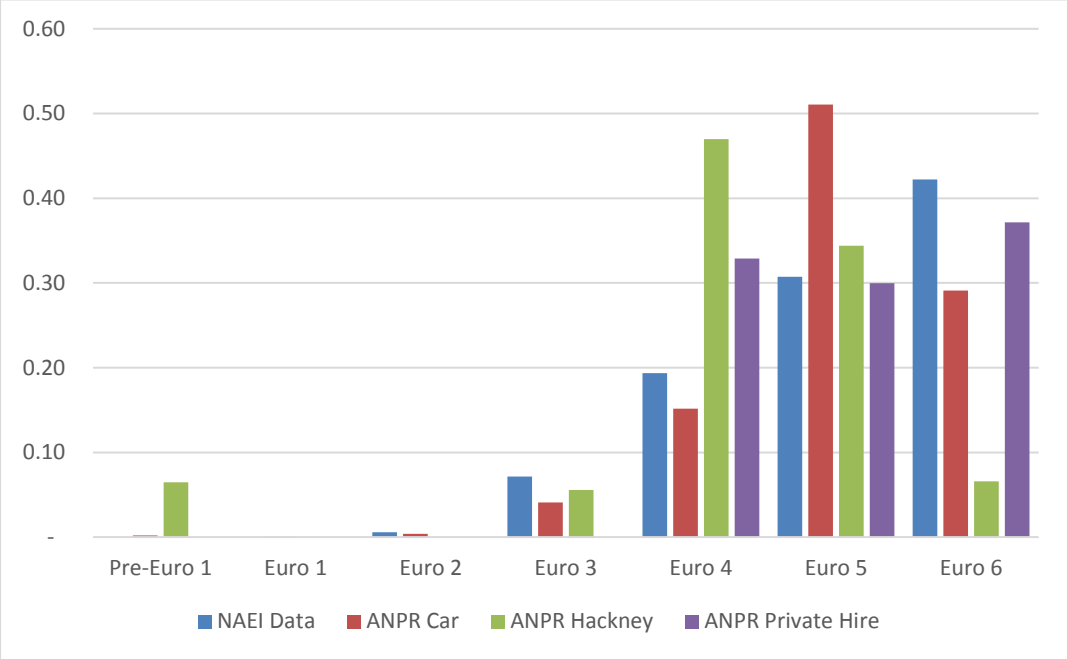


Figure 14 Diesel van Euro classification distribution

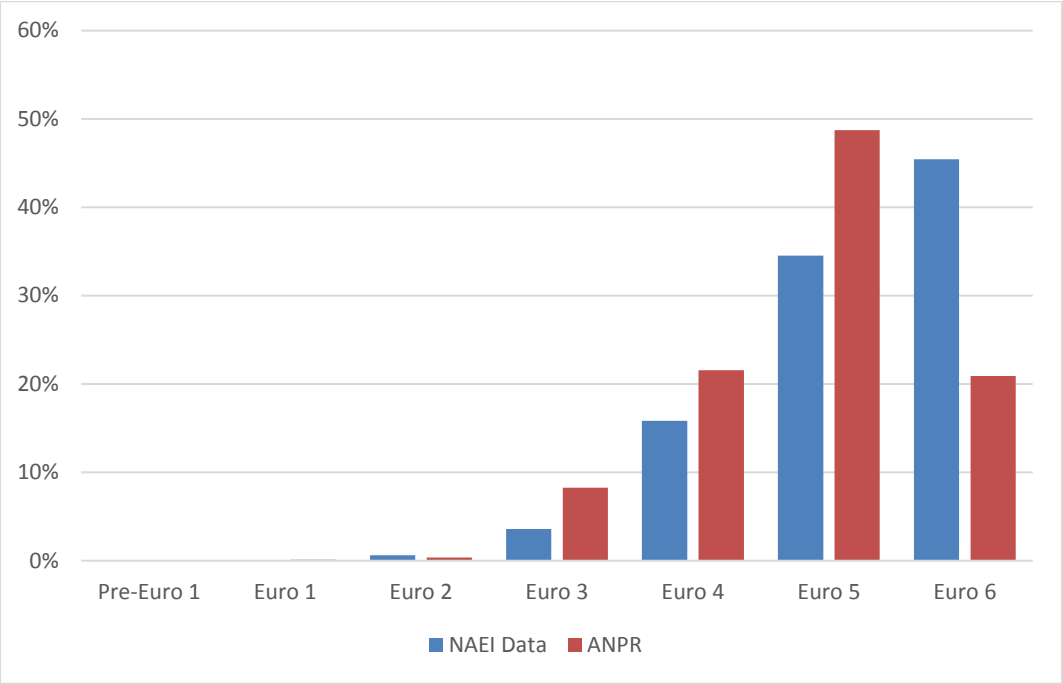


Figure 15 Rigid HGV Euro Classification distribution

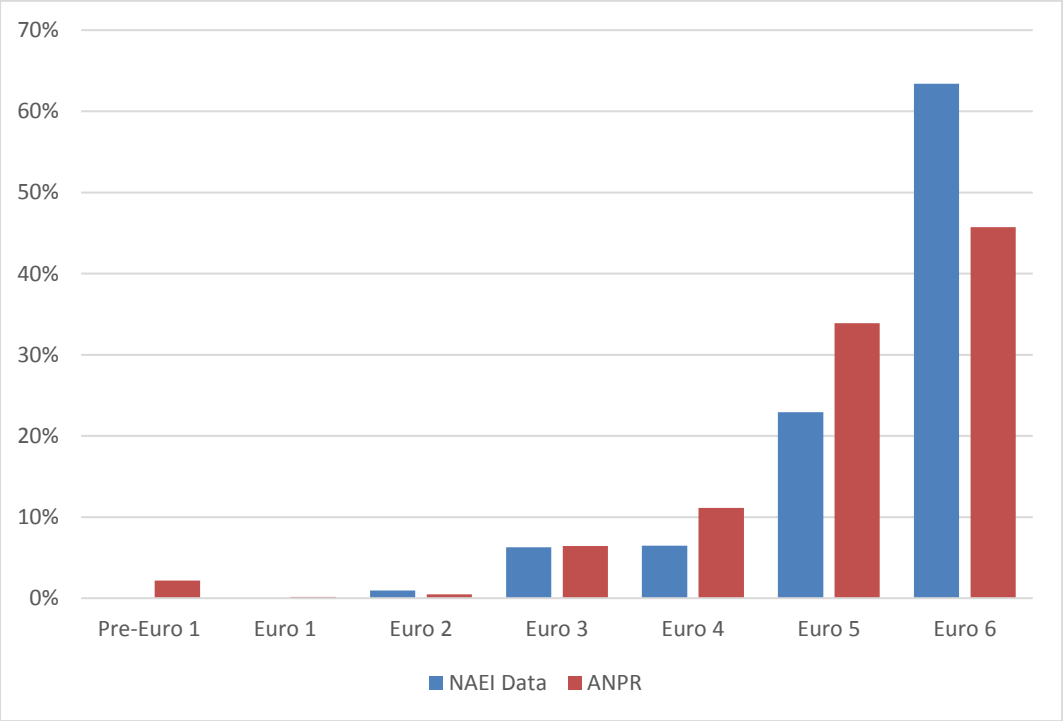
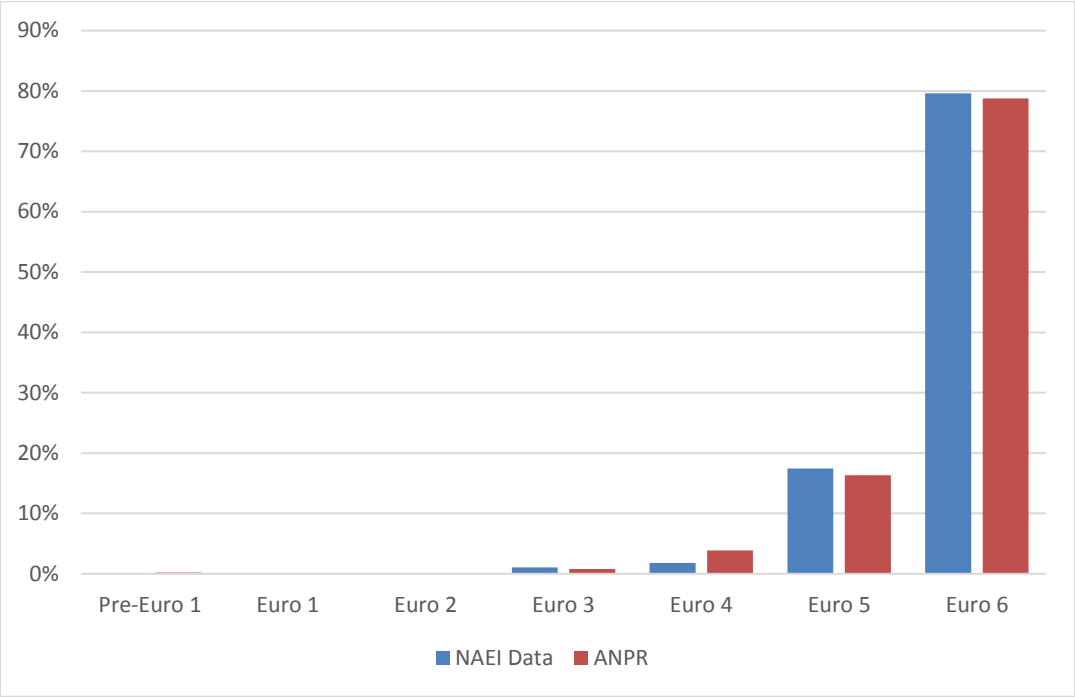


Figure 16 Artic HGV Euro Classification



4.3.3 NOx/NO_2 emissions assumptions

Link specific NOx emission factors have been calculated using the COPERT v5 emission functions for all vehicles up to and including Euro 6/VI. Emission rates have been calculated with our in-house emission calculation tool RapidEms, which is fully consistent with COPERT v5 and links directly to our RapidAir dispersion modelling system.

JAQU recommend the use of data on primary NO_2 emissions (fNO_2) by vehicle type which is available via the NAEI website (based on 2014 NAEI) to provide a more detailed breakdown than the LAQM NOx to NO2 convertor. This suggests a link specific f-NO_2 emissions estimate for use in the NO_2 modelling.

Based on this requirement, the RapidEms road emissions calculation tool now includes additional functionality to calculate NO_2 emission rates for each road link. Link specific fNO_2 fractions can then be calculated for each link by dividing NO_2 by total road NOx emission rate. Calculating link specific NO_2 emission rates also facilitates dispersion modelling of both road NOx and NO_2 across the entire model domain to produce separate concentration rasters, which can then be combined with background concentrations to calculate NO_2 concentrations in each grid cell.

The recently updated version (v6.1) of the LAQM NO_x to NO_2 conversion spreadsheet has been used to convert road NOx, fNO_2 and background NOx into NO_2 concentrations where results at discrete receptor locations are required. This currently includes all NO_2 monitoring site locations and receptors placed at 4m from the PCM road links.

4.4 Non-road transport modelling and background concentrations

We have considered two types of non-road transport sources of NO_x emissions (or background concentration) data.

1. **Large local point sources**: A review of large point sources such as Part A processes regulated by the Environment agency included in NAEI was undertaken. No locations were considered close enough to Cardiff's modelling domain for to carry out separate dispersion modelling. For example, the majority of point sources do not contribute a substantial tonnage of NOx, with the exception of a steel manufacturing plant and an energy from waste installation. However, as this assessment estimates NO_2 annual mean in the same areas of the PCM model, it is only when PCM links are within close proximity that further consideration is required. The closest source is 770m upwind from PCM roads and it is considered that representation of these sources in Defra's background concentrations sufficiently represents background contributions.

2. **Sm**all **local point sources:** The European Pollutant Transfer Register (PRTR) has been reviewed and the majority of registered A2 and B permitted processes were screened out for insignificant contributions to NOx for example cement batching and mineral processing. However, there are a few additional sources which were considered further. A galvanising factory near the Bute East Dock was screened out due to a distance of >600 metres to roads included in the PCM model. Background contributions from a crematorium 200 metres downwind of census ID 99671 were not included in dispersion modelling. It was considered that NOx contributions through dispersion modelling will not be significantly different to Defra's background industrial contributions. As such process contributions represented within the Defra's background maps were considered satisfactory.

3. **Rail emissions:** Cardiff concluded in their 2009 updated and screening assessment that emissions from rail did not need to be considered further. Consequently, emissions from rail were considered to be satisfactorily represented by Defra's background concentrations.

4. **General background sources:** The 1km resolution LAQM background maps were used to provide estimates for all sources with the exception of motorway, primary and trunk roads contribution.

To avoid double counting of modelled road transport sources motorway, primary and trunk roads contributions were discounted from Defra's background maps.

4.5 Measurement data for model calibration

CCC's 2015 automatic and diffusion tube annual mean NO_2 measurements from roadside sites were considered for model verification. Further information on model verification has been presented within Appendix 1. Information on monitoring data QA/QC, diffusion tube bias adjustment factors etc. will be as presented in the CCC's 2016 LAQM Annual Progress Report.

5 Projected future year scenario modelling

5.1 Road transport future year baseline

The assessment year for all future scenarios is 2021. The basic projections used for the future year baseline scenario are:

- **AADT flows for future baseline year** were provided from the SEWTM. Further information on how these traffic flows were derived and how local growth in traffic is calculated is presented in 'Transport Modelling Methodology Report'[24].
- **Projected fleet split (vehicle type):** All future year scenarios will have the 4 core vehicle category fleet splits provided from the traffic model in the same breakdown as provided for the 2015 base year. The further split of HGVs into artic and rigid, and cars into private hire and hackneys will use the same ratios as derived for the 2015 baseline.
- **Projected fuel type and Euro class distribution:** a local fuel type and Euro class distribution has been projected forward from the local ANPR results to provide Euro class distributions for each of the future modelling years. This projection has been carried out in line with the draft methodology provided by JAQU. This has been done by deriving future scaling factors from the national NAEI data, applying these to the local ANPR results and then normalising to 100%. This gives an evolution of the local fleet that is slightly behind the national fleet. This can be seen in Figure 12 through to Figure 16, which shows that the average Euro classes across all ANPR sites have a slower uptake of Euro VI than NAEI.
- **Compliance split for future fleet** All future scenarios, including the baseline 2021 scenario, have a separate fleet mix for compliant and non-compliant vehicles. The projected 2021 Euro standards for different vehicle types were split into categories of compliant and non-compliant. The Euro standards which fit into these two categories are listed within Table 4.

Table 4 vehicle type Euro standards categorised as compliant/non-compliant

Compliant				Non-Compliant			
Car	Vans	HGV – Rigid/Artic	Bus	Car	Vans	HGV – Rigid/Artic	Bus
Euro 4-6	Euro 4-6	Euro VI	Euro VI	Euro-3 and older	Euro-3 and older	Euro-V and older	Euro-V and older

Ricardo provided the 2015 and 2021 compliance split at each ANPR location to enable the traffic modellers to split their highway matrices (vehicle categories) into compliant/non-compliant vehicle types. As a result, traffic model outputs provided contained traffic flow (AADT) accompanied with a compliant/non-compliant factor for all modelled vehicles. This was used to apportion traffic flows to the compliant/non-compliant fleet mixes.

- **Future year scenarios average vehicle speed data:** The same volume-weighted average speed approach mentioned in section 4.3.1 was adopted for the future baseline scenarios. The same speeds were applied to both compliant and non-compliant vehicles.
- **Projected vehicle NOx emission rates** will be calculated using the latest COPERT v5 NOx emission functions applied to AADT, speed, fleet and vehicle age composition for each future baseline year being modelled.

5.2 Scheme option modelling projections

This section provides the modelling methodology for the CASAP and CAZ scenarios as reflected in air quality modelling, see Table 1 for information on measures included in traffic modelling.

[24] 367590 Air Quality Transport Modelling Technical Note CASAP CAZ

5.3 CASAP 1 and 2

Measures accounted for in the emissions modelling: Taxi Licensing (Euro 6 for new licensees) and electric buses on service routes 27, 49/50 and 44/45. As noted within Table 1 the transport modelling methodology incorporates the remainder of the CASAP 1 and CASAP 2 measures. The effects of these changes are reflected within the traffic flows and compliance split provided by the traffic modelling and therefore emission calculations undertaken as part of the dispersion modelling. Consequently, it is only the taxi and electric buses measures that have specific assumptions within the air quality methodology to reflect changes upon the fleet and subsequent emission calculations for CASAP 1 and 2.

- **Taxi licensing:** information on private hire vehicles and hackneys registered with CCC was provided by the Council's licensing department. In addition, the ANPR data to produce Euro standards for the taxi fleet mix. Since the Euro standards defined by the ANPR dataset and from CCC's taxi licensing result in a different Euro standard composition (one is based on trips and the other vehicle numbers) a % shift approach was used to assess the impact of the licencing change. The taxi information included the number of taxis which fall into 3 age categories; 10 years or older, between 10 and 4 years old and under 4 years old of registered taxis. This was used to determine the current % of the taxi fleet naturally compliant. It has been assumed that all vehicles which are older than 10 years will register a new taxi under 5 years. This results in an 18% increase in the number of compliant taxis. This was used as an adjustment factor to shift 18% of the non-compliant (i.e. non Euro 6) taxi traffic flows (AADT) to compliant taxi traffic flows (AADT) for all roads in the study area.
- **Zero Emission Buses (ZEB):** The ambition of ZEB is to implement 36 electric buses on Cardiff City Buses' service routes. These would replace the oldest vehicles in the fleet and so the remaining fleet would consequently have a newer profile. There are 3 service routes which are being targeted with ZEB buses; 27, 49/50 and 44/45. This has been reflected in emission calculations of buses in the following way:
    - **Electric buses:** This modelling exercise only focuses upon dispersion modelling of NO_2. As such an electric bus produce zero NO_2 emission and so a fleet penetration % has been calculated to reduce bus traffic flows emissions are calculated with.
    - **Electric buses:** The % ZEB reductions were applied to the routes on which the buses operated. It is assumed that every service contributes an equal number of bus traffic flows along the route and so the ZEB reduction are only applied in proportion to the ZEB services along that route. This generates the % reduction in bus traffic flows assumed for roads used by ZEB targeted services is as follows:
        - **27:** a 20% reduction in bus traffic flows;
        - **44/45:** a 14% reduction in bus traffic flows; and
        - **49/50:** a 14% reduction in bus traffic flows.
    - **Bus fleet turnover:** The introduction of ZEBs will allow the older buses to be phased out. CCC provided Ricardo with the Euro standard details of Cardiff City Bus's fleet. This enabled the % of compliant buses to be calculated for Cardiff City Bus before the introduction of ZEB. CCC intend to replace 36 Euro 3 buses with ZEBs. Consequently, the effects of fleet turnover upon the % of compliant buses was calculated and resulted in a 3.26% shift from compliant to non-compliant buses. The actual Euro standards used for emission calculations was derived from an ANPR survey projected to 2021. Using the Cardiff City Bus's Euro standard mix with ZEB directly would be a change in methodology. As such, the 3.26% shift to compliant buses with ZEB was used as an an adjustment factor to transfer bus traffic flows (AADT) from non-compliant to compliant bus emission calculations.

5.4 CASAP 3

The measures reflected in air quality modelling is the retrofitting of all buses to Euro VI. In this case all remain non-electric buses were assumed to be Euro VI in the emissions calculations.

5.5 CAZ 1

This is a charging clean air zone which encompasses the inner-city centre, and is bordered by the following roads A4119, A4160 and A4161 as shown Figure 3. The charge of £10 associated with CAZ 1 applies to cars only and the behavioural response in relation to this charge has been based upon a JAQU default response data (taken from modelled responses to the London ULEZ). The majority of the upgrade assumption recommended by JAQU have been outlined within the transport modelling report. These are based on a £12.50 charge and have been scaled down to reflect the £10 charge. The traffic model outputs generated, and used in the air quality modelling, then take account of re-distribution of traffic and the affect upon proportions of compliant/non-compliant vehicles. The emissions model then takes this new split of compliant vehicles and associate it with the mix of euro standards outlined in Table 4 when calculating emissions.

The one JAQU upgrade assumption which has not been reflected in traffic modelling and therefore reflected in directly in the emission calculations is the change to petrol and diesel proportions. As would be expected the number of naturally compliant petrol vehicles is much higher as older petrol vehicles (2006) are classed as compliant. The JAQU upgrade assumptions account for this with a shift from non-compliant diesel to older compliant petrol vehicles.

It is assumed that the mix of compliant and non-compliant petrol/diesel euro standards are the same before and after the CAZ. To elaborate on this, there is no upgrade assumption to a specific euro standard only that the vehicle is compliant.

5.6 CAZ 2

The CAZ 2 charging clean air zone covers the exact same area as CAZ 1. However, only goods vehicles are targeted, with a planned charge for LGVs at £10 and HGVs £50. As with CAZ 1, these charges are less than the generic JAQU charges (based on the London ULEZ) and subsequently upgrade assumptions have been scaled down by the traffic modellers.

The JAQU upgrade assumptions also have a shift from petrol to diesel, like that assumed for cars, for the LGVs and this is handled directly in the emissions model.

Appendix 1: Model Verification

Verification of the model involves comparison of the modelled results with any local monitoring data at relevant locations; this helps to identify how the model is performing and if any adjustments should be applied. The verification process involves checking and refining the model input data to try and reduce uncertainties and produce model outputs that are in better agreement with the monitoring results. This can be followed by adjustment of the modelled results if required. The LAQM.TG(16) guidance recommends making the adjustment to the road contribution of the pollutant only and not the background concentration these are combined with.

The approach outlined in LAQM.TG(16) section 7.508 – 7.534 has been used in this case. All roadside diffusion tube NO_2 measurement sites in Cardiff have been used for model verification. A single road NOx adjustment factor was derived and used to calculate:

- Citywide modelling results at receptor points adjacent to relevant PCM road links.
- Citywide 1m resolution NO_2 annual mean concentration rasters providing a continuous representation of the spatial variation in modelled concentrations.

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 NOx concentrations were compared with concentrations measured at the various monitoring sites during 2015. The model output of Road NOx (the total NOx originating from road traffic) was compared with measured Road NOx, where the measured Road NOx contribution is calculated as the difference between the total NOx and the background NOx value. Total measured NOx for each diffusion tube was calculated from the measured NO_2 concentration using the latest version of the Defra NOx/NO_2 calculator (v6.1).

The initial comparison of the modelled vs measured Road NOx identified that the model was under-predicting the Road NOx contribution at most locations. Refinements were subsequently made to the model inputs to improve model performance where possible.

The gradient of the best fit line for the modelled Road NOx contribution vs. measured Road NOx contribution was then determined using linear regression and used as a 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 17.

The total annual mean NO_2 concentrations were then determined using the NOx/NO_2 calculator to combine background and adjusted road contribution concentrations.

Some clear outliers (n = 7) were apparent during the model verification process, whereby we were unable to refine the model inputs sufficiently to achieve acceptable model performance at these locations. These sites were excluded from the model verification. The reasons why acceptable model performance could not be achieved at these sites include:

- Sites located next to a large car park, bus stop, petrol station, or taxi rank that has not been explicitly modelled due to unknown activity data.
- No traffic model road link included where the NO_2 sampler is located, or not all road links included e.g. at a junction.

The RapidAir canyon allocator identified Westgate Street as a canyon, however including a canyon in this location leads to very scattered data in the model verification and the sites located in this canyon do not follow the general trends shown by the remainder of the monitoring locations. Consequently,

the canyon in Westgate was manually removed which resulted in the relationship between measured and modelled concentrations at sites in this street following similar trends to the other verification sites, and reduced the error in the model predictions.

To present a conservative approach to adjusting future year predictions of road NOx concentrations, a primary NOx adjustment factor (PAdj) of 1.807 based on model verification using all of the 2015 NO_2 measurements was applied to all modelled Road NOx data prior to calculating an NO_2 annual mean.

A plot comparing modelled and monitored NO_2 concentrations before and after adjustment during 2015 is presented in Figure 18.

Figure 17: Comparison of modelled Road NO_x Vs Measured Road NO_x before and after adjustment

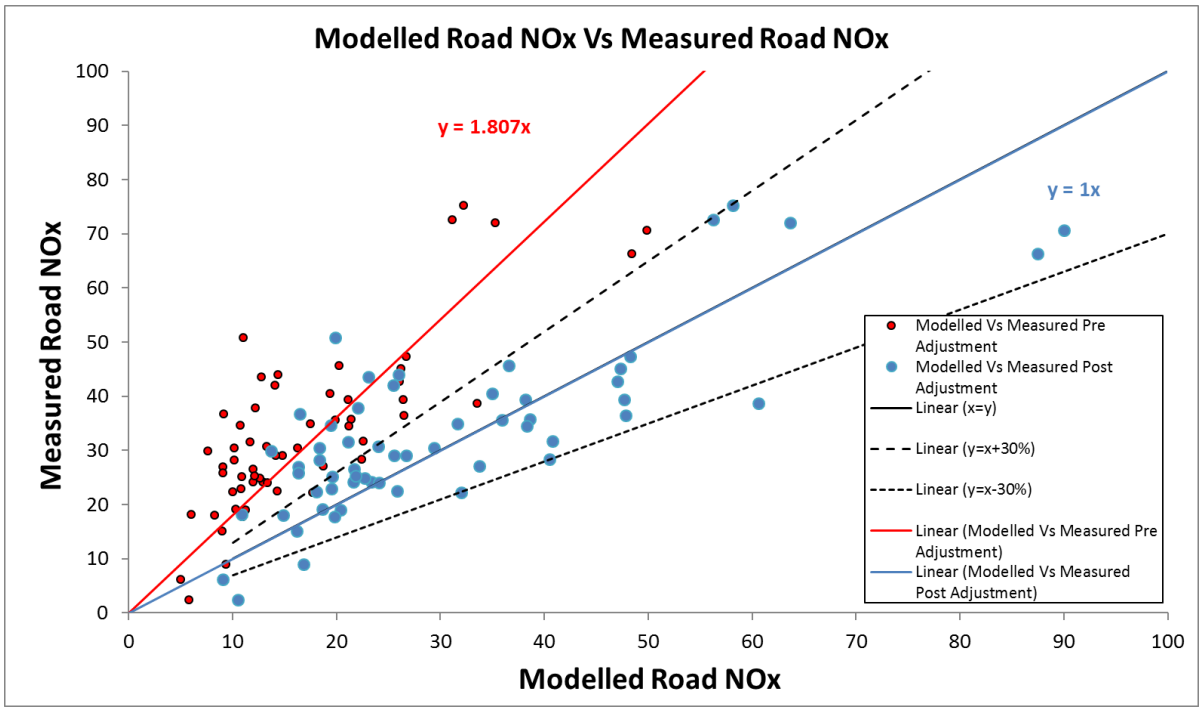
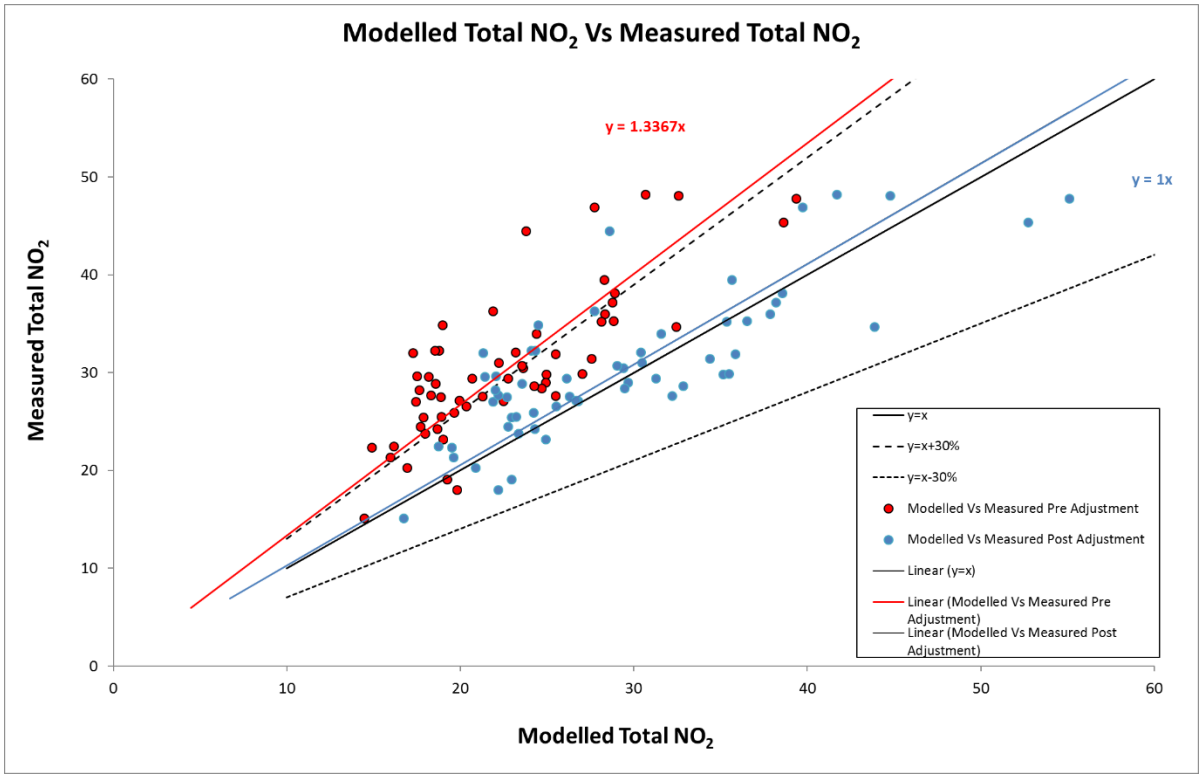


Figure 18 Modelled vs. measured NO_2 annual mean 2015 before and after adjustment



Model performance

To evaluate the model performance and uncertainty, the Root Mean Square Error (RMSE) for the observed vs predicted NO_2 annual mean concentrations was calculated, as detailed in Technical Guidance LAQM.TG(16). This guidance indicates that an RMSE of up to 4 µg/m^3 is ideal, and an RMSE of up to 10 µg/m^3 is acceptable. The calculated RMSE is presented in Table 5. In this case the RMSE was calculated at 5.1 µg.m^{-3}which is close to the ideal range suggested by the guidance.

Table 5 Comparison of measured and modelled concentrations at measurement locations in 2015, and the model root mean square error.

NO_2 monitoring site	Measured NO_2 annual mean concentration 2015 (µg.m^{-3})	Modelled NO_2 annual mean concentration 2015 (µg.m^{-3})
DT33	46.9	39.7
DT44	27.1	26.8
DT45	32.1	30.4
DT56	29.6	22.0
DT58	48.3	41.7
DT81	35.3	36.5
DT82	23.8	23.4
DT85	22.4	19.5
DT86	34.9	24.5
DT96	31.1	30.5
DT97	30.5	29.4
DT98	25.4	22.9
DT99	29.8	35.2
DT100	28.9	23.5
DT106	29.4	31.3
DT107	30.7	29.0
DT111	21.3	19.6
DT112	27.1	21.9
DT119	27.7	32.2
DT124	22.5	18.7
DT126	36.0	37.9
DT128	29.6	21.4
DT129	31.5	34.4
DT130	35.2	35.3
DT131	39.5	35.6
DT133	31.9	35.8
DT139	29.4	26.1
DT140	36.3	27.7
DT141	32.3	24.1
DT143	38.2	38.6
DT144	37.2	38.2
DT145	29.9	35.5
DT146	26.6	25.5

NO_2 monitoring site	Measured NO_2 annual mean concentration 2015 ($\mu g.m^{-3}$)	Modelled NO_2 annual mean concentration 2015 ($\mu g.m^{-3}$)
DT147	27.7	22.2
DT148	27.5	22.7
DT152	27.6	26.3
DT153	29.0	29.7
DT156	25.9	24.2
DT157	27.2	26.7
DT158	25.5	23.2
DT159	34.0	31.6
DT161	32.3	24.3
DT162	24.5	22.7
DT163	23.2	24.9
DT164	20.3	20.9
DT165	15.1	16.7
DT166	32.1	21.3
DT167	28.3	22.0
DT168	24.3	24.3
DT170	19.1	23.0
DT171	18.1	22.2
DT172	44.5	28.6
DT173	28.4	29.5
DT175	34.7	43.9
DT174	28.7	32.8
DT176	47.8	43.9
DT177	48.1	55.1
DT178	45.4	44.8
	RMSE (all sites)	**5.1 $\mu g/m^3$**
	Fractional Bias	**0.05**
	Correlation Co-efficient	**0.81**

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR
United Kingdom

t: +44 (0)1235 753000
e: enquiry@ricardo.com