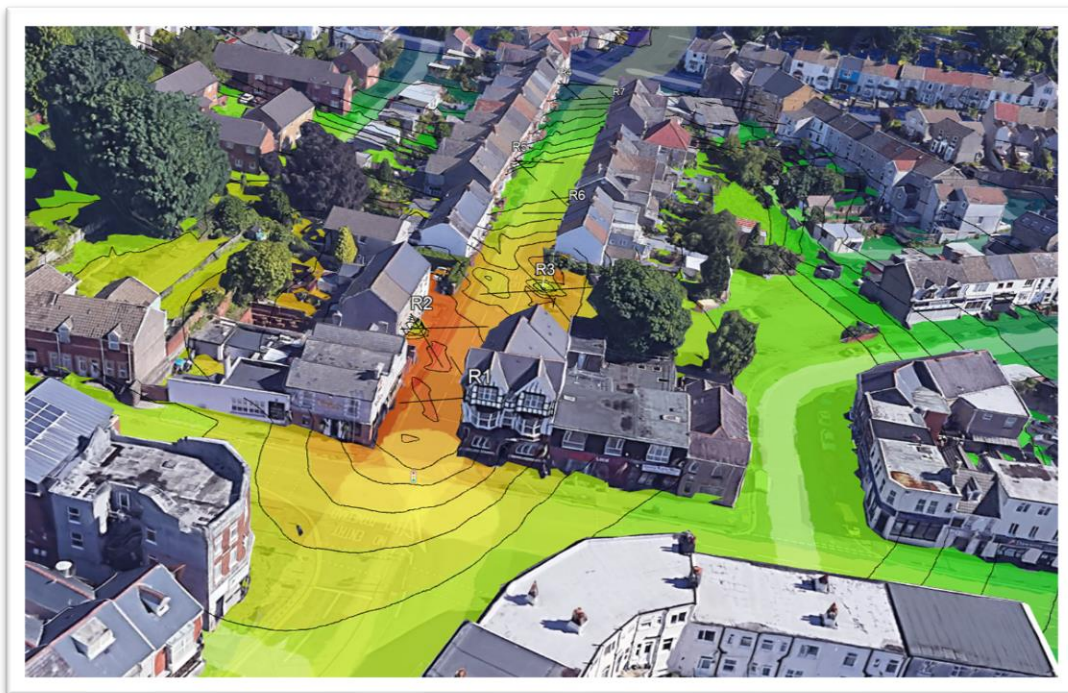


DRIVE-THRU DISPERSION MODELLING WITH ROADVENT

Report for Pollution Solution Holdings Ltd



June 2023

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Confidential



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PROJECT:

DRIVE-THRU DISPERSION MODELLING WITH ROADVENT

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1. Executive Summary

- This report details a study carried out for Pollution Solution Holdings Ltd where a Roadvent in-road suction vent system was modelled to determine the reduction of nitrogen dioxide (NO₂) from vehicle emissions at a real drive-thru location in the UK.
- The World Health Organization (WHO) Air quality guidelines were revised in 2021 where it is recommended that annual average ambient NO₂ does not exceed 10 ug/m³ and 24-hour exposure should not exceed 25 ug/m³.
- Modelling was used to estimate the hourly, daily and annual average concentrations of NO₂ at key human exposure receptor points at the drive-thru including two serving hatches and an ordering point.
- A traffic simulation model based on visiting traffic data at the drive-thru road system predicted hourly traffic emissions that people were exposed to.
- Baseline dispersion modelling was carried out using the NO₂ emission data and local meteorological data to predict hourly, daily and annual average NO₂ concentrations on-site and exposure levels at each of the receptor points.
- The model was rerun with a 30m Roadvent system located on drive-thru road closest to serving hatches to estimate reductions in exposure.
- NO₂ annual average concentrations were reduced by 7.3 ug/m³ and 4.6 ug/m³ at the two serving hatches respectively if a Roadvent system were installed.
- Roadvent reduced daily average NO₂ concentrations that were above the WHO recommended 24-hour exposure guideline in one serving hatch to just 1 day throughout the year compared to 39 days otherwise (i.e. a 97.4% reduction of 38 days). In a second serving hatch, Roadvent reduced the exceeding number of days from 13 to none.
- Finally, Roadvent induced reductions in NO₂ concentrations were used to predict reductions in relative risk for key health outcomes including adult asthma hospital admissions, out-of-hospital cardiac arrests and stroke instances.
- The risk of adults being admitted to hospital for asthma would be reduced by approximately 1.2%, if NO₂ was reduced by 42% on half the days of the year.
- The risk of out-of-hospital cardiac arrest would be reduced by 1.46%, if air pollution (NO₂) was reduced by 35.8%.
- The risk of emergency hospitalisation for stroke would be reduced by approximately 2.3%, if NO₂ was reduced by 42% on half the days of the year.
- It is possible that assumed average working days lost due to sickness absences of 4.4 days per employee, could be reduced for employees at drive-thru serving hatches as modelled in this study.

2. Background

This report details the data and results obtained on behalf of Pollution Solution Holdings Ltd where a Roadvent in-road suction vent system was modelled to determine the hourly, daily and annual reduction of nitrogen dioxide (NO₂) from vehicle emissions at key receptor points on a road system at a typical fast-food drive-thru. The study further estimates potential risk reduction for some key health outcomes due to NO₂ reduction and lower exposure at the key receptor points.

The World Health Organization (WHO) Air quality guidelines were revised in 2021 where it is now recommended that annual average ambient NO₂ does not exceed 10 ug/m³ and 24-hour exposure should not exceed 25 ug/m³ (Table 1).

Table 1. The World Health Organization (WHO) Air quality guidelines.

Pollutant	Averaging time	2005 AQGs	2021 AQGs
PM2.5 (ug/m ³)	Annual	10	5
	24 hour ^a	25	15
PM10 (ug/m ³)	Annual	20	15
	24 hour ^a	50	45
O3 (ug/m ³)	Peak season ^b	-	60
	8 hour ^a	100	100
NO2 (ug/m ³)	Annual	40	10
	24 hour ^a	-	25
SO2 (ug/m ³)	24 hour ^a	20	40
CO (mg/m ³)	24 hour ^a	-	4

µg = microgram; ^a 99th percentile (i.e. 3-4 exceedance days per year). ^b Average of daily maximum 8-hour mean O₃ concentration in the six consecutive months with the highest six-month running- average O₃ concentration. Note: Annual and peak season is long-term exposure, while 24 hour and 8 hour is short-term exposure.

To help nations work towards the new annual and 24-hour guidelines, interim targets were set for all pollutants. For the NO₂ annual average, these interim targets are 40, 30 and 20 ug/m³ respectively. The guideline for the 1-hour maximum NO₂ exposure level of 200 µg/m³ was unchanged.

Air pollution can also impact productivity within the workplace particularly due to absences due to sickness and hospital admissions. In 2018, 141 million working days were lost due to sickness absences, an average of 4.4 days per employee (CBI, 2020)

It is estimated that there are currently around 2,256 drive-thru's in the UK with around a thousand being just one prominent brand of fast-food chain (Guardian, 2023). Therefore, road systems at drive-thru's with significant traffic driving slowly in low gear, idling and frequent stop-starting could lead to increased levels of NO₂ within the immediate drive-thru vicinity, increased exposure to serving staff and increased risk of detrimental health impacts.

The Roadvent system works by NO₂ (and other pollutants) being drawn into the system through vents that are installed in the road surface and then pumped through pipes into a filtration unit that captures most of the pollutants. In work previously undertaken by Cambustion at an installation located within Millbrook Proving Ground, UK, a series of controlled tests showed that Roadvent successfully reduced potential exposure to humans from roadside pollution levels by 91% (Airqualitynews, 2022).

The overall aim of this project was therefore to carry out a modelling process to estimate the hourly, daily and annual average concentrations of NO₂ at key human receptor points including two serving hatches and an ordering point at a real, busy fast-food drive-thru in the UK.

Hourly temporal vehicle patterns were estimated and fed into a traffic simulation model based on the drive-thru road system to predict hourly traffic emissions from vehicles travelling through the road system.

Emission data for NO₂ were then used to carry out dispersion modelling to predict baseline (i.e. no Roadvent installed), local NO₂ concentrations on site and exposure levels at each of the receptor points. The model was rerun with a 30m Roadvent system located on the drive-thru road segment closest to serving hatches and an ordering point to estimate potential reductions in exposure.

Finally, potential Roadvent induced reductions in NO₂ concentrations at receptor points were used to predict reductions in relative risk for key health outcomes including adult asthma hospital admissions, out-of-hospital cardiac arrests and stroke instances.

3. Methodology

3.1. Site selection

To model transport emissions from queuing traffic at a typical drive-thru an exemplar fast-food restaurant was chosen at a location in South Wales. The drive-thru location was selected based on it being typically representative of a number of factors in an urban area including: a well-known national outlet having well characterized hourly traffic patterns; predictable traffic volume; 24-hour opening; a flat terrain (i.e. non-complex surrounding geography); non-extreme meteorological conditions; likely standard (in terms of emissions) vehicles visiting; predicted background NO₂ levels being not unusual or greatly impacted by other sources.

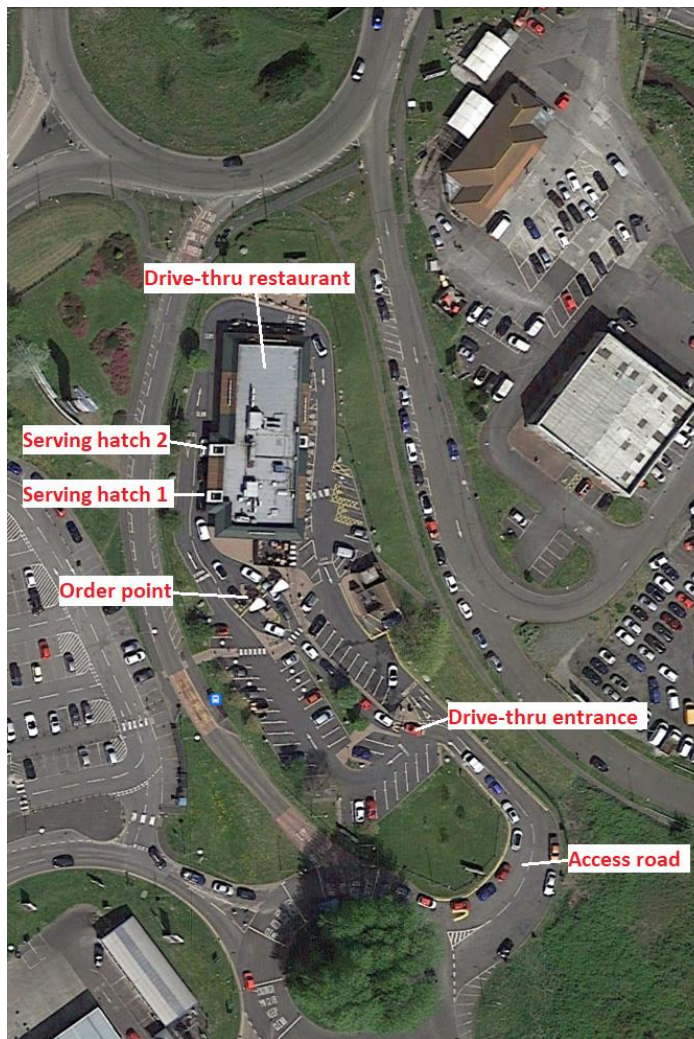


Figure 1. Exemplar restaurant and drive-thru site map showing location of buildings, road infrastructure and locations of drive-thru entrance, order point and serving hatches.

The restaurant is encompassed by a road layout that includes a single lane leading from the main site entrance and proceeding in a northerly direction to a dual-lane order point (facilitated by intercom) (Figure 1). Vehicles then re-enter a single lane leading to two serving hatches on the west façade of the building.

Vehicles then proceed to leave the site via a single lane that circles around the building on the north side to the exit on the east side.

3.2. Traffic count data

Hourly weekday traffic count patterns at the drive-thru were estimated using a twin track approach. Firstly, a survey was carried out on a weekday by two observers positioned adjacent to the drive-thru who counted visiting traffic between 8.00am and 10.00pm. The count data were converted to number of vehicles visiting per hour. Secondly, typical predicted hourly traffic count data were obtained from publicly available planning applications for drive thru restaurants that were published within the last seven years. A typical example shows the expected number of vehicles attending a proposed restaurant at a 15 minute breakdown frequency between 10.00am and 10.00pm where the number of vehicles visiting the drive-thru can be calculated (Snodland, 2020).

The data retrieved from the site survey and planning proposals allowed the construction of a typical weekday hourly probability distribution for vehicles visiting a drive-thru of the exemplar type (Figure 2).

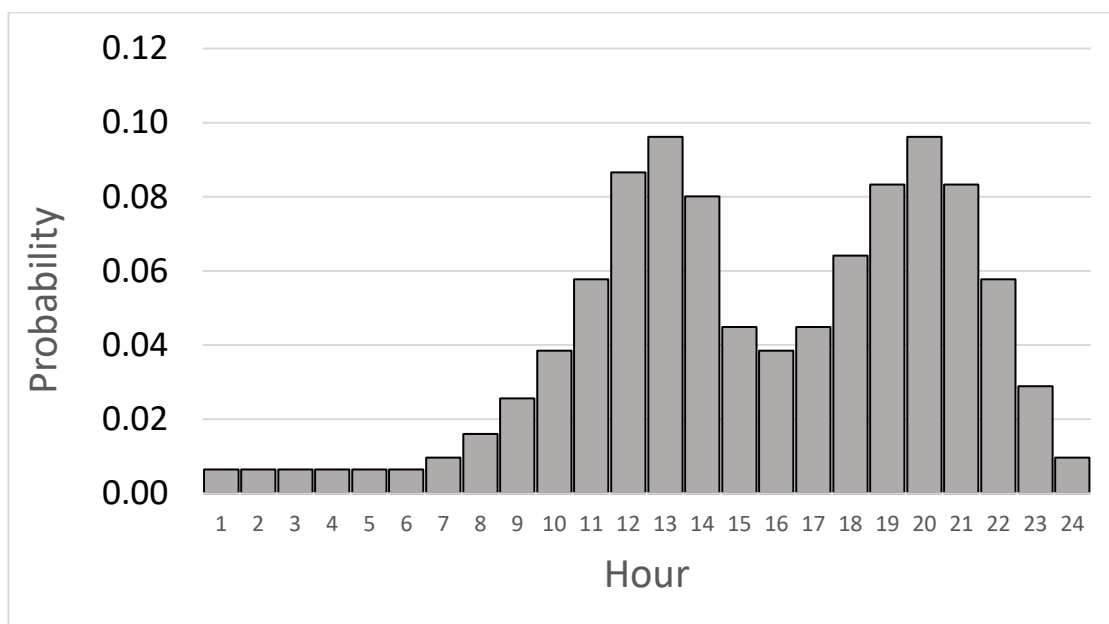


Figure 2. Hourly probability distribution of vehicles using a drive-thru of the type chosen.

Following the site survey, a total daily traffic count of 1500 visiting vehicles for the drive-thru was considered for further modelling. The hourly probability distribution was then used to calculate the predicted typical weekday hourly vehicle traffic count for the drive-thru (Figure 3). The hourly vehicle counts were then used as input for the traffic simulation to estimate temporal emission patterns from moving and queuing traffic at the site during a 24 hour period.

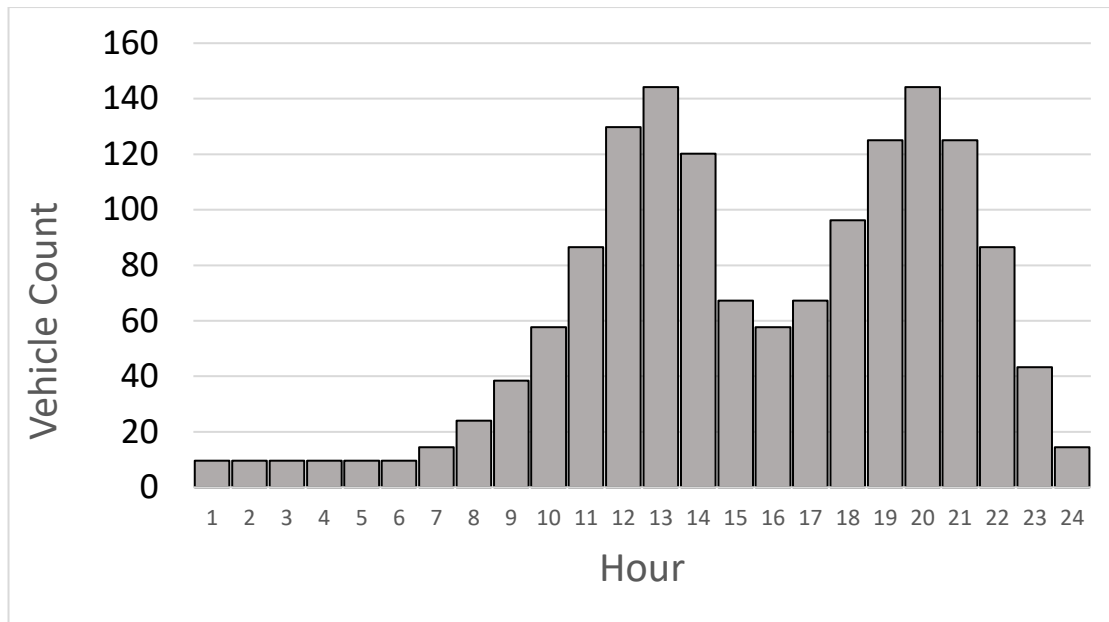


Figure 3. Predicted typical weekday hourly vehicle traffic count for drive-thru.

3.3. Traffic flow simulation

To determine predicted NO_x/NO₂ emissions from vehicles using the drive-thru, a traffic simulation model was required that accounted for movement and idling of vehicles using the road system over the desired time period.

Traffic flow movement at the drive-thru was modelled for 1500 vehicles over a typical weekday 24 hour period using the Simulation of Urban Mobility (SUMO) software and the hourly traffic count data as input. SUMO is an open source, highly portable, microscopic scale and continuous traffic simulation package designed to handle large networks (Lopez et al., 2018). It allows for intermodal simulation and comes with a large set of tools for road network and scenario creation.

3.3.1. Drive-thru road network creation

SUMO requires a road network that represents the layout of road segments being modelled. Open Street Map was used to select a region of local roads including and surrounding those of the drive-thru complex. An *osm* format file with the local road infrastructure was exported from Open Street Map and the SUMO netconvert tool was used to import the road network as an xml file into the netedit package. The network was edited in Netedit 1.16.0 to remove unnecessary road segments.

The resulting network provided a series of to-scale road segments relevant to traffic usage at the drive-thru (Figure 4). Each vehicle in the simulation entered the drive-thru road network via the entrance, proceeded to a serving hatch (in either corresponding lane depending on occupancy and then proceeded via the single lane to one of the serving hatches.

The network was modified further to stop vehicles at the order point and hold them there for a minimum of 60 seconds to simulate an average food order time. A vehicle could only progress from that point if there was

space in front to do so. Vehicles were further held at a serving hatch for a minimum of 90 seconds to simulate average food pick up time. Following food pick up, a vehicle commenced along the road network to the exit.

To calculate differential NO_x emissions across the road network as required for dispersion modelling, five segments of road (RS1 to RS5) were defined between the distal serving hatch and drive-thru lane entrance.

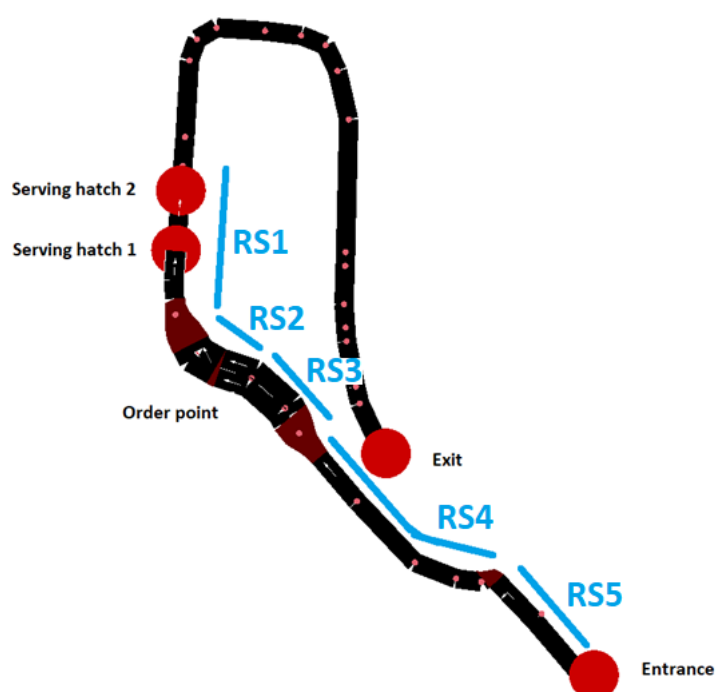


Figure 4. To-scale road network for drive-thru constructed for SUMO traffic simulation. Locations of serving hatches and order point are highlighted. The five segments of road regions (RS1-RS5) treated separately for emissions calculations and dispersion modelling are highlighted in blue.

3.3.2. Vehicle route and emission type definitions

For the SUMO microscopic traffic simulation, each of the 1500 vehicles was automatically assigned a defined departure time, and a route through the network. The departure and arrival properties, lane to use and vehicle velocity dependent on time and traffic volume was further pre-defined by the software. Each vehicle was assigned physical properties including 'car' or 'van' depending on the predicted frequency of each in the typical vehicle fleet. Using the on-site survey data, vehicles were predominantly classed as car.

Given that the current vehicle fleet composition will differ in proportions of diesel and petrol fuel type as well as Euro Standard emissions class, National Atmospheric Emissions Inventory fleet projection data (BEIS, 2019) were used to determine the approximate split of each class in 2022 based on the modelled road network being urban road (Table 2). The average projected proportions of petrol and diesel vehicles across England, Scotland, Wales and Northern Ireland in 2022 were calculated as 0.54 and 0.45 respectively. The projected 2022 proportions of Euro Standard class for conventional engine cars (outside London) in the UK fleet composition is shown in Table 1. These proportions were then used to predict the typical number of petrol and diesel vehicles within each Euro Standard class visiting the drive-thru per hour over a 24-hour weekday period (Figure 5).

Table 2. UK car fleet composition projections for 2022.

Class	Frequency			
	Petrol	f-NO ₂	Diesel	f-NO ₂
Euro 4	0.05	0.05	0.06	0.21
Euro 5	0.17	0.08	0.27	0.16
Euro 6_1	0.11		0.17	
Euro 6_2	0.25		0.23	
Euro 6_3	0.30		0.24	
Euro 6 (Total)	0.66	0.04	0.64	0.25

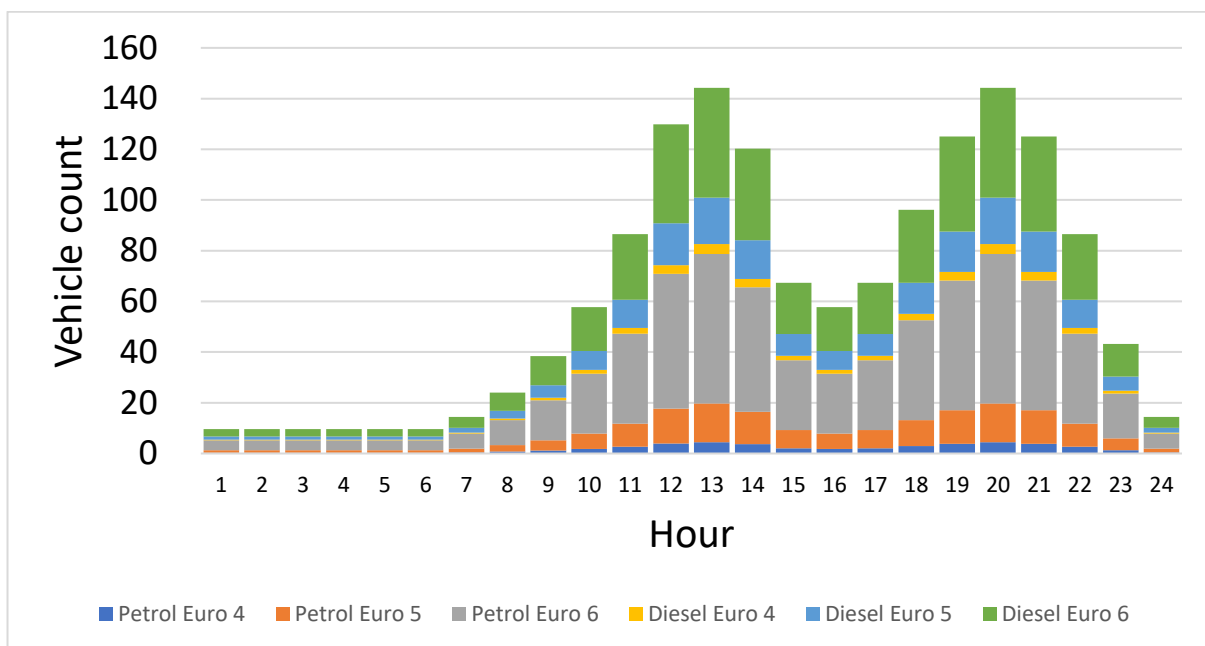


Figure 5. Distribution of number of petrol and diesel vehicles per Euro Standard class per hour at the drive-thru over a 24-hour period.

3.3.3. Traffic flow simulation

The petrol and diesel vehicle numbers per Euro Standard class per hour were used as input to the SUMO duarouter tool to create vehicle routes from entrance to exit through the drive-thru road network during a 24 hour period. The network and route data were then used as input for the simulation in the SUMO GUI with a one second time step between a total run time of 86400 seconds (24 hours). Parameters were optimized to ensure accurate vehicle speed, vehicle distance and collision avoidance. Figure 6 shows a snapshot of vehicles queueing within the drive-thru road network at a one second simulation time-point.

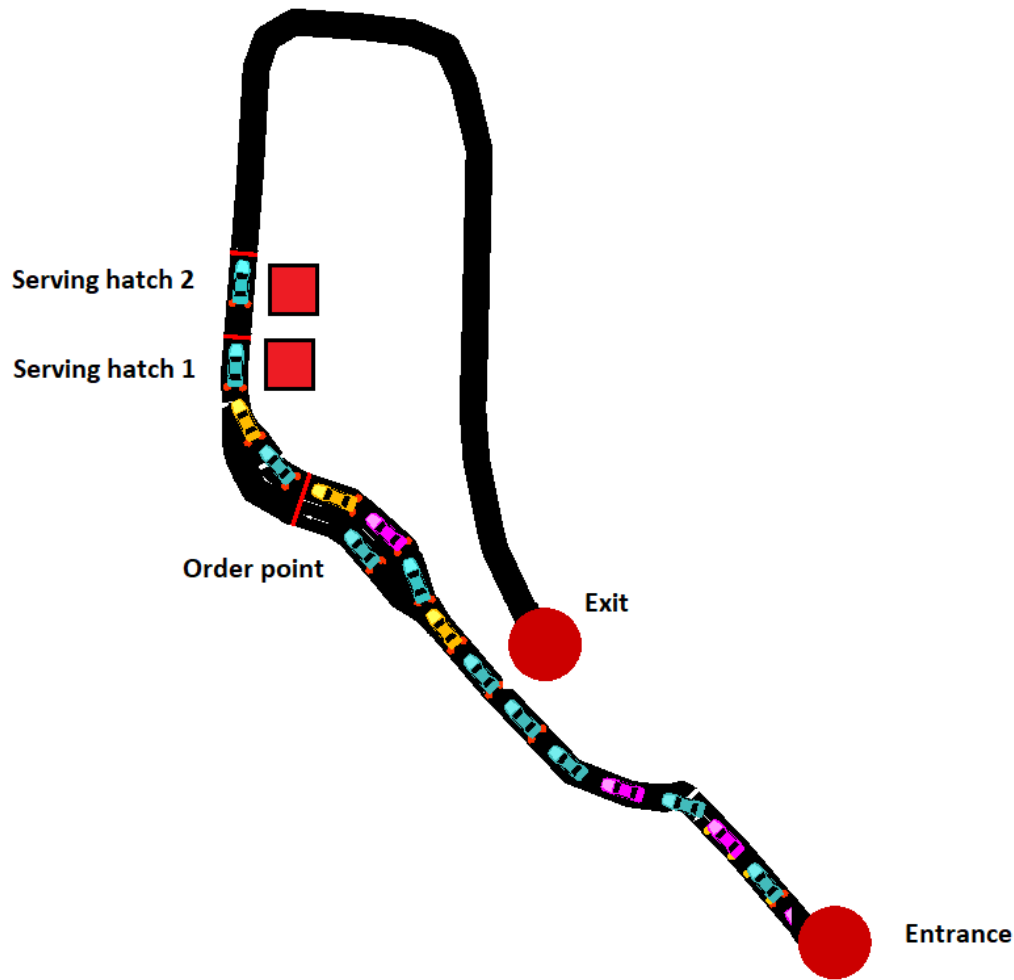


Figure 6. A snapshot of vehicles queueing within the drive-thru road network at a busy simulation time-point.

3.3.4. NOx emission calculations

SUMO simulates vehicular pollutant emissions, including NO_x, based on the Handbook Emission Factors for Road Transport (HBEFA) version 4.2 emission factors (HBEFA, 2022). In the UK, it is common practice to use the “Computer Program to Calculate Emissions from Road Transport” (COPERT) emission factors within traffic modelling that estimates emissions of all regulated air pollutants from different vehicle categories as a function of average speed. As stated in Defra’s Air Quality Expert Group report, “Exhaust Emissions from Road Transport” report (Defra, 2021), the HBEFA emission factors are based on the simulation of a huge number of driving situations and vehicle categories. HBEFA is therefore a “traffic situation” model rather than an average speed model like COPERT and the emission factors account for different traffic situations (e.g. how congested the road is) as well as road type. Given the driving behaviours on a drive-thru road system HBEFA is therefore deemed to be a more appropriate model for estimating NO_x emissions from vehicles in this study.

The simulation was instructed to calculate absolute NO_x emissions (mg/s) for each hour of the simulation for each segment in the drive-thru road network. This gave an estimate of NO_x emissions per hour in a typical weekday at the drive-thru for input into dispersion modelling.

3.4. GRAL Dispersion modelling

The dispersion modelling technique chosen to determine the contribution of NO_x and subsequently NO₂ from traffic at serving hatches in the demonstrator drive-thru restaurant was the Graz Mesoscale Model (GRAMM)/Graz Lagrangian model (GRAL) (Öttl and Kuntner, 2018). The GRAL modelling system was developed by the Graz University of Technology, Institute for Internal Combustion Engines and is a non-steady state air quality model which has been used extensively in Europe including Wales (Caerphilly County Council, 2018). An example of an application using GRAL to determine near-roadside air quality is shown in Romanov (2020). An example of using GRAL to models levels of NO₂ at a roadside site in exceedance of current limit values the UK is shown in Ricardo (2017).

3.4.1. Drive-thru considerations and model domain

Dispersion modelling in a drive-thru scenario can be challenging as air pollutant concentrations can be influenced by low wind speeds that arise from flows around buildings and other structures. GRAL is a sophisticated micro-scale air quality modelling method applicable to a small domain such as a single, short span of roadways and is described in Öttl and Kuntner (2018). Therefore, the GRAL dispersion model was used to derive the predicted contributions of NO₂ (from NO_x) from idling and moving traffic within the drive-thru roadway given impacts of fine resolution topography including local buildings. This approach also ensured that the conditions to be able to accurately model the effect of emissions reduction through a Roadvent system installed within the drive-thru roadway were set appropriately. In this study we have used some of the recommendations as followed in the modelling carried out for previous studies in Wales including that for Caerphilly County Council in the Hafod-Yr-Ynys case in 2018.

GRAL models can account for variable 3D building structures within the canyon. Building footprint data for each property including the drive-thru restaurant and relevant adjacent buildings within the surrounding area were taken from high resolution maps. Building height data were retrieved from the Ordnance Survey MasterMap Topography Layer Building Height Attribute collection. A prognostic approach was set to account for building use within the models.

The modelled area was framed by 100m x 146m grid encompassing the restaurant and drive-thru complex with a spatial resolution of each grid cell was of 2m resolution (Figure 7).

The entire grid therefore enabled prediction of NO₂ concentrations at 1.5m height across 50 points in the horizontal plane and 73 points in the vertical plane. Three modelled receptors were declared at the two serving hatches and ordering point at a height of 1.5m to approximate the average height of a human in order to estimate exposure at these points.

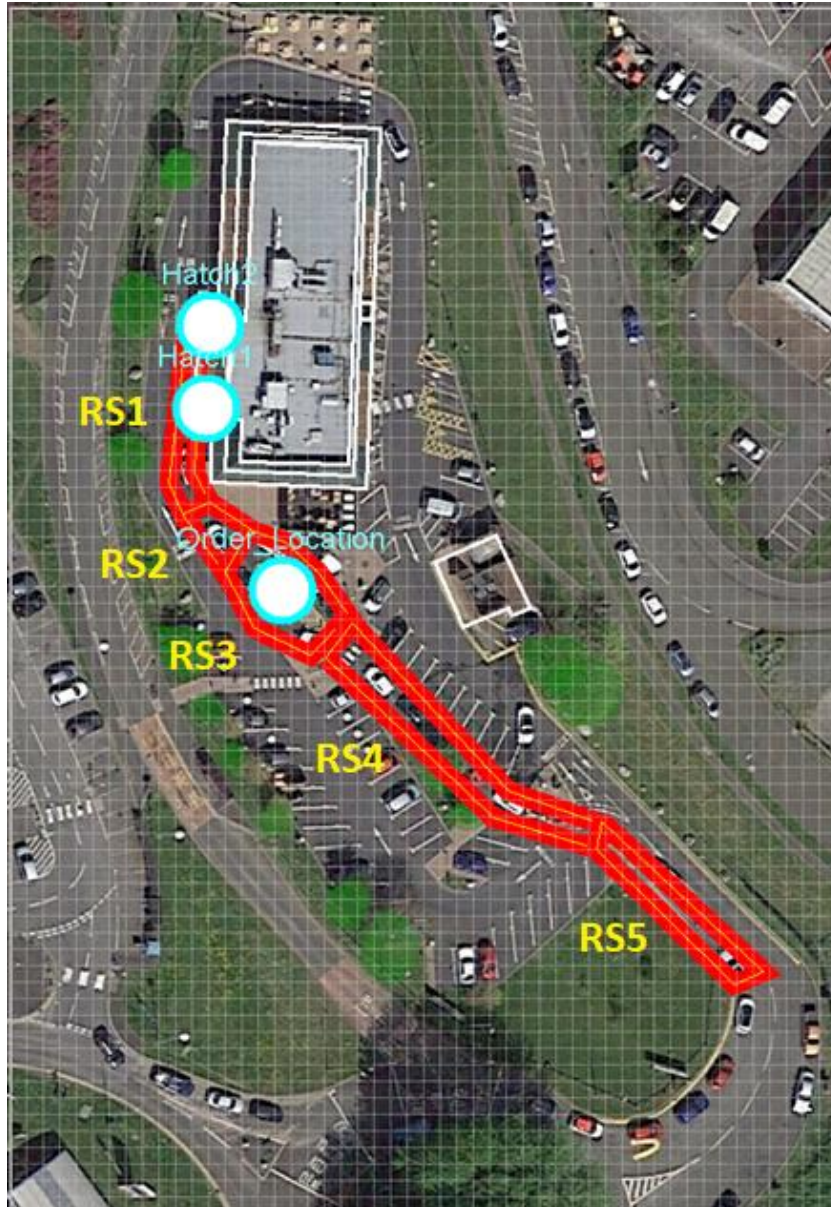


Figure 7. Modelled domain for the drive-thru restaurant area and road network. The restaurant buildings and out buildings (with roof layer outlines) are outlined in white. The order location and serving hatches are shown along with the five line sources bordered in red representing different modelled road segments (RS1-RS5). The model domain grid is shown with individual 2m white squares.

The elevation above sea level at the south and north ends of the modelled area was 6m and 7m respectively. The estimated gradient between these end points is thus approximately 0.008m. The terrain type for dispersion modelling purposes was therefore considered flat without needing to account for differing terrain impacts.

Five line sources were created in the model domain between the distal serving hatch and drive-thru lane entrance that aligned with the same road segments (RS1-RS5) used in SUMO to estimate hourly NOx emissions (Figure 7).

3.4.2. Meteorological data

Meteorological data for dispersion modelling used in GRAL were obtained from the UK Met Office (Met Office, 2019). Midas-open catalogue is the open data version of the Met Office Integrated Data Archive System (MIDAS) for land surface station data (1853 – present). It contains land surface observations data from the Met Office station network that have been designated as public sector information and provided under an Open Government Licence. Midas-open is a subset of the fuller Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current), containing only UK mainland land surface observations owned or operated by Met Office. MIDAS Open comprises of hourly and daily weather measurements and observations of parameters relating to temperature, rainfall, sunshine, radiation, wind and weather observations such as present weather codes, cloud cover, snow etc.

For this study, hourly data from 2019 were retrieved for Pembrey Sands weather station. The weather station is situated approximately 15 km in a west/north west direction from the drive-thru site. This station, due to its close proximity, was considered to best represent meteorological conditions experienced at the drive-thru and surrounding area. The year 2019 was chosen as it contained greater than 99.7% completeness for days with data. Pembrey Sands station is 7 meters above sea level with latitude and longitude coordinates of 51.714 and -4.367 respectively.

Mean wind speed velocity for the year modelled was 12.5 m/s and the wind direction was generally recorded as south-westerly (Figure 8).

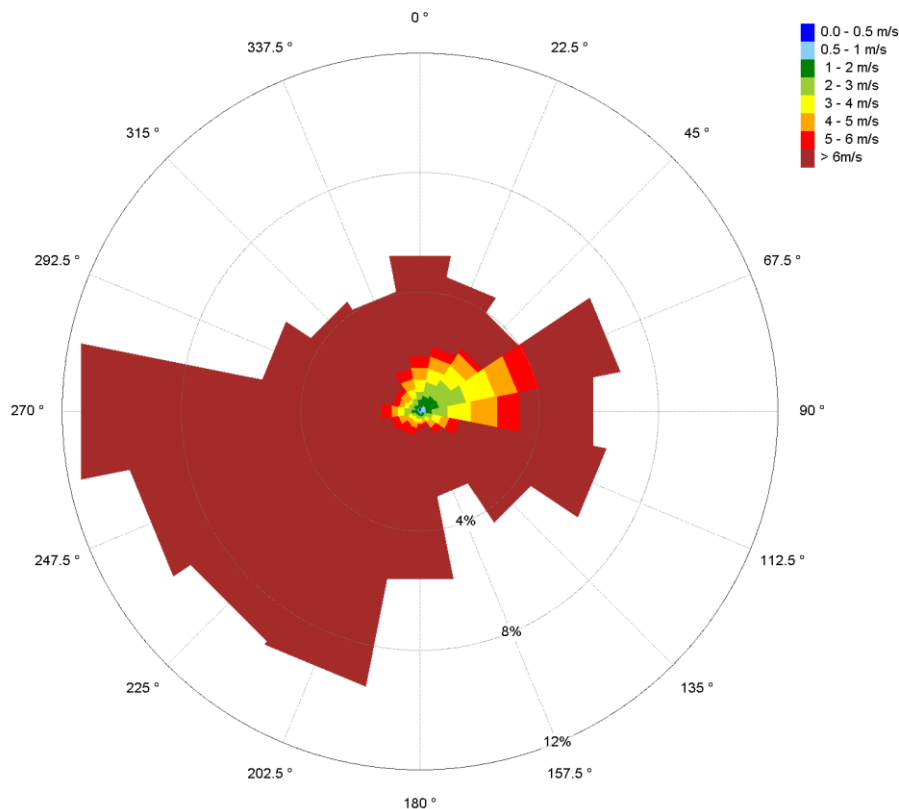


Figure 8. Windrose plot showing frequency of direction of wind direction relative to wind speed.

3.4.3. NO₂ background data

Background NO₂ concentration data for the modelled site was retrieved from Defra's Pollution Climate Mapping (PCM) model. The PCM is used to produce background maps, 1x1 km grids of pollutant concentrations, for the UK. The NO₂ background concentration for the model domain was estimated as 12.1 ug/m³.

3.4.4. NO₂ emissions calculations

Hourly total NO₂ emissions were calculated for input into the GRAL model. The hourly NO_x emissions provided for each line segment from the SUMO traffic model were converted to NO₂ concentrations using Defra's 2022 projected 'Fraction of NO_x Emitted by Vehicles as NO₂ (by volume)' factors shown in Table 2 for each vehicle emission class. The maximum hourly NO₂ concentrations were then declared for each line source along with an emission time series of diurnal modulation factors proportionate to the emissions observed for each hour in the SUMO model. This allowed the GRAL model to use more accurate NO₂ emissions across hours of the day rather than a single overall average concentration. Similarly, a seasonal time-series based on monthly NO₂ concentration patterns was added to the model to adjust for higher concentrations at certain periods of the year. Prior to input into the GRAL model, NO₂ concentrations for each line source were converted to kg/h as required and the background concentration value added.

A baseline model with no Roadvent system was initially created to determine an entire time-series of NO₂ concentration contribution to each serving hatch and ordering point from each road segment of each hour of each day in the modelled year. The modelling was repeated with a Roadvent system in-situ but where the two line sources (RS1) positioned adjacent to the serving hatches and extending 30m back towards the order point (but not including it) had NO₂ emission concentrations reduced by 90% (Figure 9).

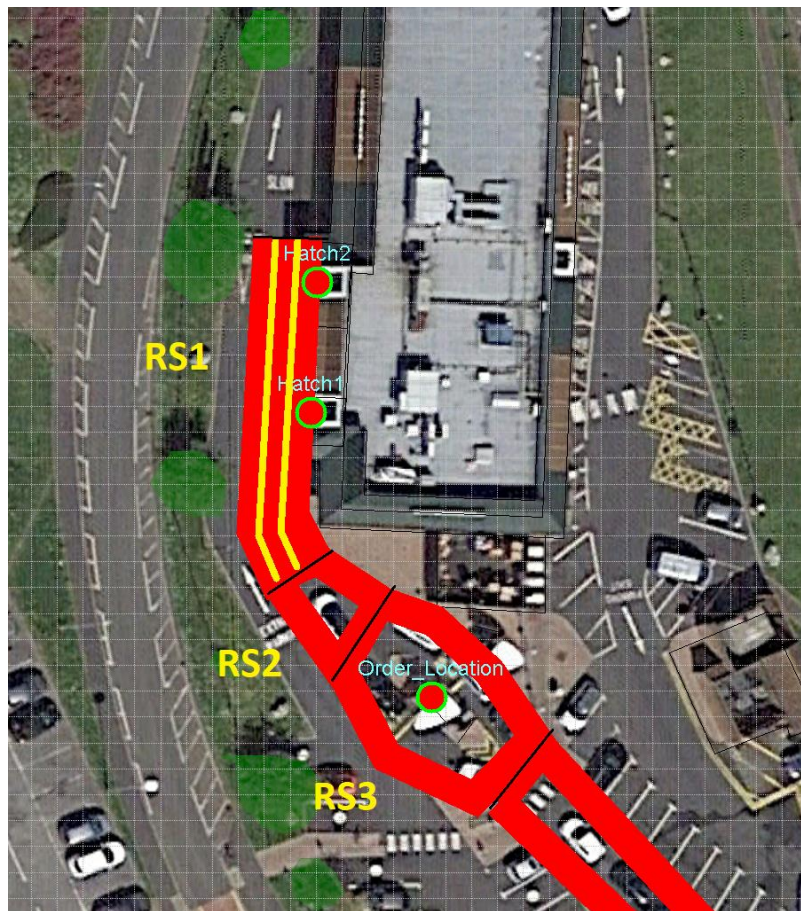


Figure 9. The Roadvent system was modelled at a 30m length in road segment 2 (RS1) in close proximity to the two serving hatches. The system is represented as two yellow lines (the lines are for illustrative purpose only and width is not to scale).

This allowed approximation of NO₂ removal at source at the empirical maximum removal capacity of 90% level. The two roadvent pollution intake slots, that would be installed as standard, sit discreetly within the top level of the road surface, forming an almost flush finish and therefore were not assumed to impact on the topology of the model domain. NO₂ emissions at all other line sources in the model were not adjusted as it was assumed that a Roadvent system distal to these stretches would not remove NO₂ from vehicles at that point. Again, an entire time-series of NO₂ concentration contribution to each serving hatch from each road segment of each hour of each day in the modelled year was created to compare against baseline data.

3.5. Calculation of change in relative risk for health outcomes

NO₂ concentration data generated through the dispersion modelling at key exposure points allows for quantification of the change in risk for a health outcome through a health impact analysis. Health impact assessments for air pollutants are usually carried out to describe detrimental impacts to a population. The health impacts can however be described at the local level for a specific population group e.g. asthmatics.

Using the approach of Williams et al (2019), changes in relative risk for a set of health outcomes were determined given reductions in concentrations of NO₂ reported for hatch 1 in this study. Hatch 1 was selected as this location was deemed, following assessment of modelling outputs, to have the greatest impact on health and benefits of exposure reduction.

A number of scenarios were assessed where relative risk for health impacts following exposure to NO₂ have previously been well characterized in the literature:

- Adult asthma hospital admissions
- Out-of-hospital cardiac arrests
- Stroke

Briefly, the change in relative risk is calculated as follows. For each receptor location (e.g .drive-thru hatch 1), NO₂ data is used as a surrogate for exposure. A quantitative relationship between exposure of air pollution and a particular health is then established. This relationship uses a concentration response function (CRF) which allows prediction of relative risks across a range of concentrations for the pollutant. Generally, CRF's used to predict relative risks for defined health outcomes are derived from published literature with subsequent review by the UK government for impact pathway approaches (Defra, 2023). If a wide population were being assessed then a baseline incidence rate is calculated for the health outcome for in the absence of an air pollution exposure change.

Exposure to NO₂ at the drive-thru scenario however is relevant to a small number of people so we do not make attempts here to calculate relative risk at the population level. Instead, in this study, we only focus on determining health impacts at the local level by using CRF's to calculate change in relative risk for a specific health group and then create statements describing the impact following NO₂ reduction in an easily understandable way (Williams et al, 2019).

The CRFs used in this analysis may reflect the effects of short-term exposures (effects taking place on the same day or a few days after higher pollutant concentrations), or the effects of long-term exposures (occurring after years or exposure). Relative risks (RR) for a health impact are usually provided in the literature as a percentage change for a defined concentration range, usually over 10 ug/m³ using the following formula:

% change in risk per 10ug/m³ change in NO₂ = $(RR - 1) * 100 \%$

4. Results

4.1. NO₂ dispersion at drive-thru

This section provides outputs from the GRAL dispersion modelling of NO₂ at the drive-thru road system. The results presented firstly show NO₂ pollution maps for each of the road segments modelled for baseline and with a 30m Roadvent system installed at RS1. Annual average, hourly time-series and daily time-series data are also presented at the three key exposure receptor points to show the overall temporal impacts of NO₂ reduction with a Roadvent installed.

4.1.1. NO₂ annual average concentrations

Figure 9 shows the spatially distributed modelled NO₂ annual average concentrations mapped as contours following dispersal from all road segments, RS1 to RS5, for baseline (Figure 10A) and with the 30m Roadvent present (Figure 10B). Figures 11 to 15 further show the modelled NO₂ annual average concentrations mapped following dispersal from each of the road segments RS1 to RS5.

Annual average NO₂ concentrations and reductions at each receptor site at baseline and with a Roadvent system are shown in Table 3. The reduction in NO₂ is greatest at Hatch 1 followed by Hatch 2. NO₂ at the ordering point is reduced only slightly which is likely due to the Roadvent system position not being proximal and generally upwind to this receptor point.

Table 3. Annual average NO₂ concentrations (ug/m³) and reductions at each receptor site at baseline and with a Roadvent system

	Hatch1	Hatch2	Ordering Point
Baseline	20.4	17.2	16.0
Roadvent	13.1	12.7	14.8
Reduction	7.3	4.6	1.2

The modelling suggested that a Roadvent system would help NO₂ annual average concentrations to be reduced to below the WHO interim target of 20 ug/m³ at Hatch 1. Achievement of the revised WHO recommended guideline of 10 ug/m³ would likely require an extension of the Roadvent system along the drive-thru road towards the entrance.

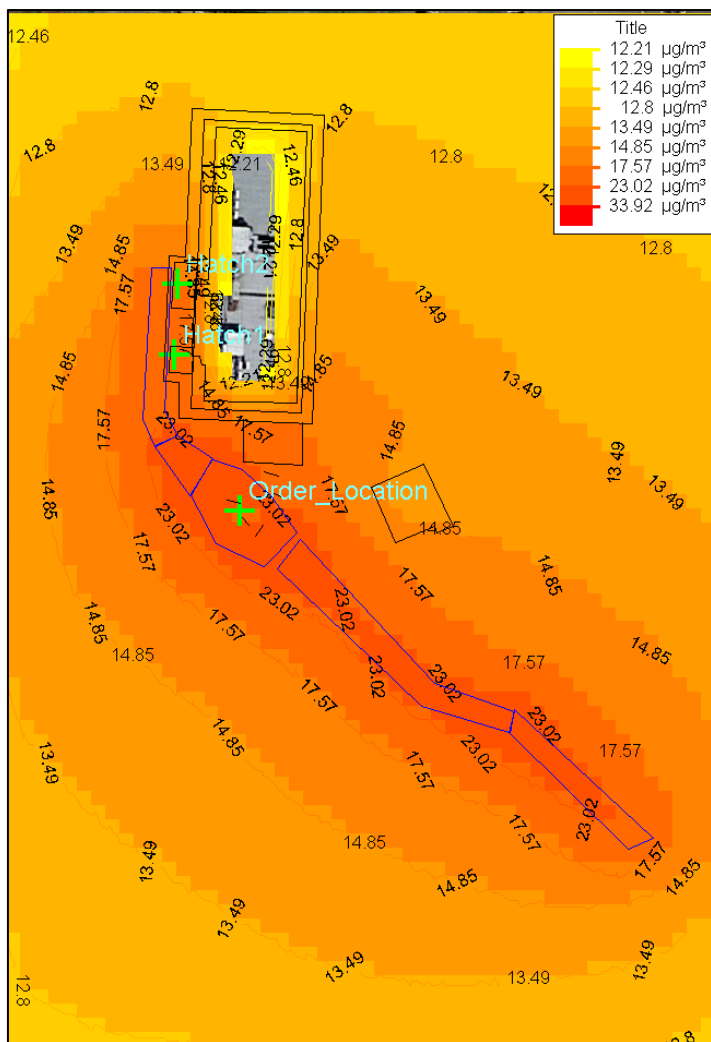


Figure 10A. Modelled NO₂ annual average concentrations mapped following dispersal from all road segments for baseline conditions.

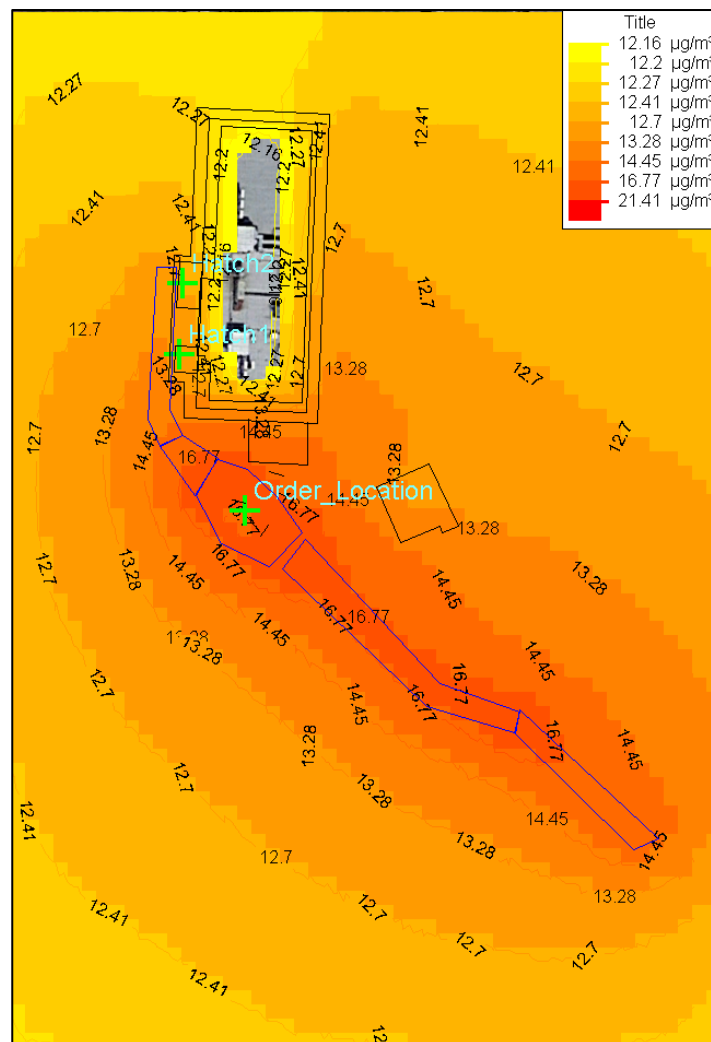


Figure 10B. Modelled NO₂ annual average concentrations mapped following dispersal from all road segments with Roadvent at RS1.

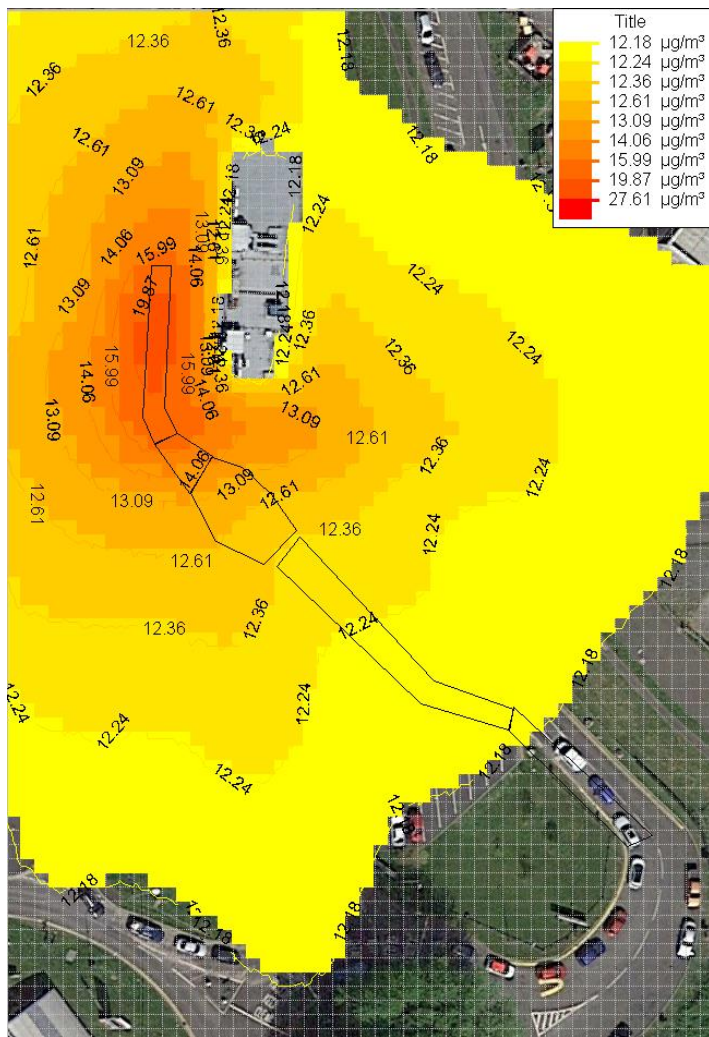


Figure 11A. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS1 for baseline conditions.

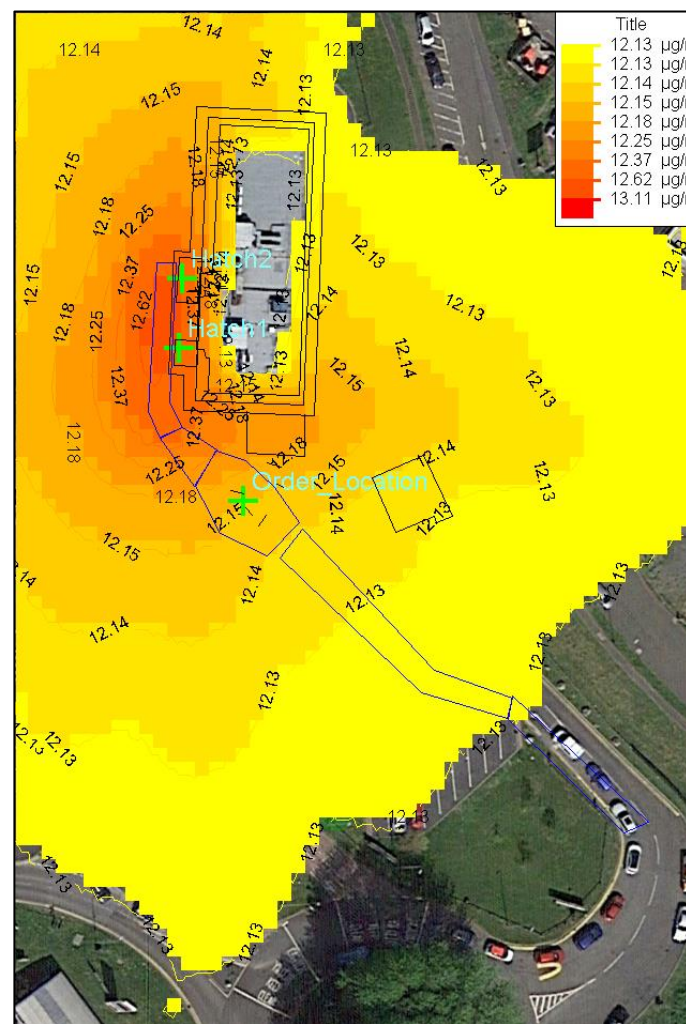


Figure 11B. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS1 with Roadvent at RS1.

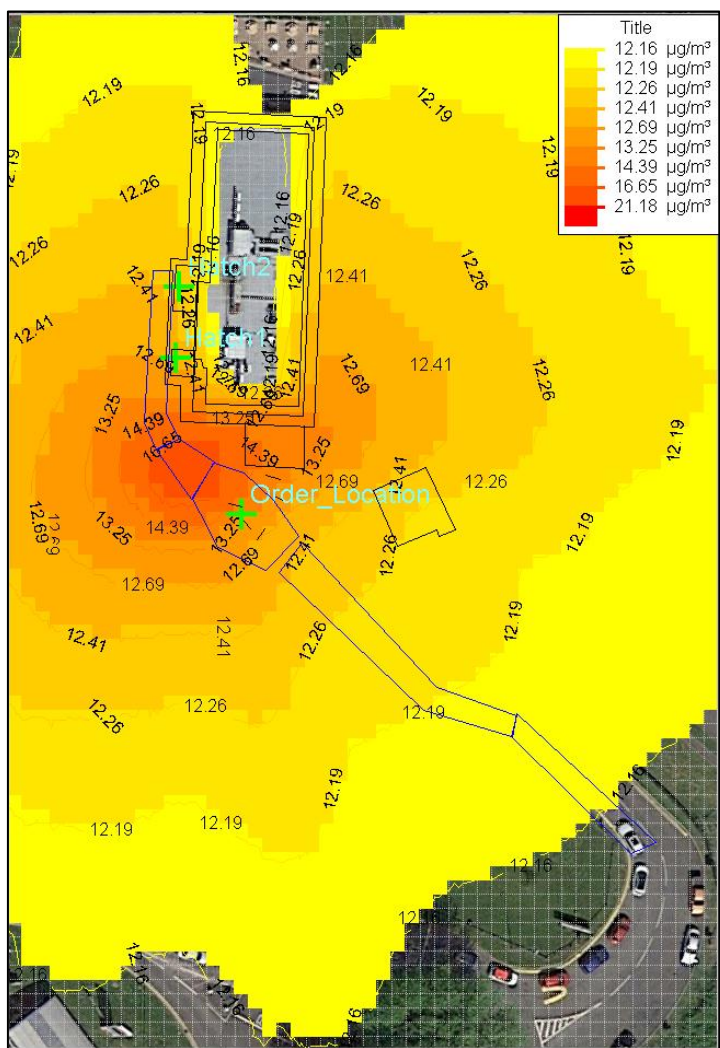


Figure 12A. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS2 for baseline conditions.

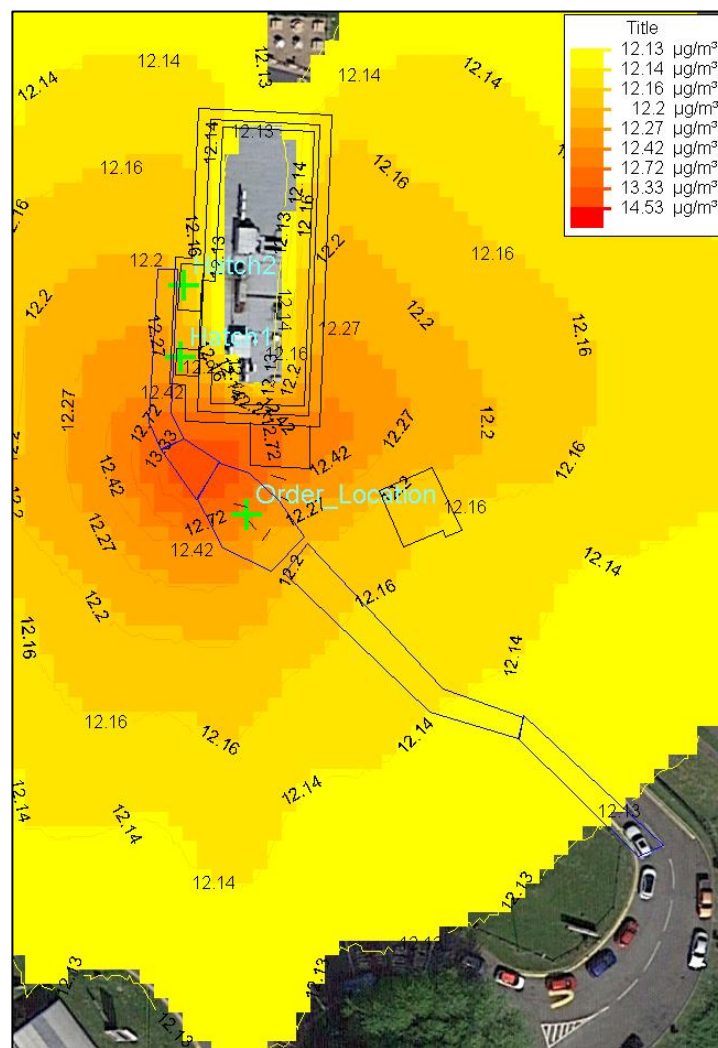


Figure 12B. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS2 with Roadvent at RS1.

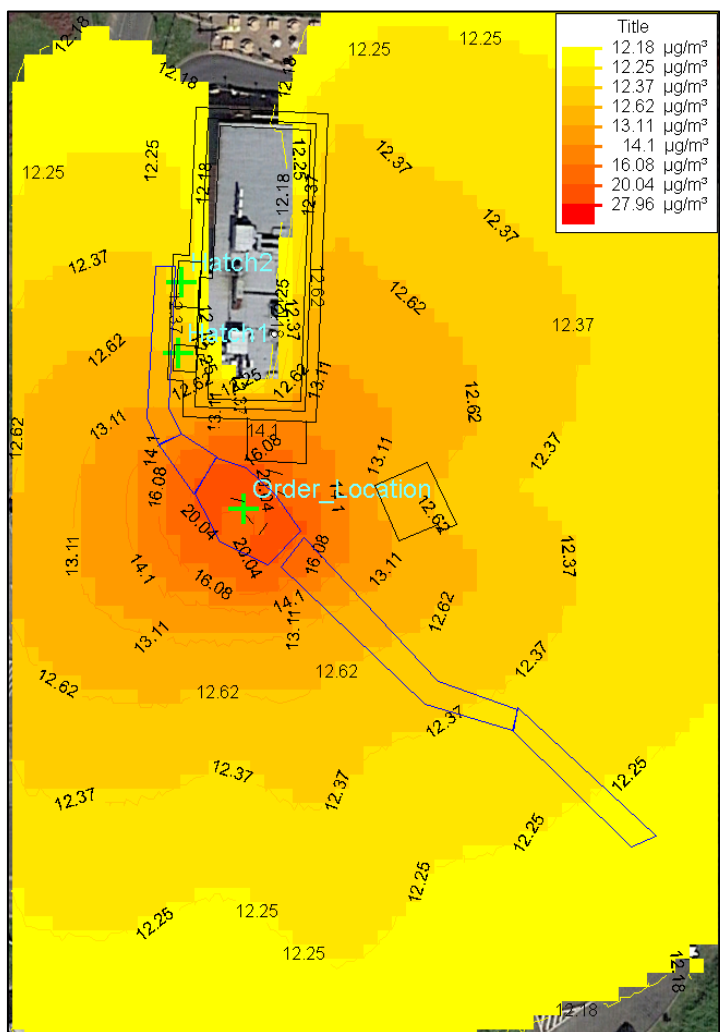


Figure 13A. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS3 for baseline conditions.

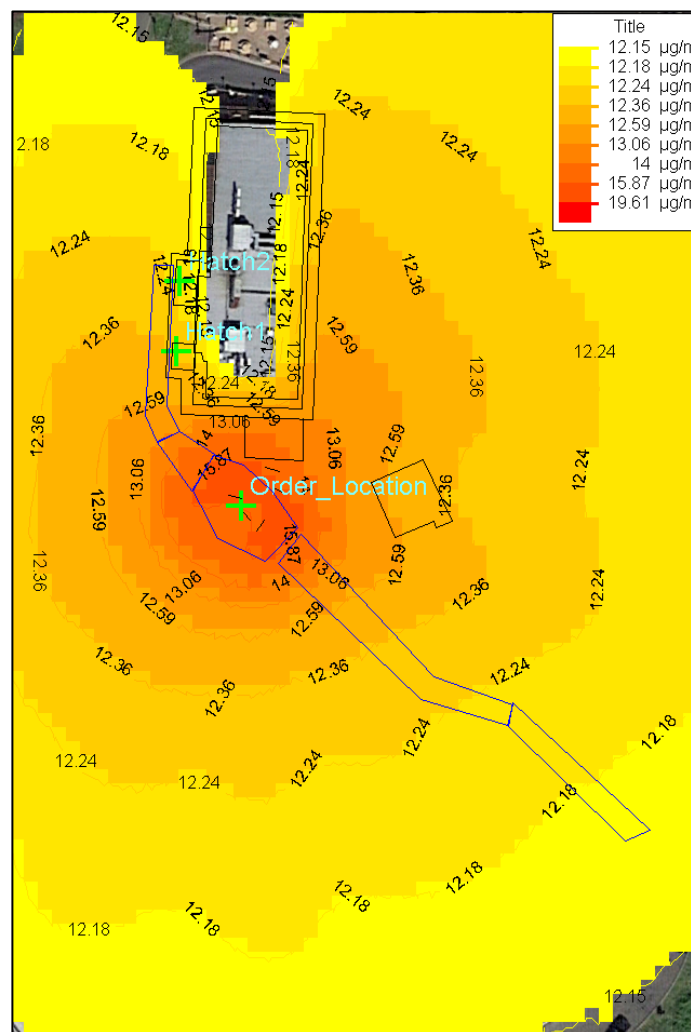


Figure 13B. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS3 with Roadvent at RS1.

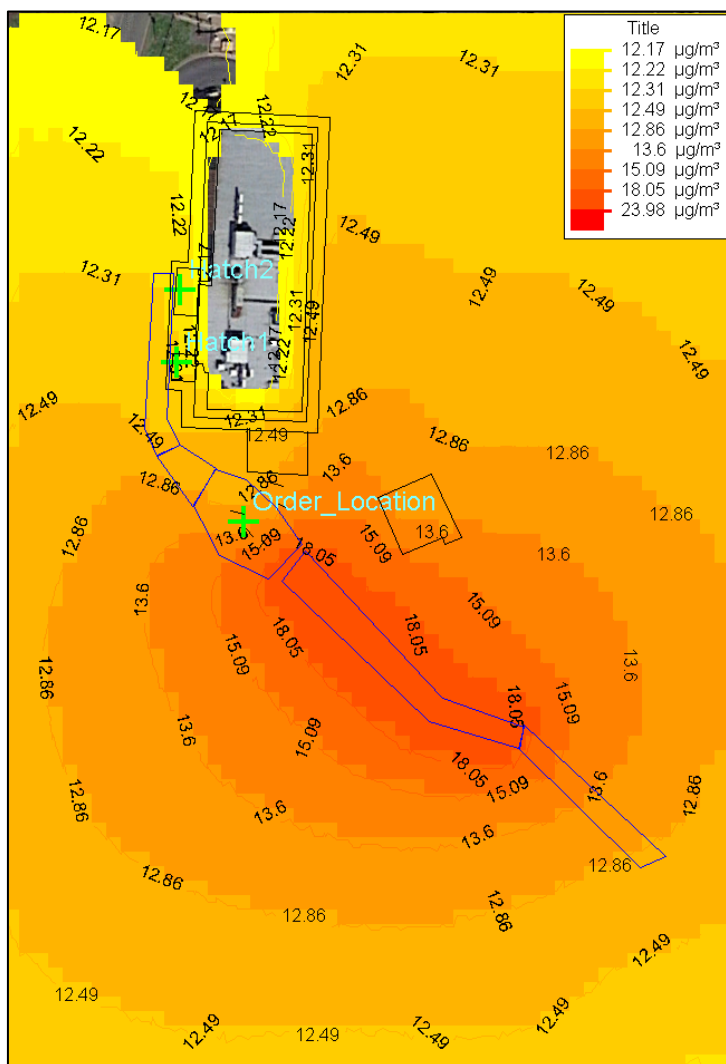


Figure 14A. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS4 for baseline conditions.

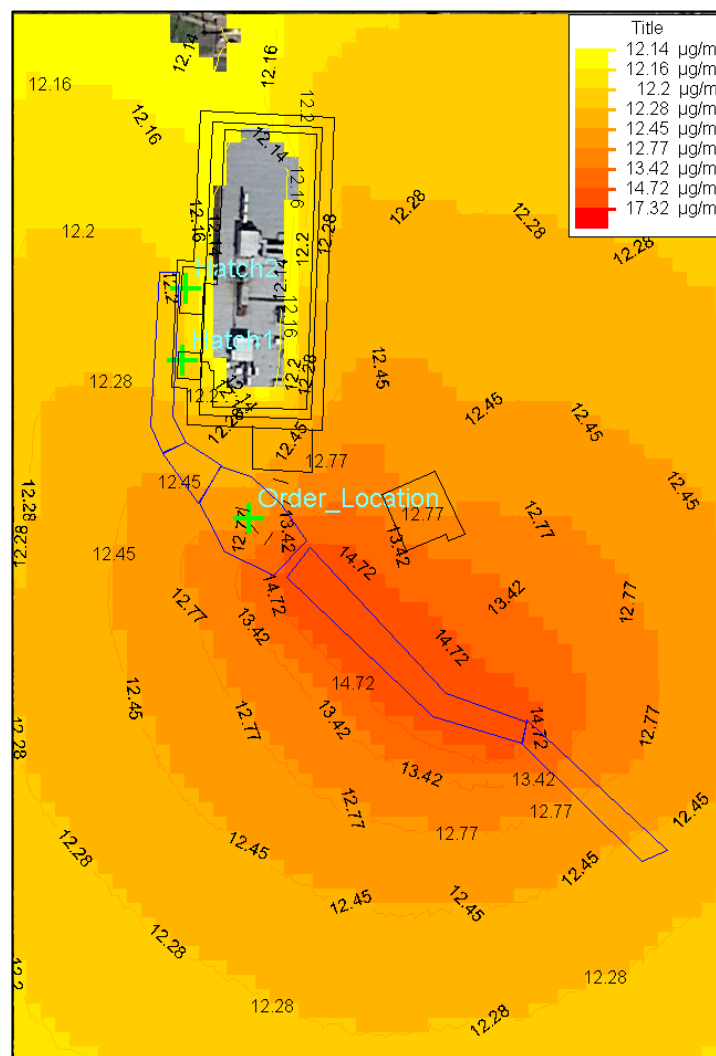


Figure 14B. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS4 with Roadvent at RS1.

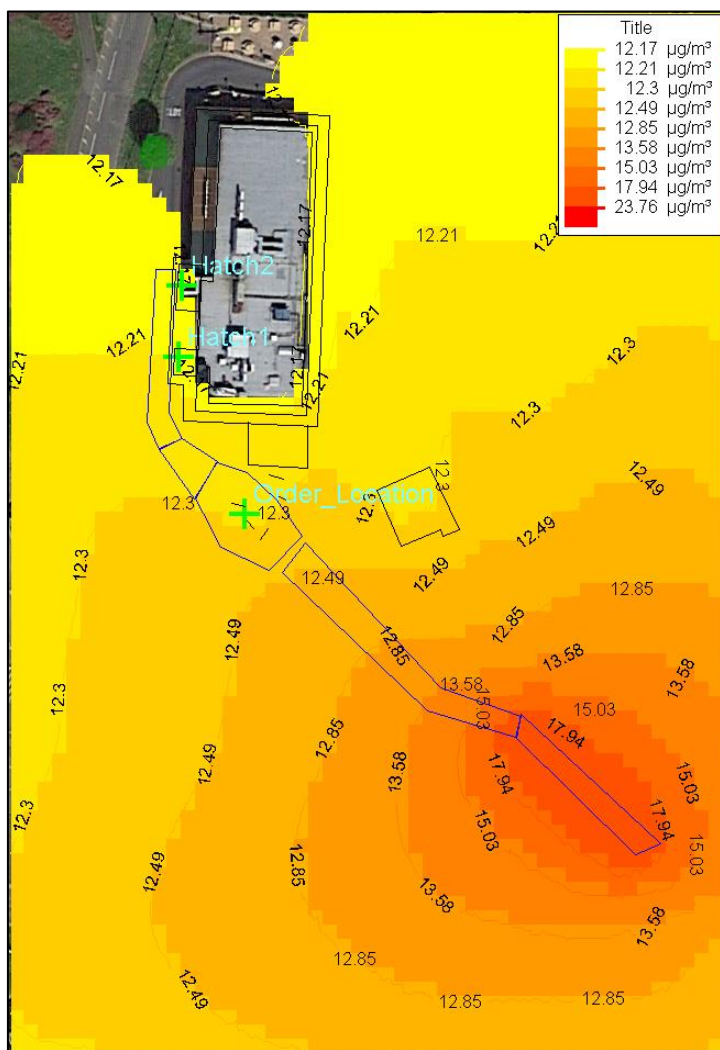


Figure 15A. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS5 for baseline conditions.

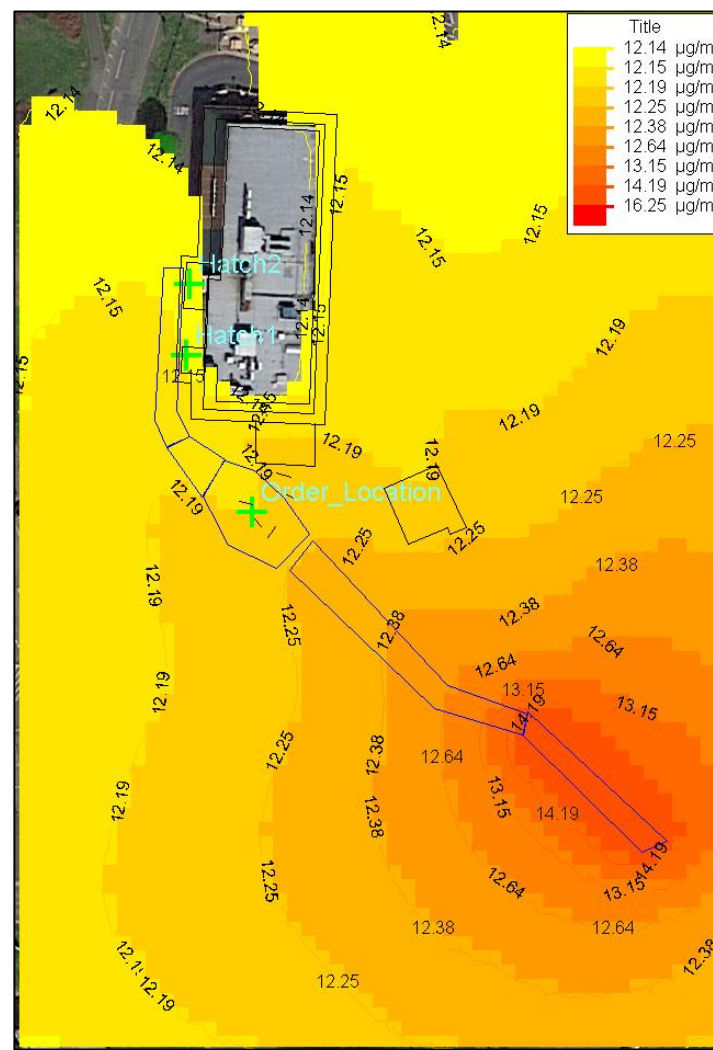


Figure 15B. Modelled NO₂ annual average concentrations mapped following dispersal from road segment RS5 with Roadvent at RS1.

4.1.2. NO₂ hourly time-series

Modelled hourly NO₂ concentrations for the entire year at baseline and with a 30m Roadvent system at RS1 are shown in for hatch 1 (Figure 16), hatch 2 (Figure 17) and the ordering point (Figure 18). The modelled hourly concentration differences that might occur if a Roadvent system were installed in RS1 are also shown for each receptor point.

The number of hours during the year when NO₂ concentrations were above thresholds set at 20 ug/m³ intervals between 20 ug/m³ and 200 ug/m³ were counted for hatch 1, hatch2 and the ordering point for the baseline model (Table 4) and model with Roadvent at RS1 (Table 5). The predicted reduction in hours (and percentage of total hours) above these thresholds due to Roadvent being installed are presented in Table 6 and Figure 19. There were no instances in either model where hourly NO₂ concentrations exceeded the WHO guideline of 200 ug/m³.

Table 4. Number of hours and percentage of total hours during the year when NO₂ concentrations in the baseline model are above certain thresholds at receptor points.

Baseline						
NO ₂ concentration greater than (ug/m ³)	Hatch 1		Hatch 2		Ordering Point	
	Hour Count	%	Hour Count	%	Hour Count	%
20	3321	38.02	1409	16.13	811	9.28
40	340	3.89	221	2.53	145	1.66
60	229	2.62	100	1.14	66	0.76
80	127	1.45	28	0.32	29	0.33
100	59	0.68	13	0.15	12	0.14
120	26	0.30	8	0.09	9	0.10
140	20	0.23	5	0.06	7	0.08
160	13	0.15	3	0.03	5	0.06
180	6	0.07	0	0	5	0.06
200	5	0.06	0	0	5	0.06

Table 5. Number of hours and percentage of total hours during the year when NO₂ concentrations in the Roadvent model are above certain thresholds at receptor points

Roadvent						
NO ₂ concentration greater than (ug/m ³)	Hatch 1		Hatch 2		Order Point	
	Hour Count	%	Hour Count	%	Hour Count	%
20	70	0.80	41	0.47	520	5.95
40	21	0.24	2	0.02	71	0.81
60	6	0.07	0	0	27	0.31
80	0	0	0	0	10	0.11
100	0	0	0	0	8	0.09
120	0	0	0	0	6	0.07
140	0	0	0	0	5	0.06
160	0	0	0	0	3	0.03
180	0	0	0	0	2	0.02
200	0	0	0	0	1	0.01

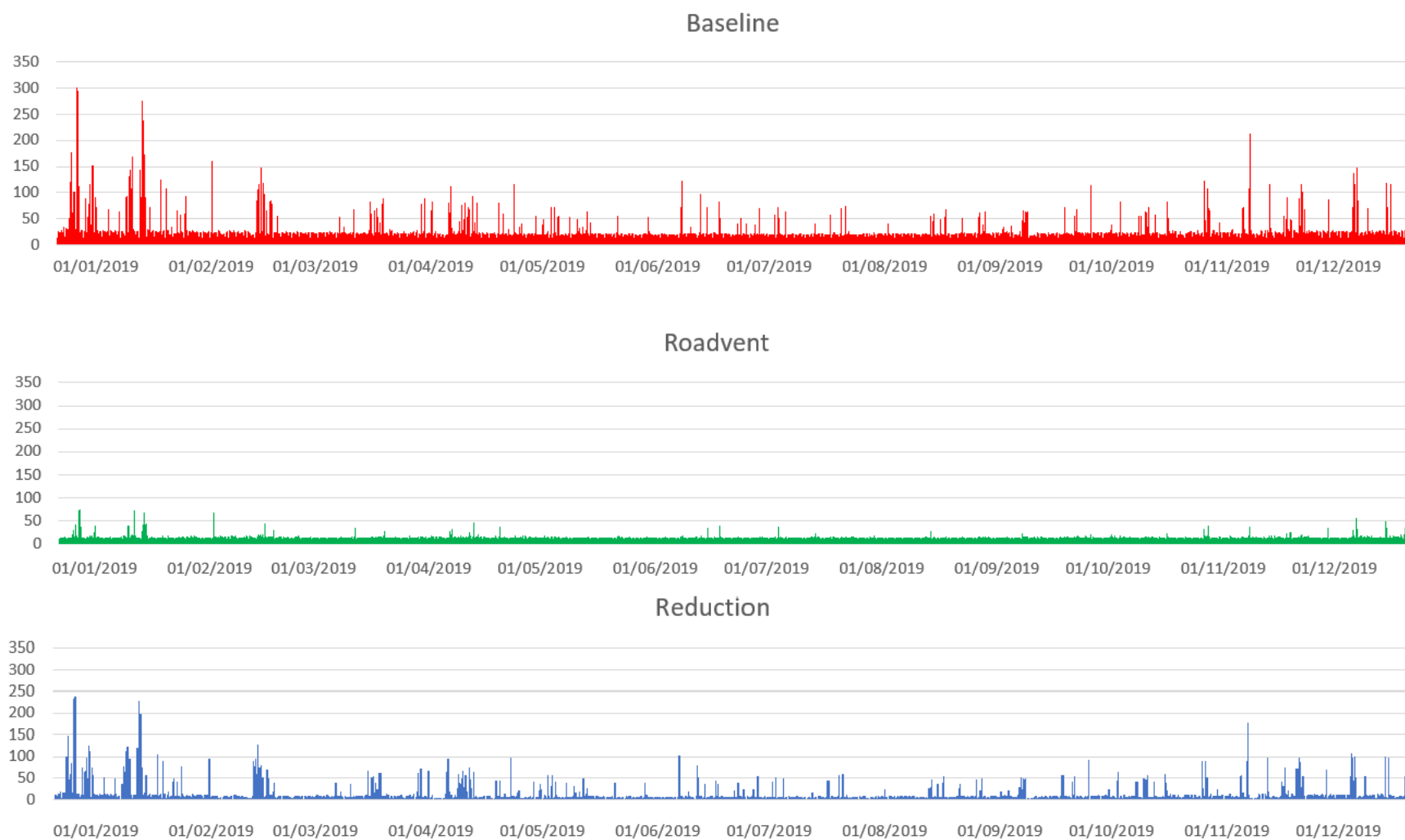


Figure 16. Modelled hourly NO₂ concentrations at baseline, with a 30m Roadvent system in RS1 and the predicted concentration reduction at hatch 1. The y axis shows concentrations in $\mu\text{g}/\text{m}^3$; the x axis shows the start date for each month.

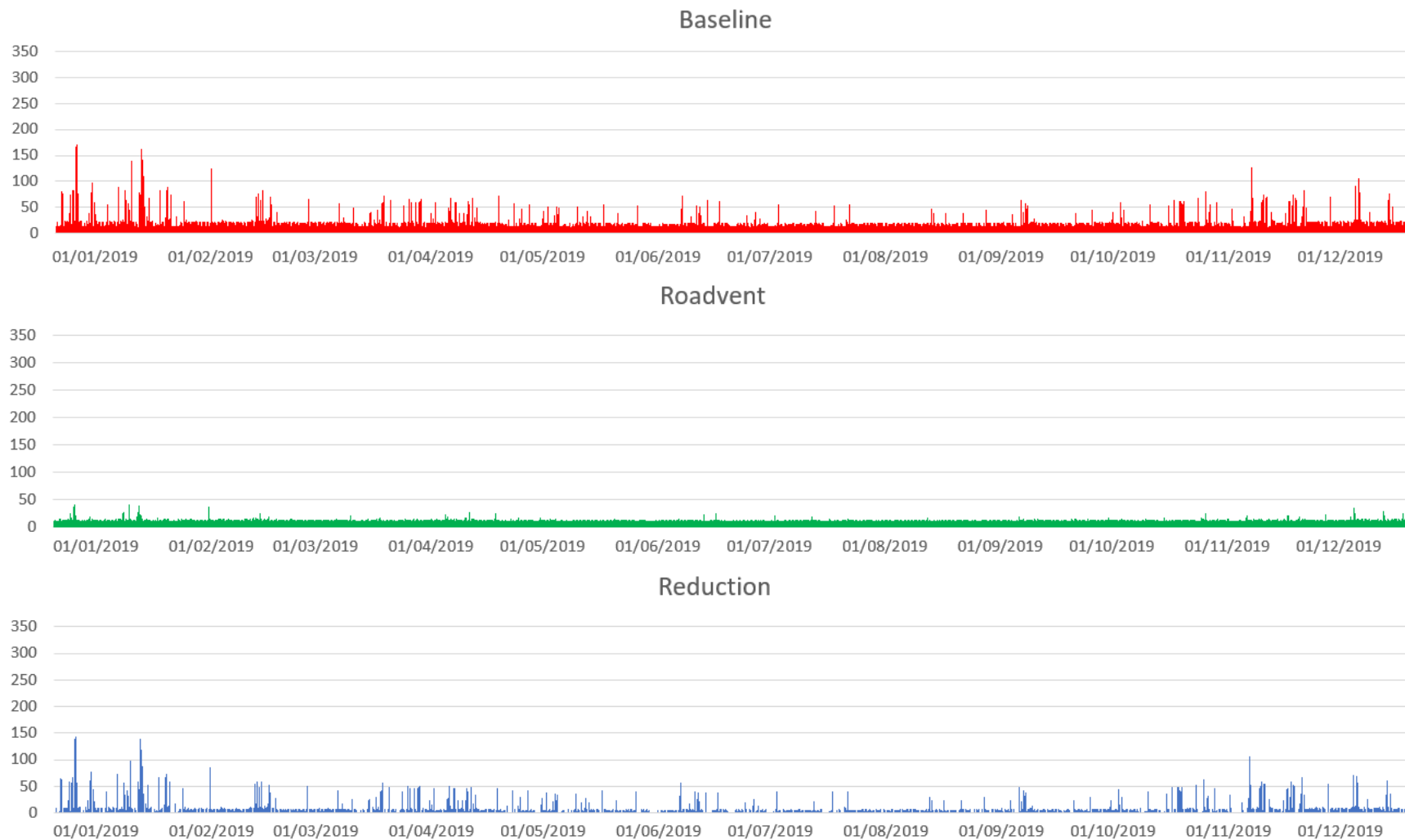


Figure 17. Modelled hourly NO₂ concentrations at baseline, with a 30m Roadvent system in RS1 and the predicted concentration reduction at hatch 2. The y axis shows concentrations in $\mu\text{g}/\text{m}^3$; the x axis shows the start date for each month.



Figure 18. Modelled hourly NO₂ concentrations at baseline, with a 30m Roadvent system in RS1 and the predicted concentration reduction at the ordering point. The y axis shows concentrations in $\mu\text{g}/\text{m}^3$; the x axis shows the start date for each month.

Table 6. Predicted reduction of hours and percentage of total hours during the year when NO₂ concentrations would be above certain thresholds at receptor points if a Roadvent was installed at RS1.

NO ₂ concentration greater than (ug/m ³)	Hatch 1		Hatch 2		Order Point	
	Day Count reduction	%	Day Count reduction	%	Day Count reduction	%
20	3251	37.22	1368	15.66	291	3.33
40	319	3.65	219	2.51	74	0.85
60	223	2.55	100	1.14	39	0.45
80	127	1.45	28	0.32	19	0.22
100	59	0.68	13	0.15	4	0.05
120	26	0.30	8	0.09	3	0.03
140	20	0.23	5	0.06	2	0.02
160	13	0.15	3	0.03	2	0.02
180	6	0.07	0	0	3	0.03
200	5	0.06	0	0	4	0.05

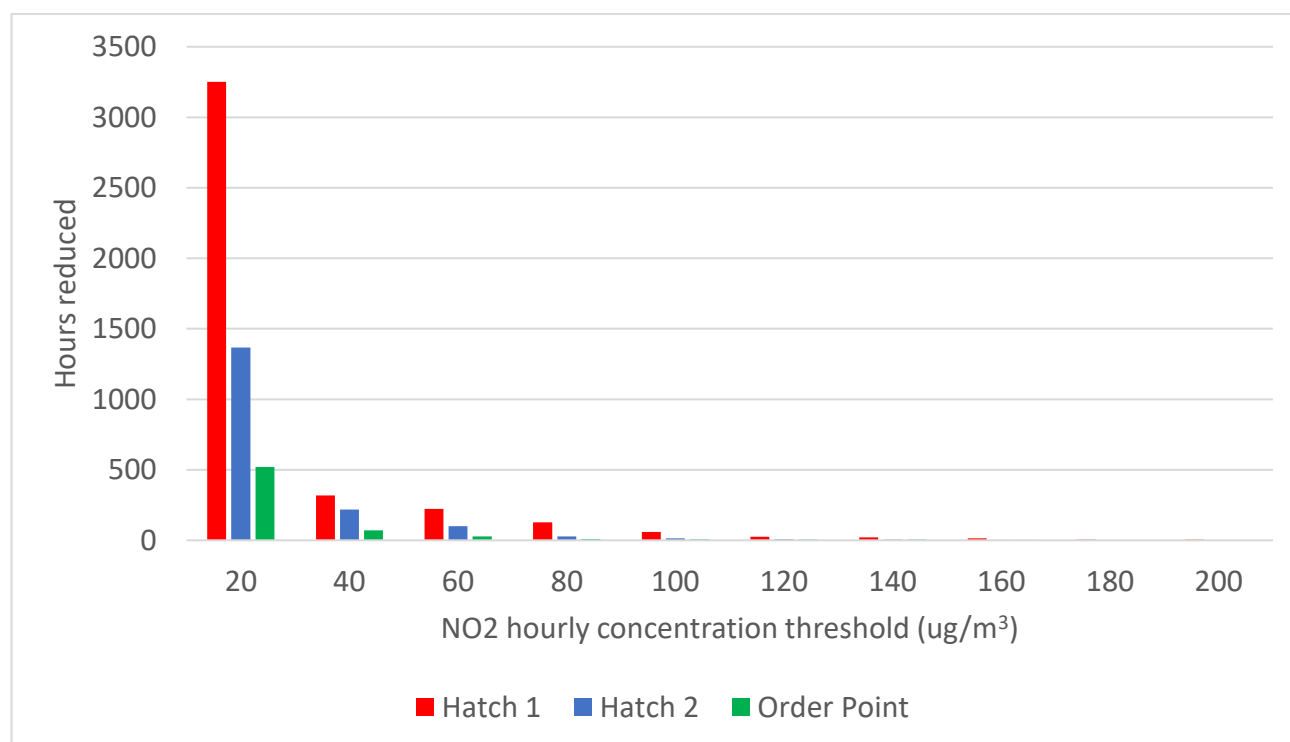


Figure 19. Bar chart showing predicted reduction of hours and percentage of total hours during the year when NO₂ concentrations would be above certain thresholds at hatch , hatch 2 and the ordering point if a Roadvent was installed at RS1.

4.1.3. NO₂ daily time-series

Modelled daily average NO₂ concentrations for the entire year at baseline and with a 30m Roadvent system are shown in for hatch 1 (Figure 20), hatch 2 (Figure 21) and the ordering point (Figure 22). The modelled daily concentration differences that might occur if a Roadvent system were installed in RS1 are also shown for each receptor point.

The number of days during the year when NO₂ concentrations were above thresholds set at 5 ug/m³ intervals between 5 ug/m³ and 50 ug/m³ were counted for hatch 1, hatch2 and the ordering point for the baseline model (Table 7) and model with Roadvent at RS1 (Table 8). The predicted reduction in days (and percentage of total days) above these thresholds due to Roadvent being installed are presented in Table 9 and Figure 23. The modelling suggests that Roadvent could reduce the number of days when NO₂ concentrations are below the WHO interim target of 25 ug/m³ by 38 (10.41% days of the year) i.e. just one day a year.

Table 7. Number of days and percentage of total days during the year when NO₂ concentrations in the baseline model are above certain thresholds at receptor points.

Baseline						
NO ₂ concentration greater than (ug/m ³)	Hatch 1		Hatch 2		Ordering Point	
	Day Count	%	Day Count	%	Day Count	%
5	365	100	365	100	365	100
10	365	100	365	100	365	100
15	365	100	297	81.6	165	45.3
20	100	27.4	44	12.1	24	6.6
25	39	10.7	13	3.6	11	3.0
30	19	5.2	4	1.1	5	1.4
35	12	3.3	3	0.8	3	0.8
40	7	1.9	1	0.3	2	0.5
45	6	1.6	1	0.3	1	0.3
50	6	1.6	1	0.3	1	0.3

Table 8. Number of days and percentage of total days during the year when NO₂ concentrations in the Roadvent model are above certain thresholds at receptor points

Roadvent						
NO ₂ concentration greater than (ug/m ³)	Hatch 1		Hatch 2		Order Point	
	Day Count	%	Day Count	%	Day Count	%
5	365	100	365	100	365	100
10	365	100	365	100	365	100
15	13	3.6	2	0.5	97	26.6
20	2	0.5	0	0	13	3.6
25	1	0.3	0	0	4	1.1
30	0	0	0	0	2	0.5
35	0	0	0	0	1	0.3
40	0	0	0	0	1	0.3
45	0	0	0	0	0	0
50	0	0	0	0	0	0

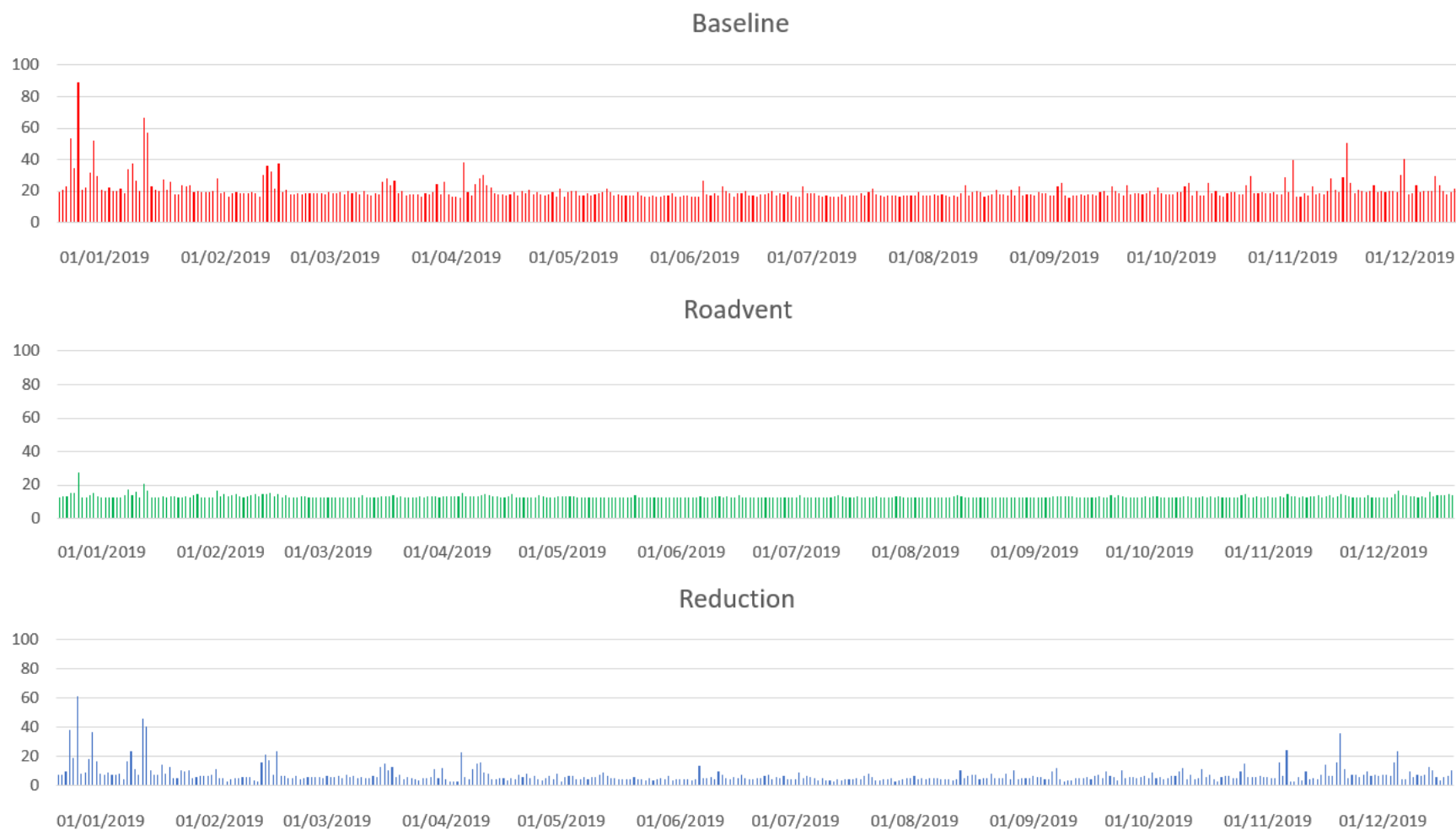


Figure 20. Modelled daily average NO₂ concentrations at baseline, with a 30m Roadvent system in RS1 and the predicted concentration reduction at hatch 1. The y axis shows concentrations in ug/m³; the x axis shows the start date for each month.

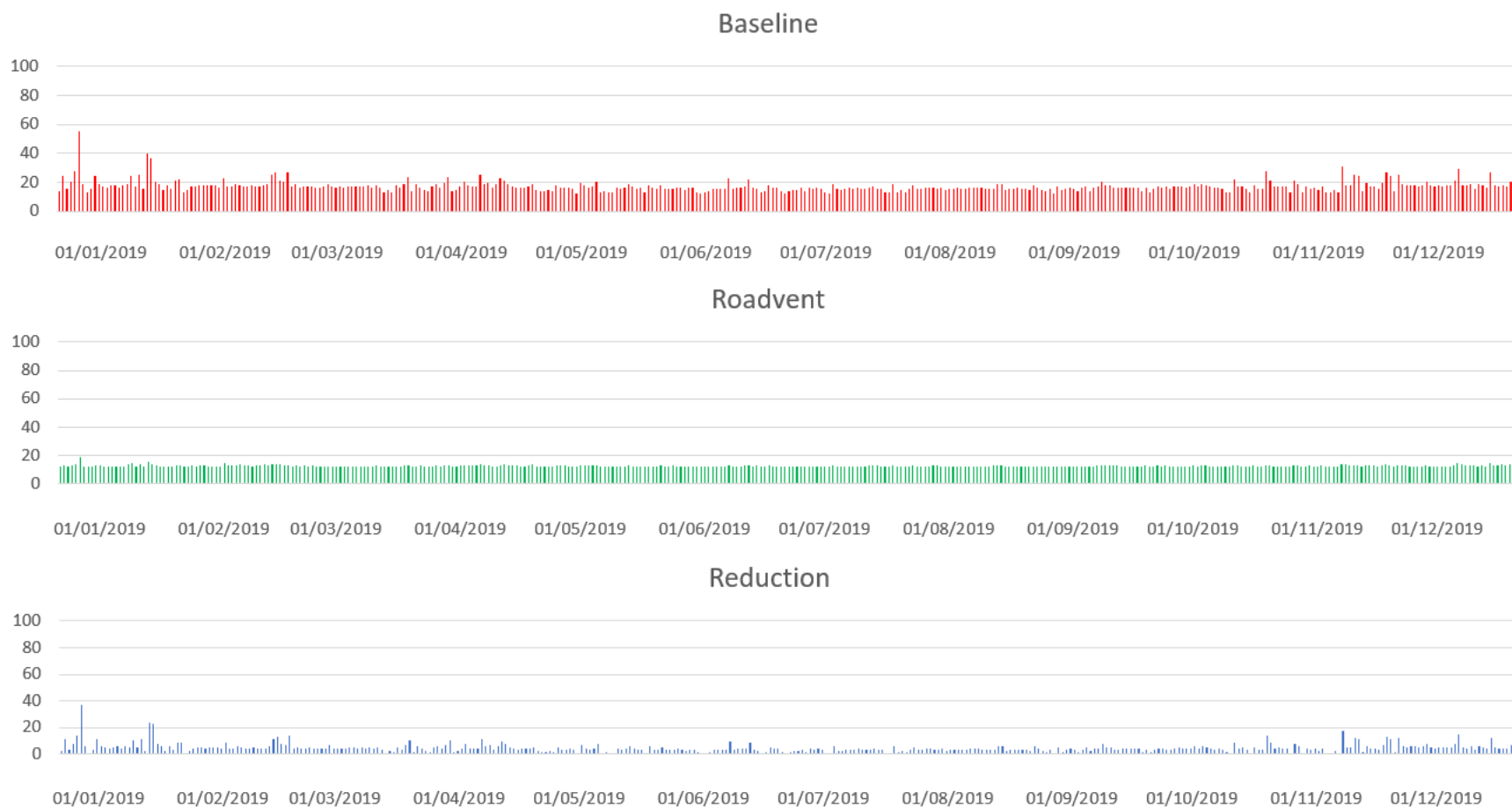


Figure 21. Modelled daily average NO₂ concentrations at baseline, with a 30m Roadvent system in RS1 and the predicted concentration reduction at hatch 2. The y axis shows concentrations in $\mu\text{g}/\text{m}^3$; the x axis shows the start date for each month.



Figure 22. Modelled daily average NO₂ concentrations at baseline, with a 30m Roadvent system in RS1 and the predicted concentration reduction at the ordering. The y axis shows concentrations in $\mu\text{g}/\text{m}^3$; the x axis shows the start date for each month.

Table 9. Predicted reduction of days and percentage of total hours during the year when NO₂ concentrations would be above certain thresholds at receptor points if a Roadvent was installed at RS1.

NO ₂ concentration greater than (ug/m ³)	Hatch 1		Hatch 2		Order Point	
	Day Count reduction	%	Day Count reduction	%	Day Count reduction	%
5	0	0	0	0	0	0
10	0	0	0	0	0	0
15	352	96.44	295	80.82	68	18.63
20	98	26.85	44	12.05	11	3.01
25	38	10.41	13	3.56	7	1.92
30	19	5.21	4	1.10	3	0.82
35	12	3.29	3	0.82	2	0.55
40	7	1.92	1	0.27	1	0.27
45	6	1.64	1	0.27	1	0.27
50	6	1.64	1	0.27	1	0.27

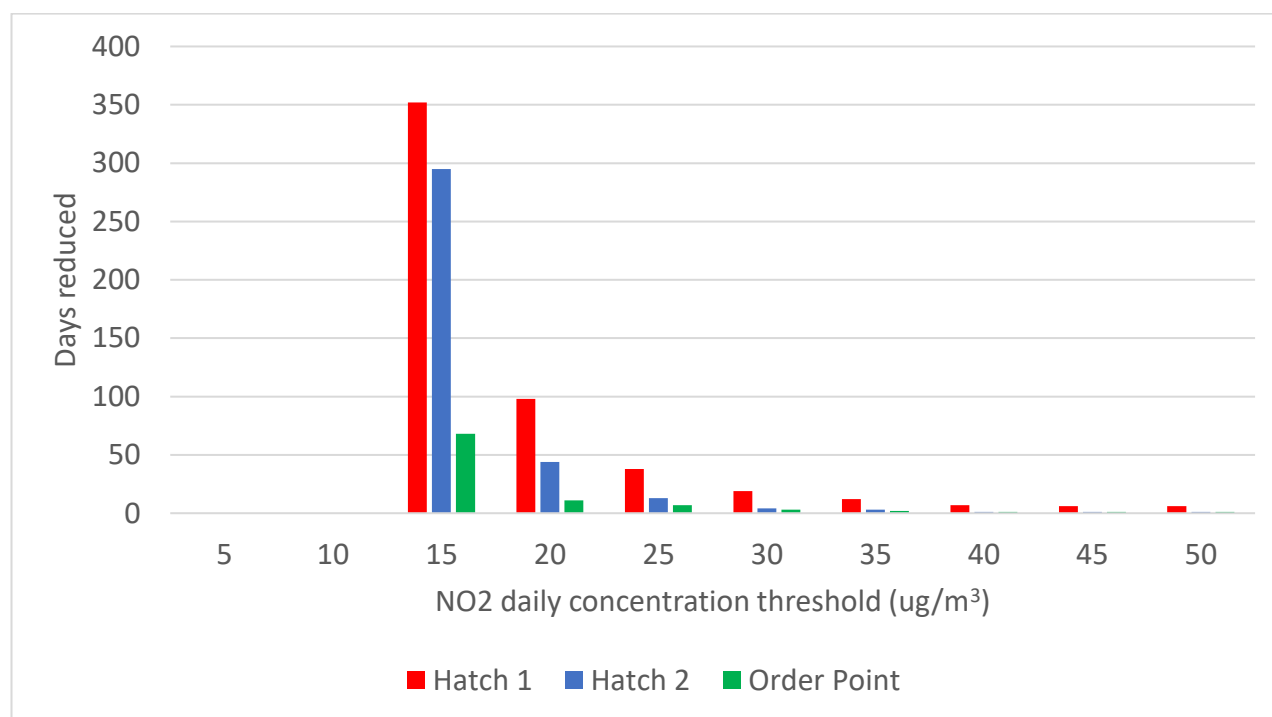


Figure 23. Bar chart showing predicted reduction of days and percentage of total hours during the year when NO₂ concentrations would be above certain thresholds at hatch, hatch 2 and the ordering point if a Roadvent was installed at RS1.

4.2. Health impact analysis

This section provides an assessment of potential reduction in risk of adverse health events to people exposed at the drive-thru following NO₂ concentration reduction caused by the presence of a Roadvent system. (Williams et al, 2019).

4.2.1. Adult asthma hospital admissions

The risk of adults being admitted to hospital for asthma would be reduced by approximately 1.2%, if NO₂ was reduced by 42% on half the days of the year. This air pollution reduction is the difference between a typical higher air pollution day at the drive-thru and a typical lower pollution day.

Days with higher pollution have larger numbers of admissions to hospital for asthma than days with lower pollution. The CRF used is based on a relative risk of 1.012 per 10 µg/m³ increase in NO₂ which equates to 1.2% change in asthma admissions in adults per 10 µg/m³ increase in NO₂ (Walton et al, 2019). The upper 95% confidence intervals of the percentage change reported in that study was 2.3%.

The percentage increase per 10 µg/m³ was then adjusted to account for an observed change in daily average higher and lower NO₂ concentrations during the year modelled for the drive-thru, with and without a Roadvent system.

Following previous guidance (Williams et al, 2019), we calculated the figure that is the difference between the average concentration in the top 50% of daily average for baseline data and the equivalent figure if Roadvent were installed (Table 6). We assumed half the days of the year were at the 75th percentile (roughly equivalent to the average of the top half of the range of concentrations) to start with and were all reduced to the 25th percentile (roughly the average of the lower half of the range of concentrations). The resulting typical higher concentration reduction due to Roadvent being installed was calculated as 9.8 µg/m³ which was roughly a 42% change (Table 10).

Table 10.

	Baseline	Roadvent	Difference	% Reduction
Average NO ₂ concentration within top 50% daily values	23.5	13.7	9.8	41.8

The concentration reduction of 9.8 µg/m³ is approximately equivalent to 10 µg/m³ thus the change in risk for adult asthma hospital admissions was calculated as 1.2% if a Roadvent system was installed.

4.2.2. Out-of-hospital cardiac arrests

The risk of out-of-hospital cardiac arrest would be reduced by 1.46%, if NO₂ was reduced by 35.8%.

Higher NO₂ concentrations can result in larger numbers of out-of-hospital cardiac arrests. The CRF used is based on a relative risk of 1.02 per 10 µg/m³ increase in NO₂ which equates to 2% increase in the risk of out-of-hospital cardiac arrest per 10 µg/m³ increase in NO₂ (Zhao et al, 2017). The upper 95% confidence intervals for the relative risk was 1.03%.

The percentage increase per 10 µg/m³ was then adjusted to account for an observed change in annual average NO₂ concentrations modelled for the drive-thru, with and without a Roadvent system (Table 11). The resulting reduction due to Roadvent being installed was calculated as 7.3 µg/m³ which was roughly a 3.8% change.

Table 11. Percent reduction in annual average NO₂ concentration at hatch 1.

	Baseline	Roadvent	Difference	% Reduction
Annual average NO ₂ concentration	20.4	13.1	7.3	35.8

The relative risk for out-of-hospital cardiac arrest was then adjusted to 1.46 to account for the reduction of 7.3 µg/m³ rather than 10 µg/m³. If a Roadvent system was installed, the risk of out-of-hospital cardiac arrest would be reduced by 1.46%.

4.2.3. Stroke

The risk of emergency hospitalisation for stroke would be reduced by approximately 2.3%, if NO₂ was reduced by 42% on half the days of the year. This air pollution reduction is the difference between a typical higher air pollution day at the drive-thru and a typical lower pollution day.

Like asthma, days with higher pollution have larger numbers of emergency hospitalisation for stroke than days with lower pollution. The CRF used is based on a relative risk of 1.023 per 10 µg/m³ increase in NO₂ which equates to 2.3% change in out-of-hospital cardiac arrest per 10 µg/m³ increase in NO₂ (Shah et al, 2015). The upper 95% confidence intervals of the percentage change reported in that study was 3.5%.

The percentage increase per 10 µg/m³ was then adjusted to account for an observed change in daily average higher and lower NO₂ concentrations during the year modelled for the drive-thru, with and without a Roadvent system. We calculated the figure that is the difference between the average concentration in the top 50% of daily average for baseline data and the equivalent figure if Roadvent were installed (Table 10 for the same calculation). We assumed half the days of the year were at the 75th percentile to start with and were all reduced to the 25th percentile. The resulting typical higher concentration reduction due to Roadvent being installed was calculated as 9.8 µg/m³ which was roughly a 42% change.

The concentration reduction of 9.8 µg/m³ is approximately equivalent to 10 µg/m³ thus the change in risk for emergency hospitalisation for stroke was calculated as 2.3% if a Roadvent system was installed.

5. Conclusions

- A combination of traffic emissions modelling suitable for drive-thru scenarios and mesoscale dispersion modelling permitted estimations of NO₂ concentration reductions at key points on the roadway system if a 30m Roadvent was installed.
- The predicted reductions in NO₂ annual average concentrations at the two drive-thru serving hatches were 7.3 ug/m³ and 4.6 ug/m³ if a Roadvent system were installed at this point.
- The predicted reduction by Roadvent for daily average NO₂ concentrations to below the WHO recommended 24-hour exposure guideline of 25 ug/m³ was 38 days throughout the year.
- This meant that just 1 day throughout the year was predicted to be above the 25 ug/m³ guideline in one serving hatch and no days above in the other serving hatch.
- The Roadvent model also suggested that the number of hours during the year when NO₂ concentrations were above 20 ug/m³ could be reduced by as much as 37% at one of the serving hatches.
- Modelled Roadvent induced reductions in NO₂ concentrations were used to predict reductions in relative risk for key health outcomes including adult asthma hospital admissions, out-of-hospital cardiac arrests and stroke instances.
- The risk of adults being admitted to hospital for asthma would be reduced by approximately 1.2%, if NO₂ was reduced by 42% on half the days of the year.
- The risk of out-of-hospital cardiac arrest would be reduced by 1.46%, if NO₂ was reduced by 35.8%.
- The risk of emergency hospitalisation for stroke would be reduced by approximately 2.3%, if NO₂ was reduced by 42% on half the days of the year.
- Given the assumed average working days lost due to sickness absences of 4.4 days per employee, it is possible that this average could be reduced for employees at drive-thru serving hatches as modelled in this study.
- Although not modelled due to the uncertainty of confounding impacts of PM_{2.5} or robustness of evidence, it is possible for the relative risk of employee absenteeism due to key health impacts such as hospital admissions following NO₂ exposure to be calculated in the future pending sufficient data (CBI, 2019).

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