Project 971706 :

Tool to assess air quality impacts of elevated roads within the Strategic Road Network

Phase 2 report

Prepared for
Highways England

14th August 2020

CERC

Report Information

CERC Job Number:	FM1272
Innovate UK Project:	971706
Job Title:	Tool to assess air quality impacts of elevated roads within the Strategic Road Network
Prepared for:	Highways England
Report Status:	Final
Report Reference:	FM1272/R1/20
Issue Date:	14 August 2020

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Issue	Date	Comments
1	22/06/2020	Draft
2	15/07/2020	Draft
3	14/08/2020	Final

Contents

1. Executive Summary

Overview

a) This Phase 2 project 'Tool to assess air quality impacts of elevated roads within the Strategic Road Network' follows on from the successful completion of the Phase 1 feasibility project 'Feasibility of tool to assess air quality impacts of elevated roads within the Strategic Road Network'.

b) An 'elevated road' in this context is defined to be a road that is: elevated relative to ground level; and open underneath the road, allowing wind flow both above and below the road structure. A typical example is a 'flyover'.

c) The project has been completed on time and to budget.

d) CERC worked closely with Highways England (HE) during the project, in particular when deciding which sites to use for the model evaluation study. The project team has provided HE with updates regarding project progress.

e) A release version of ADMS-Roads including the elevated roads module is now available for use by Highways England. This version of the model will be made available to all current ADMS-Roads, ADMS-Urban and ADMS-Airport users in July 2020 (approximately 200 organisations).

f) Following the Phase 1 feasibility project, the elevated roads sub-model was at Technology Readiness Level (TRL) 5 ('technology validated in relevant environment') and is now at TRL 8 ('System complete and qualified'). Following the general release of the model, the system will move to TRL 9 ('Actual system proven in operational environment').

COVID-19 impact

g) The impact of COVID-19 on the technical aspects of this project has been minimal, as CERC successfully transitioned to 100% of staff working from home in mid-March 2020, in line with government guidance.

h) COVID-19 has impacted on the publicity aspects of the project, as conferences where results were due to be presented have been postponed. CERC commit to presenting at these events after project completion.

i) COVID-19 has impacted on the training aspect of the project, with the Highways England training course being delayed until after project completion; it is possible that this training course will be delivered online rather than face-to-face.

Integration of the elevated roads sub-model into ADMS-Roads

j) The Phase 1 feasibility project tested four approaches to modelling 'flyover-type' elevated sections of roads; 'Approach 3' was found to be most representative of the physical processes involved and consequently this approach has been integrated into ADMS-Roads during this Phase 2 project.

k) The integration process involved ensuring compatibility with other model options including terrain and deposition.

l) The model development work was undertaken according to CERC's Quality Management System for software development, which includes: 'Subversion' source management software; a comprehensive change control system; peer review of software changes, scientific work products, data analysis and test cases; centralised issue-tracking; and standardised software acceptance testing.

m) A release version of ADMS-Roads (version 5.0.1.1) is now available.

Evaluation approach

n) The new version of ADMS-Roads has been evaluated using three datasets, two from the UK (Birmingham and London) and one from Antwerp in Belgium.

o) The Birmingham site is in Oldbury, where Birmingham Road passes beneath an elevated section of the M5. Measured pollutant concentration data collated for this site includes monthly diffusion tube data and hourly measurements from a reference monitor 150 m from the motorway.

p) The London site is in Hounslow, Brentford, and incorporates two reference monitors located in close proximity (less than 10 m) to elevated sections of the M4. Concentrations recorded at one of these monitors are also strongly influenced by emissions from a ground-based road (A4) in addition to a row of adjacent houses, which form an asymmetric street canyon; the other monitor does not have any complicating factors in the vicinity.

q) The Antwerp site datasets are from a field campaign where pollutant concentration measurements were recorded either side of two sections of a highway: one elevated, one at ground level. The elevated and ground-based measurements were recorded during different time periods, and the monitors were placed at a range of distances from the highway.

r) The UK sites have been used for model evaluation. Measurement data from the Antwerp study has been analysed in an attempt to quantify the impact of elevation on ground level concentrations; the data has then been used for model evaluation.

s) Source apportionment calculations have been undertaken for the UK studies, including analyses by wind direction.

t) Contour plots showing the relative impact of elevated sections of road compared to ground-based roads have been generated.

u) Some sensitivity testing has been undertaken in order to assess how model concentrations vary with increasing height of the elevated road.

Evaluation results

v) The model demonstrates good performance when predicting pollutant concentrations in the vicinity of elevated sections of road.

w) The Birmingham study allowed a detailed evaluation of the variation of NO2 pollutant concentrations with increasing distance from the elevated road; model performance was good with over 82% of modelled values within 25% of monthly diffusion tube measurements. Using the model to calculate ‘indicative’ source apportionment for this pollutant shows that the impact of the motorway on ground level concentrations is smaller than that from the local road at all measurement locations, including less than 50 m from the motorway. The influence of the road elevation is virtually undetectable at the reference monitor located 150 m from the elevated road.

x) Despite concentrations at one of the London site monitors being strongly influenced by an adjacent ground-based road and being located within an asymmetric street canyon, model performance at this site was very good; the model also demonstrated good performance at the 'simpler' site located in a parkland area away from any other major road sources. The model is able to predict NO2 annual averages very close to the measured values, with fractional bias values less than 0.03, while analyses of hourly values give correlations over 0.65 and number of points within a factor of two of the observed over 0.80.

y) The Antwerp measurement analysis was complicated by a number of confounding factors including: the measurements were recorded in the vicinity of the elevated section and the ground section at different times; the receptors were placed at differing distances from the road for each campaign; and the traffic flow differed on each section of the road. Accounting for these and other complications allowed an intercomparison of measurements recorded in the vicinity of the elevated and ground-based highway. The elevated road increment is as low as 50% of ground-based increment, for certain meteorological conditions.

z) The results from model sensitivity testing agree well with the Antwerp dataset measurements in terms of the magnitude of the reduction of near-ground concentrations resulting from road elevation.

aa) The extensive evaluation exercise demonstrates that ADMS-Roads performs well when configured to represent elevated sections of road.

bb) The evaluation exercise highlighted the model's ability to assess the variation in pollutant concentrations associated with different road elevations, allowing an assessment of different pollutant mitigation options.

Guidance

cc) The new elevated roads module can assist with the modelling of a number of road layouts that include elevated road sections, specifically: flyovers; bridges over cuttings; bridges over valleys; and road bridges formed by embankments.

dd) Practical guidance on how to represent these different road layouts has been provided.

Discussion

ee) The evaluation exercise demonstrated that ADMS-Roads can be used to quantify the significant influence that road elevation has on the pollutant concentrations of near-ground receptors.

ff) Releasing this new model to ADMS-Roads /ADMS-Urban /ADMS-Airport users with valid licences (over 200 organisations) will allow more accurate air quality assessments of road schemes involving elevated road sections.

2. Introduction

This project has successfully implemented a new method for quantifying the impact of the dispersion of emissions from elevated sections of roads within the widely-used ADMS-Roads software tool. Improved modelling methods enable more accurate assessment of air quality impacts when elevated roads are to be modified or added to the SRN. The model has been specifically designed to calculate pollutant impacts in the vicinity of flyover-type elevated roads, but it is also useful for other complex road layouts involving elevated sections; guidance on best practice has been provided. Adding this method to the Highway England "toolbox" of assessment methods should assist in making informed decisions regarding road layout and design.

The project has involved model development work undertaken in line with CERC's Quality Management System. Following initial integration of the elevated road module in ADMS-Roads, a beta version of the model was created, suitable for use in the evaluation part of the project. A comprehensive evaluation exercise was undertaken including evaluation of model results against diffusion tube and reference measurements from the UK, and additionally standalone analyses of a suitable non-UK field campaign measurement dataset. The model evaluation exercise was successful, and demonstrated that the new model is suitable for use in assessing the impact of pollutant dispersion from elevated roads.

This project has been undertaken on time and within budget. The project consisted of five work packages. A brief overview of the activities within each of the work packages is given below, with reference to the tasks defined in the Gantt chart (Appendix A) and the sections of this report where more detail is provided (shown in bold red text):

- **Project management and meetings (WP1)**
  An official inception meeting (T1.1) did not take place as planned due to HE being busy with other project commitments. However, CERC had a number of telephone calls with HE at the beginning of the project to discuss the evaluation methodology approach, and then subsequently to discuss evaluation site options, and associated datasets (T1.2). Quarterly meetings with the Innovate UK Monitoring Officer Mike Catania were held via teleconferencing software. The Gateway Meeting (M1.1) took place on 31st March, which allowed CERC to demonstrate that the Gateway Acceptance Criteria had been achieved:
    - Beta version of ADMS-Roads including elevated roads (M2.1)
    - Evaluation database collated (T3.2)

  The planned ADMS-Roads training course to be held at the Highways England offices (M1.2) has been postponed due to COVID-19 restrictions. This course will take place after project completion, possibly online. The Final Meeting will take place on 15th July, again online.
- **Integration of sub-model into ADMS-Roads (WP2)**
  The best method for modelling elevated roads identified during the feasibility study ('Approach 3') was integrated in ADMS-Roads (T2.1). This integration involved allowing compatibility between the elevated roads sub-model and other model options including complex terrain and deposition. A beta version of ADMS-Roads including the new elevated roads option was made available for evaluation (M2.1). No further

code modifications were required following the evaluation exercise (T2.2). The release version of the model is now available for use by Highways England (version 5.0.1.1). This version of the model will be made available to all model users with valid licences in July 2020 (D2.1). **The model formulation, user instructions and example output is presented in Section 3.**

- **Testing and evaluation (WP3)**
  The evaluation database requirements were specified (T3.1) and documented (M3.1). This resulted in three types of sites being considered for evaluation, with two or three options within each site type. The datasets associated with seven sites were collated (T3.2) and documented (M3.2). Following discussion with HE, one site from each site type was selected, with other sites being kept in reserve. The beta version of ADMS-Roads was used in the scientific evaluation study (T3.3); this was completed on time (M3.3). The results of the model evaluation study have been documented in the final report (D3.1). **The model evaluation approach is described in Section 4 and the model evaluation results are presented in Section 5.**
- **Documentation and reporting (WP4)**
  Quarterly reports have been submitted on time (T4.1). User documentation[1] describing the technical details of the elevated roads module has been written (T4.2, D4.1). User documentation[1] describing how to use the new feature has also been written (D4.2). Some preparation for the training course has been made (T4.3), although this task is to continue beyond the end of the project. A draft final report has been written (D4.3) and a presentation (D4.4) summarising the main outcomes of the project will be given at the Final Meeting.
  A general discussion of project results is given in Section 11212.
- **Publicity and marketing (WP5)**
  The publicity and marketing activities have proceeded as planned, apart from where the COVID-19 pandemic has impacted on activities. It has not been possible, as yet, to promote the new elevated roads model at trade events as planned (T5.1). Dr Jenny Stocker has been invited to talk about elevated roads at the upcoming Institute of Air Quality Management's (IAQM) Dispersion Modellers User Group Meeting (DMUG)[2], but this meeting has been postponed, likely until at least February 2021. Also, CERC usually exhibit at the Institute of Air Quality Management's 'Routes to Clean Air' conference, but this does not appear to be going ahead this year, in any format. CERC have been accepted to give an oral presentation describing the scientific aspects of this work at the 2020 conference associated with the international 'Initiative on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes' (Harmo 2020), although this conference is now scheduled to take place in summer 2021[3]. Following the general release of the new version of ADMS-Roads to all licenced users, further promotional activities will take place including mentioning the new module in the ADMS Newsletters (M5.2), sending information to CERC's overseas partners (M5.4) and presenting the results at the autumn ADMS-Urban and ADMS-Roads User Group Meeting (M5.5); Highways England representatives are welcome to attend this event as ADMS licence holders. An advert promoting the latest release of the model will be submitted to Air Quality News at an appropriate time (M5.3).

[1] 'What's New in ADMS-Urban, ADMS-Roads and ADMS-Airport 5.0.1?'
[2] https://iaqm.co.uk/event/dmug2020-2/
[3] Note that work on this conference submission was not included in the project activities.

3. Integration of sub-model into ADMS-Roads

This section describes the integration of the elevated roads sub-model into the release version of ADMS-Roads. Section 3.1 describes how the new ‘flyover’ approach to modelling elevated roads differs from the standard approach to modelling elevated road or line sources. Practical details of how to use the new elevated roads option are provided in Section 3.2 and Section 3.3 gives release information. Section 3.4 provides a technical summary of the approach for modelling elevated roads.

A number of approaches for modelling the dispersion of emissions from flyover-type elevated road were evaluated during the feasibility study; the approach implemented corresponds to ‘Approach 3’ described in the feasibility study report[4]. The integration process has involved making the elevated roads option compatible with other model options including the terrain and deposition modules.

3.1 Approach to modelling elevated roads

The standard approach to modelling an elevated line/road source in ADMS-Roads is to allow material to disperse freely through the source itself (Figure 1 (a)). In reality, the downward dispersion of vehicular emissions on an elevated road will only occur once the material has been advected past the downwind edge of the road. The elevated road model option implemented in ADMS-Roads accounts for this by limiting the downward spread of the plume during its traversal over the road surface (Figure 1 (b)). The vertical concentration distribution at a given downwind distance is then described by two adjoining half-Gaussian functions with the same amplitude (to ensure continuity in the concentrations) but different standard deviations. Technical details are provided in Section 3.4.

[4] Phase 1 report for project ‘Feasibility of tool to assess air quality impacts of elevated roads within the Strategic Road Network’ (CERC report reference FM1245/R1/19)

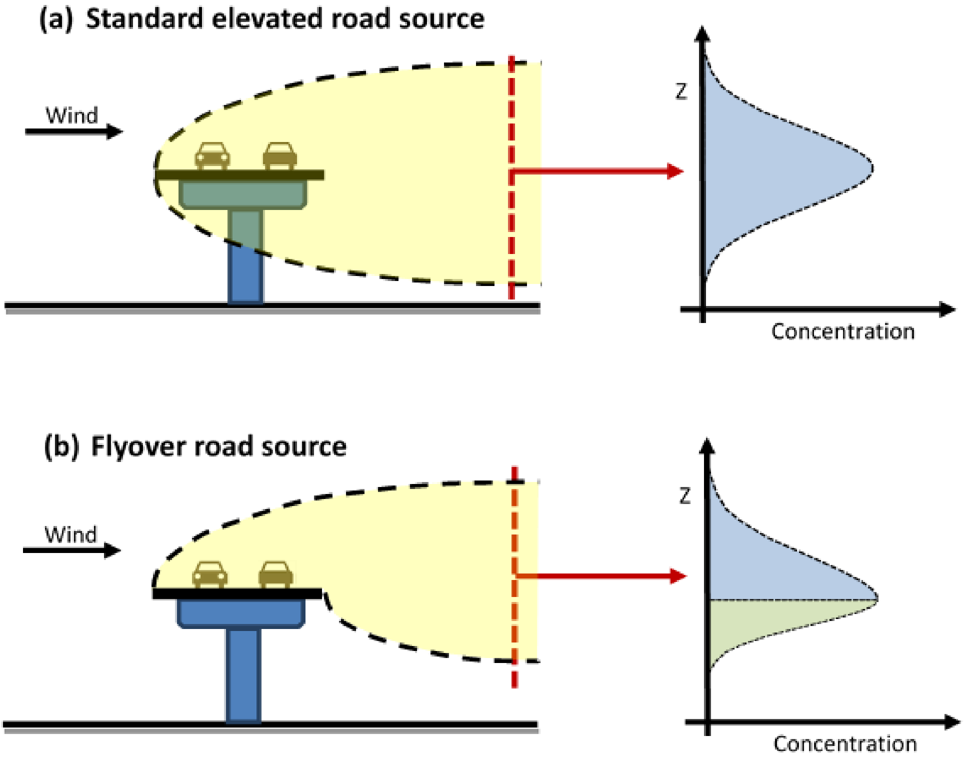


Figure 1 – Schematic of modelling approach for (a) a standard elevated road source and (b) a flyover road source

3.2 Modelling elevated roads using ADMS-Roads

In order to model an elevated road, the source elevation must be specified. Figure 2 shows the ADMS-Roads source screen with a source of elevation 6 m. The elevated road must also be specified as a 'flyover' using the **Additional Input file**. This is done via a new or existing *.uai* file (as described in Section 3.1.8 of the ADMS-Roads User Guide) so that the **Flyovers** option (keyword FLYOVERS) is enabled, as shown in Figure 3.

The model will then use the flyovers approach for any road source that satisfies all the following criteria:

- has a positive **Elevation of road (m)** value in the **Source** screen of the interface;
- has a **canyon height (m)** value of zero in the **Source** screen of the interface; and
- is not already being modelled as either an advanced canyon road source or a road tunnel source.

Note that a flyover road source can still be used in combination with the **Noise barriers** option. In this case, dispersion from the raised source at height H_s that affects concentrations on the non-road side of the barrier (refer to Section 10.8 of the ADMS-Roads User Guide) uses the standard elevated road approach.

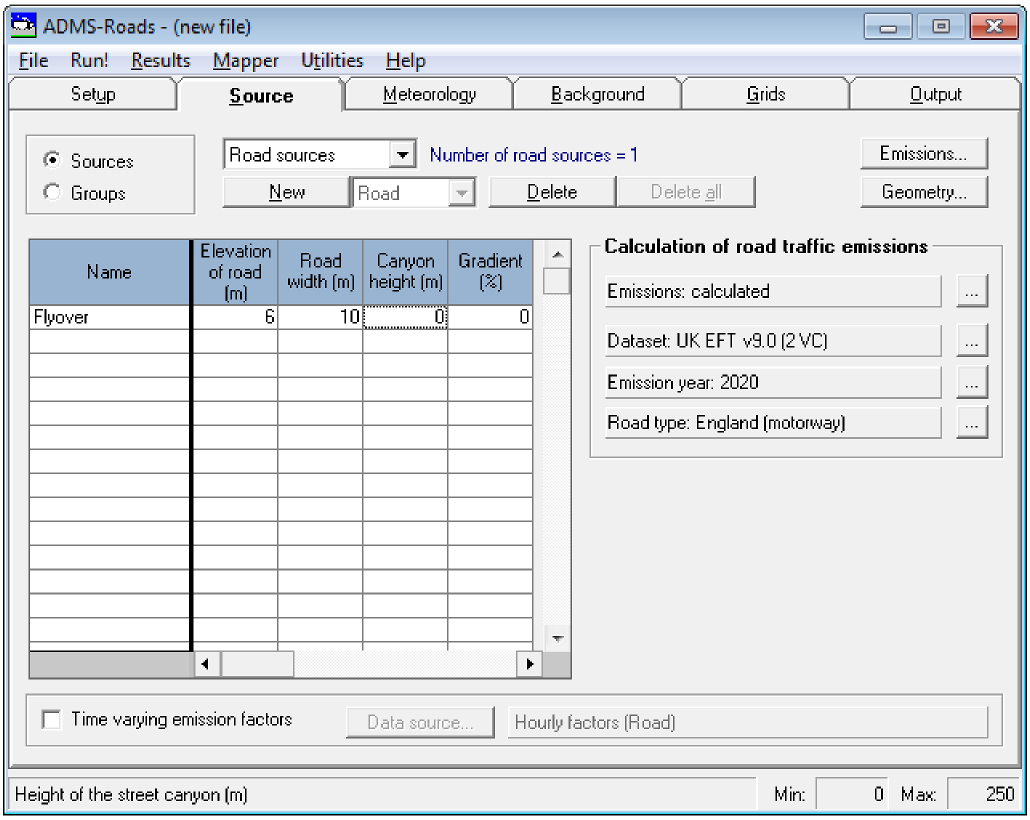


Figure 2 – ADMS-Roads interface showing an input flyover

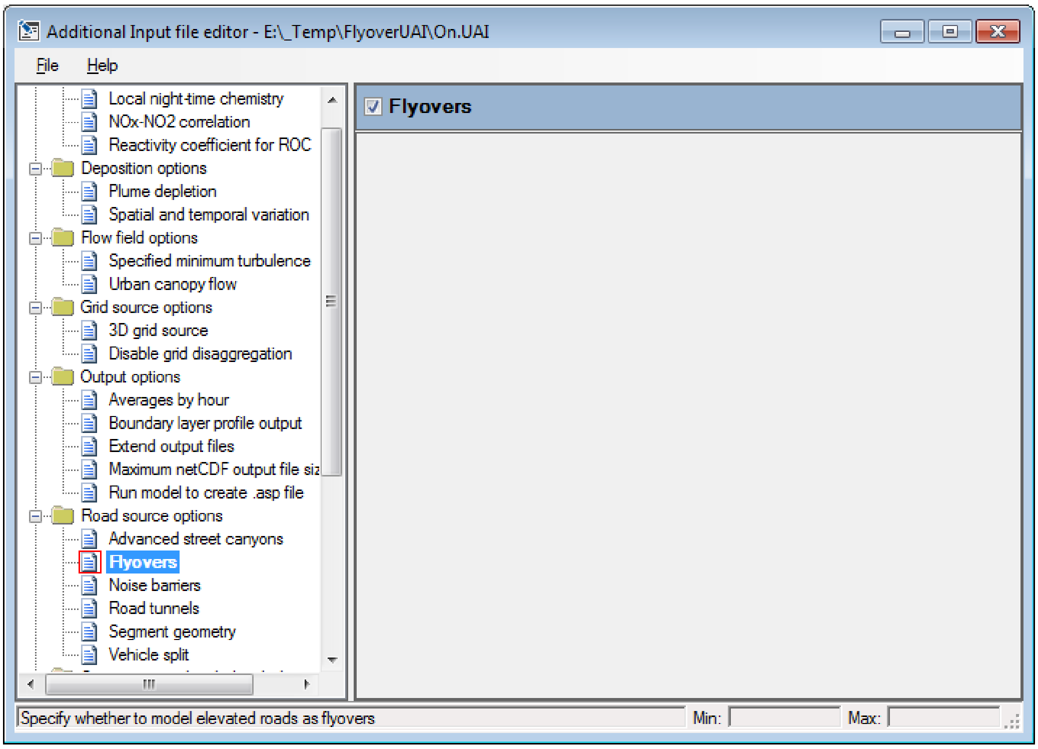


Figure 3 – The **Flyovers** section enabled in the **Additional Input file editor**

3.3 ADMS-Roads release version

The sub-model as described in Section 3.4 has been included in a release version of the ADMS-Roads model. Technical details of the Fortran model code developments are omitted for brevity. All coding was undertaken using CERC's Quality Management System for software development, which includes: 'Subversion' source management software; a comprehensive change control system; peer review of software changes, scientific work products, data analysis and test cases; centralised issue-tracking; and standardised software acceptance testing. The documents describing code changes and the review process are available for inspection, if required.

ADMS-Roads version 5.0.1.1 includes the new elevated roads sub-model. This version of the model is now available for use by Highways England (2-user licence valid until end June 2023).

3.4 Technical summary

When an elevated road source is modelled as a flyover, the downward vertical plume spread, σ_z, is held constant at h_0, the initial road source mixing height (1 m), until the plume is advected past the downwind edge of the elevate road surface. It then proceeds to grow as it would have done from the source for a standard elevated road.

Recall that concentrations downwind of a source in ADMS-Roads are calculated as:

$$C = \frac{Q}{U} g(y) f(z), \tag{1}$$

where Q is the source strength, U is the wind speed (at the mean plume height), and $g(y)$ and $f(x)$ are the Gaussian (in non-convective conditions) transverse and vertical concentration distribution functions, respectively, that both satisfy:

$$\int_{y=-\infty}^{y=+\infty} g(y)\,dy = \int_{z=-\infty}^{z=+\infty} f(z)\,dz = 1. \tag{2}$$

For flyover road sources, we split $f(z)$ into two piecewise continuous functions, $f_-(z)$ and $f_+(z)$, below and above the plume centreline height z_p:

$$f(z) = \begin{cases} f_-(z), & \text{for } z < z_p \\ f_+(z), & \text{for } z \geq z_p \end{cases}, \tag{3}$$

subject to the following two constraints:

$$\int_{z=-\infty}^{z=z_p} f_-(z)\,dz + \int_{z=z_p}^{z=+\infty} f_+(z)\,dz = 1, \tag{4}$$

$$f_-(z_p) = f_+(z_p). \tag{5}$$

Using the Heaviside function H, $f(z)$ can be written as:

$$f(z) = f_-(z)\left(1 - \mathrm{H}(z - z_p)\right) + f_+(z)\mathrm{H}(z - z_p). \tag{6}$$

While the above is suitable for an isolated source (without reflections), the dispersion of a road source in ADMS-ROADS includes the reflections from the ground and (in the presence of an inversion at $z = h$) from the boundary layer, and the above equation is thus modified to:

$$f(z) = f_-(z)\left(1 - \mathrm{H}(z - z_p)\right) + f_+(z)\mathrm{H}(z - z_p) + f_-(-z) + f_+(2h - z). \tag{7}$$

Note that no Heaviside function is applied to the last two terms because every point within the boundary layer will receive contributions from both reflections. In the absence of an inversion, the last term is dropped.

We use half Gaussian functions for $f_-(z)$ and $f_+(z)$, which have the same amplitude (in order to satisfy Eq. (5)) but different standard deviations (i.e. vertical spreads), $\sigma_{z_{f-}}$ and $\sigma_{z_{f+}}$, which are taken to be:

$$\begin{gathered} \sigma_{z_{f+}}\Big|_x = \sigma_z|_x \\ \sigma_{z_{f-}}\Big|_x = \begin{cases} h_0, & x \le x_r \\ \sigma_z|_{x-x_r}, & x > x_r \end{cases} \end{gathered} \tag{8}$$

where $\sigma_z(x)$ is the vertical spread (at a downwind distance of x from the upwind edge of the road) used by ADMS-ROADS in its standard configuration and x_r is the distance to the downwind edge of the road. The amplitude, a, of $f_-(z)$ and $f_+(z)$ is obtained by solving Eq. (4):

$$\begin{gathered} a\left(\int_{z=-\infty}^{z=z_p} \exp\left(\frac{-(z-z_p)^2}{2\sigma_{z_{f-}}^2}\right)dz + \int_{z=z_p}^{z=+\infty} \exp\left(\frac{-(z-z_p)^2}{2\sigma_{z_{f+}}^2}\right)dz\right) = 1 \\ \Rightarrow a = \frac{2}{\sqrt{2\pi}(\sigma_{z_{f-}} + \sigma_{z_{f+}})} \end{gathered} \tag{9}$$

The full equation for $f(z)$ thus becomes:

$$f(z) = \frac{2}{\sqrt{2\pi}(\sigma_{z_{f-}} + \sigma_{z_{f+}})}\left[\exp\left(\frac{-(z-z_p)^2}{2\sigma_{z_{f-}}^2}\right)\left(1 - \mathrm{H}(z-z_p)\right) + \exp\left(\frac{-(z-z_p)^2}{2\sigma_{z_{f+}}^2}\right)\mathrm{H}(z-z_p) + \exp\left(\frac{-(z+z_p)^2}{2\sigma_{z_{f-}}^2}\right) + \exp\left(\frac{-(z-2h+z_p)^2}{2\sigma_{z_{f+}}^2}\right)\right]. \quad (10)$$

In stable/neutral conditions, $z_p = z_s + h_0$, where z_s is the height of the road source. In convective conditions, the standard vertical concentration distribution function is itself defined as two piecewise continuous half Gaussian functions with $z_p = z_s + h_0 + \hat{w}t$ and standard deviations above and below this height of $\sigma_{z_+}(x) = \frac{\sigma_{w+}\sigma_z}{\sigma_w}$ and $\sigma_{z_-}(x) = \frac{\sigma_{w-}\sigma_z}{\sigma_w}$, respectively, where σ_w is the vertical component of turbulence, t is the travel time from the source, and $\hat{w}$, σ_{w_+} and σ_{w_-} are as defined in the ADMS Plume/Puff Spread and Mean Concentration Module Technical Specification document (P10/01). Eq. (8) in convective conditions thus becomes:

$$\left.\sigma_{z_{f+}}\right|_x = \left.\frac{\sigma_{w_+}\sigma_z}{\sigma_w}\right|_x$$

$$\left.\sigma_{z_{f-}}\right|_x = \begin{cases} h_0 \left.\frac{\sigma_{w_-}}{\sigma_w}\right|_0, & x \le x_r \\ \left.\frac{\sigma_{w_-}\sigma_z}{\sigma_w}\right|_{x-x_r}, & x > x_r \end{cases} \quad (11)$$

Figure 4 shows example vertical cross-sectional concentration contours calculated by implementing the above algorithms, for a cross-road flow (upper plot) and an along road flow (lower plot) for a 10 m wide section of road elevated to 10 m. These figures demonstrate the increased mixing both in-road and adjacent to the road when the wind blows across the road compared to when it blows along the road. Further, the ground-level concentrations are higher for the along-road flow compared to the cross-road flow.

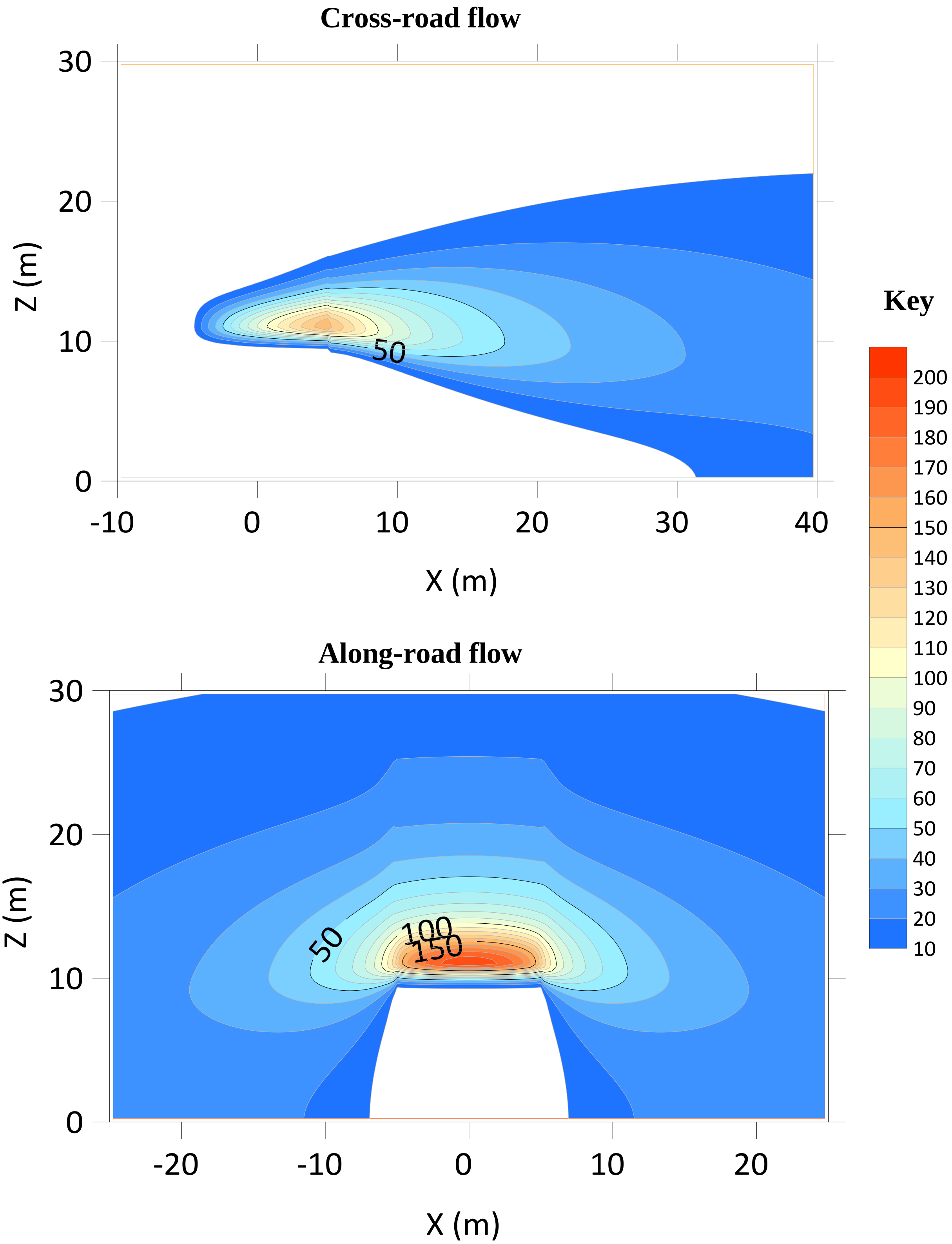


Figure 4 – Example vertical cross sections of pollutant concentration contours resulting from the ‘flyover’ elevated road module

4. Evaluation approach

Three site types were considered for evaluation:

1. Sites where there are diffusion tube measurements close to the elevated road section.
2. Sites where measurements have been taken that may be used to demonstrate the impact of elevated roads.
3. Sites where there are automatic reference monitor data close to the road, but other heavily trafficked roads may be located in the vicinity.

The criteria for selecting sites for model evaluation are given in Section 4.1. Using these criteria, a number of sites were selected as possibilities within each of the three site types listed above; these are summarised in Section 4.2. The data associated with all sites was collated (Section 4.3).

Within each site type, one primary site was selected as the most likely for providing evidence with regard to model performance; the remaining sites were held in reserve, to be used if the outcome from analysis using the primary site was inconclusive. **As the model evaluation exercise was successful, it was unnecessary to use any of the reserve sites.**

4.1 Site selection process

The following factors were taken into consideration when selecting sites for the evaluation involving measurement data:

1. **Site location** – it is preferable to select a site where the elevated road is the dominant source influencing concentrations at the selected monitor; consequently, rural sites adjacent to motorways are preferable to monitors near elevated roads in urban areas.
2. **Type of monitor** – reference monitors are much more reliable than diffusion tubes in terms of accuracy of concentration measurements, and also they provide hourly data, so wind sector and other statistical analyses can be performed. However, cost considerations allow diffusion tubes to be deployed in high density and the resulting data from multiple locations can also be useful, for example for assessing the variation in NO2 concentrations along the length of a road.
3. **Distance of elevated road to monitor** – the monitor must be located as close as possible to the elevated road.
4. **Height of elevated road** – roads that are as elevated as possible should be considered, in order to be able to resolve the influence of elevation on concentrations.
5. **Height of monitor** – ideally, the monitor would be near ground level, in order to test the new elevated roads module i.e. how well the model can account for dispersion from the elevated road down to the ground.
6. **Availability of emissions data** – traffic activity and/or emissions data should be either publicly available or owned by HE.
7. **Availability of background data** – for hourly analyses, data from rural background monitors in the vicinity are required.
8. **Availability of meteorological data** – suitable meteorological data are usually available.

4.2 Site selection

Following discussions with HE relating to site options, seven sites have been selected as possibilities for model evaluation. The sites are described in the following tables:

- Sites with NO_2 diffusion tube data (Table 1)
- Sites with high temporal resolution monitoring data (Table 2)
- Sites with automatic monitors (Table 3)

4.3 Dataset collation

The datasets associated with all seven sites were collated. The datasets are summarised in the following tables, with associated images showing the site locations:

- Sites with NO_2 diffusion tube data (Table 4)
- Sites with high temporal resolution monitoring data (Table 5)
- Sites with automatic monitors (Table 6)

4.4 Dataset selection

The justification for selection of the three primary sites was:

- The primary 'NO_2 diffusion tube site' selected for evaluation included more diffusion tube data than either of the other sites, and also a reference monitor, albeit one 150 m from the motorway.
- The primary 'high temporal resolution monitoring data site' dataset included monitoring from either side of an elevated road section, allowing calculation of the elevated road concentration increment, in addition to measurements adjacent to a ground level section of road in the vicinity; the reserve site had data from only one monitor.
- The primary 'automatic reference monitor' site selected included two monitors, one of which was located away from any other heavily trafficked roads, thus being an ideal site for model evaluation purposes; the reserve site in this case would have been unlikely to demonstrate as good results both due to the presence of adjacent busy roads and also because only DfT (rather than WEBTRIS) data were available for road traffic emissions calculations.

It would have been of interest to additionally evaluate results from one or more of the reserve sites, but insufficient resources were available within the project to do this.

Table 1 – Assessment summary for sites with diffusion tube data; site in **bold** has been used in evaluation study.

Name	Area	Pollutants	Location of AQ measurement data	Notes	Advantages	Disadvantages
Birmingham Road	**Oldbury**	**NO_x, NO_2**	**www.airqualityengland.co.uk Sandwell MBC& HE**	**High density network of diffusion tube data** **Automatic monitor ~ 150m from elevated section of M5**	**Sandwell MBC and HE have a large density of diffusion tubes on both sides of the motorway. CERC have a model configuration for Birmingham that can be refined using detailed M5 traffic data from HE, likely leading to an accurate model set up.**	**The automatic monitor is a long way from the elevated road so may not detect the elevation.**
M5/M6	Walsall	NO_2	HE	Network of diffusion tubes below elevated sections of motorway, where the M5 meets the M6	HE have a large density of diffusion tubes on the Eastern side of the motorways.	
M6	Witton	NO_2	HE	To the North of “Spaghetti Junction”, alongside elevated sections of the M6.	HE have a network of 8 diffusion tubes mainly on the Eastern side of the motorway.	

Table 2 – Assessment summary of sites with high temporal resolution reference monitoring data analysis; site in **bold** has been used in evaluation study.

Name	Area	Pollutants	Location of AQ measurement data	Notes	Advantages	Disadvantages
Antwerp	**Antwerp, Belgium**	**NO_x, NO_2, $PM_{2.5}$**	**Held by author**	**Poppel paper[5]**	**A monitor either side of flyover at ground level and elevated sections**	**Only 3 months’ data.**
Glasgow Anderston	Glasgow	NO_x, NO_2, PM_{10}, $PM_{2.5}$	www.scottishairquality.scot	Playground 60 m from raised M8	CERC has a base emissions model for Glasgow	Slightly complicated road setup with additional roads

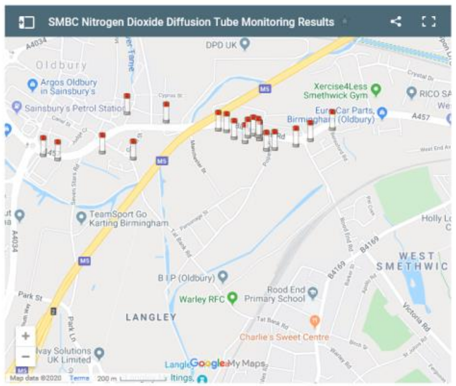
[5] *Van Poppel, M., Panis, L.I., Govarts, E., Van Houtte, J. and Maenhaut, W., 2012. A comparative study of traffic related air pollution next to a motorway and a motorway flyover. Atmospheric environment, 60, pp.132-141*

Table 3 – Assessment summary of sites with automatic monitors; site in **bold** has been used in evaluation study.

Name	Area	Pollutants	Location of AQ measurement data	Notes	Advantages	Disadvantages
Hounslow Brentford	**London**	**NO_x, NO_2, PM_{10}, $PM_{2.5}$**	**www.airqualityengland.co.uk**	**Two reference monitors alongside raised M4: one in a park; the other beside the A4.**	**Close to M4; London emissions available; HE have detailed data for M4.**	**Both the M4 and A4 are both heavily trafficked roads, so it may be difficult to distinguish elevated section. A4 isn't a HE road, so detailed data will have to be obtained from elsewhere.**
Greenwich Woolwich flyover	London	NO_x, NO_2, O_3, PM_{10}, $PM_{2.5}$	www.londonair.org.uk	Alongside major (A102) raised road	Close to A102; simple configuration; London emissions available.	Other roads nearby (although A102 dominant). A102 isn't a HE road, so detailed data will have to be obtained from elsewhere.

Table 4 – Data summary for sites with diffusion tube data; site in **bold** has been used in evaluation study.

Name	Measurements		Emissions		Meteorological dataset	Background pollutant dataset
	Reference data	Monthly Diffusion tube data	Explicit representation of roads	Gridded		
Birmingham Road, Oldbury	**AURN site (Oldbury, Birmingham Road). Only NOx and NO2 data available (2016).**	**Highways England data for 4 sites for Jan to June 2016. Sandwell MBC data for 15 sites for 2016.**	• **M5 data from WEBTRIS (s/b flow taken from junction below interested area - no other data, n/b OK)** • **Birmingham Road from DfT (site 17142) 12 hour period for a Friday (16/6/17), flows for other periods estimated using M5 diurnal profiles**	**NAEI data**	Elmdon	Wind-direction dependent combination of 4 sites: Ladybower, Market Harborough, Chilbolton, Leominster
M5/M6 Walsall	n/a	Highways England data for 9 sites for Jan to June 2016	• M5/M6 data from WEBTRIS • A4031 Walsall Road (site 73919) 12 hour period for a Tuesday (10/7/18), flows for other periods estimated using M5/M6 diurnal profiles	NAEI data		
M6 Witton	n/a	Highways England data for 10 sites April-Sept 2019	• M6 data from WEBTRIS • A4040 (site 56948) 12 hour period for a Friday (20/10/17), flows for other periods estimated using M6 diurnal profiles	NAEI data		



Birmingham Road, Oldbury (Google: Map data @2019)

M5 / M6 Walsall (Google Earth: Map data @2020)

M6 Witton (Google Earth: Map data @2020)

Table 5 – Data summary for sites for high temporal resolution reference monitoring data analysis; site in **bold** has been used in evaluation study.

Name	Measurements		Emissions		Meteorological dataset	Background pollutant dataset
	Reference data	Diffusion tubes	Explicit representation of roads	Gridded		
Antwerp, Belgium	**4 monitors: 2 either side of a flyover and 2 either side of an adjacent stretch of road not at grade. 30 minute average PM2.5 and NOx concentration data (February to April 2009).**	**n/a**	**The road has 10 lanes with an AADT of 200,000 and a high percentage of HGV.**	**n/a**	**Wind speed and direction data available from a nearby Flanders Environment Agency site (Antwerp Luchtbal) Temperature and cloud cover available from Deurne, approximately 5 km away.**	**n/a**
Glasgow Anderston	One monitor beside an elevated section of the M8, in a school playground. NOx, NO2, PM10, PM2.5 available (data for 2016 and 2017 collated; additional data available from http://www.scottishairquality.scot/)	n/a	**n/a**	**n/a**	Data for Glasgow Bishopton will be purchased at short notice, if this site is included in the study	**n/a**

Antwerp, Belgium (Poppel *et al.*, 2012)

Glasgow Anderston (Google Earth: Map data @2020)

Table 6 – Data summary for sites with automatic monitors; site in **bold** has been used in evaluation study.

Name	Measurements		Emissions		Meteorological dataset	Background pollutant dataset
	Reference data	Diffusion tubes	Explicit representation of roads	Gridded		
Hounslow Brentford	**AURN site, Hounslow, Brentford (HS5). NO_x, NO_2, $PM_{2.5}$, PM_{10} available (2019). Local authority site Boston Manor Park (HS010) NO_x and NO_2 available (2019).**	**n/a**	• **M4 data from WEBTRIS** • **A4 from DfT (site 75072) 12 hour period for a Thursday (23/3/17), flows for other periods estimated using M4 diurnal profiles**	**LAEI data**	Heathrow	Wind-direction dependent combination of 4 sites: Lullington Heath, Chilbolton, Rochester Stoke and Wicken Fen.
Greenwich Woolwich flyover	AURN site (Greenwich Woolwich Flyover). NOx, NO2, O3, PM2.5, PM10 available (2018).	n/a	• Data from DfT: A206 (site 46792) 12-hour flow for 17/9/18 and A102 (site 74531) 12-hour flow data for 10/7/18. Other periods estimated using LAEI diurnal profiles.	LAEI data		

Hounslow Brentford and Boston Manor Park (Map data: ESRI *et al.*)

Greenwich Woolwich flyover (Google: Map data @2019)

4.4.1 Birmingham Road, Oldbury

Table 4 summarises the Birmingham site datasets collated for use as input to ADMS-Roads.

In terms of modelled sources, a 2.5 km stretch of the M5 was represented explicitly in addition to 1.7 km of Birmingham Road. The elevated section of road was assumed to be 9 m high. Road source emissions were calculated using EFT v9.0 emission factors with real world NOx adjustments. Other local (volume) sources (10 m depth) were used to represent emissions from all sources not modelled explicitly, as shown in Figure 5. The volume sources over Birmingham cover 30 x 15 km, and include all the emissions available from the NAEI, i.e. industrial, residential and transport sectors. The volume sources varied in size, with smaller sources (1 x 1 km) close to the modelled area. Figure 6 shows the location of the modelled road sources and receptors in more detail.

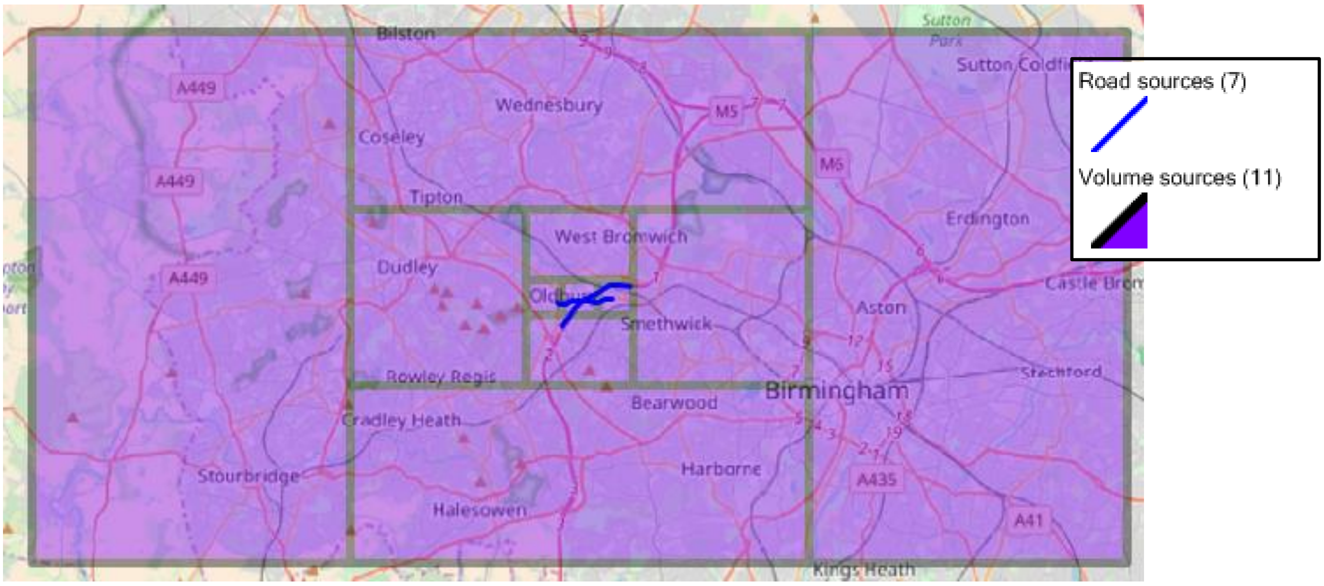


Figure 5 – Other local (volume) source locations at the Oldbury site (© Openstreet Map)

The AURN reference monitor is located 150 m from the motorway. There are seven diffusion tubes co-located with the reference monitor (within 5 m): three of these are deployed by Highways England and four by the local authority. The reference monitor height is 3.5 m and diffusion tube heights have been assumed to be 4 m (i.e. out of arms reach, on lampposts). Figure 7 shows a view of the approximate location of two diffusion tubes located on lampposts in the vicinity of the M5 (east side). Of note is that the lamppost closer to the motorway is in a small open area, whereas the other is at the end of a long street of houses, which form a low-rise (5.5 m) street canyon.

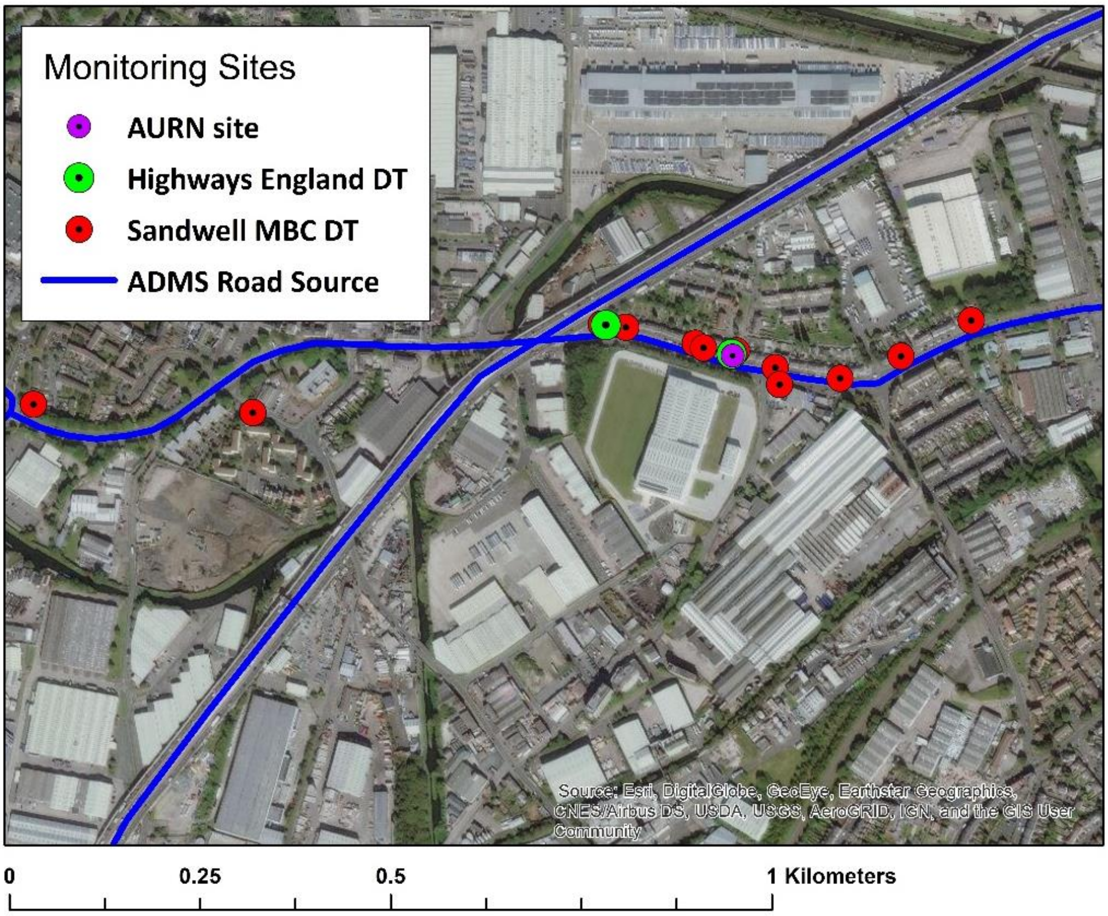


Figure 6 – Location of modelled roads and monitors at the Oldbury site. (Map data: ESRI *et al.*)

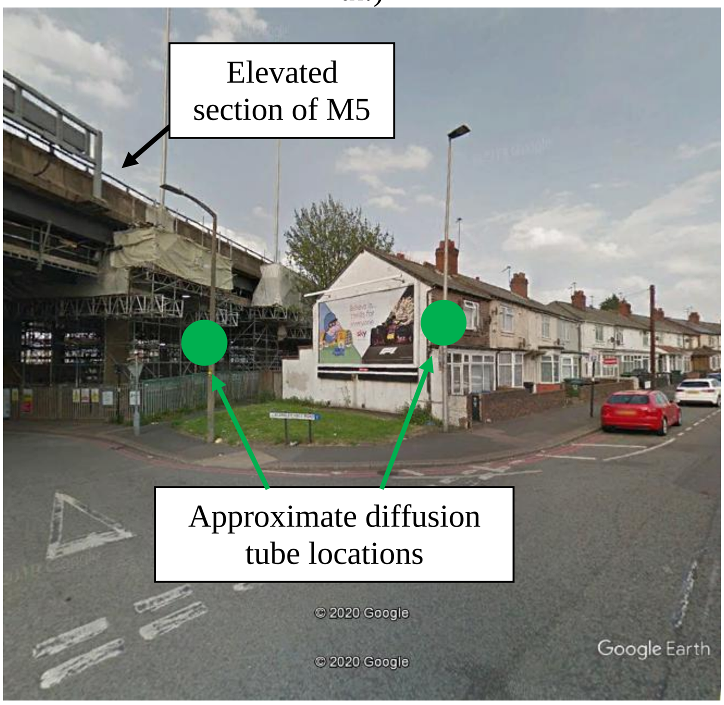


Figure 7 – Birmingham Road to the East of the M5, green dots showing approximate location of diffusion tubes. (Google Earth: Map data @ 2020)

4.4.2 Hounslow, Brentford

Table 6 summarises the London site datasets collated for use as input to ADMS-Roads.

In terms of modelled sources, a 3 km stretch of the M4 was represented explicitly in addition to 3 km of the A4. The elevated section of road was assumed to be 6 m high. Road source emissions were calculated using EFT v9.0 emission factors with real world NOx adjustments. Other local (volume) sources (10 m depth) were used to represent emissions from all sources not modelled explicitly, as shown in Figure 8. The volume sources over London cover 26 x 26 km, and include all the emissions available from the NAEI, i.e. industrial, residential and transport sectors. The volume sources varied in size, with smaller sources (1 x 1 km) close to the modelled area. Figure 9 shows the location of the modelled road sources and receptors in more detail.

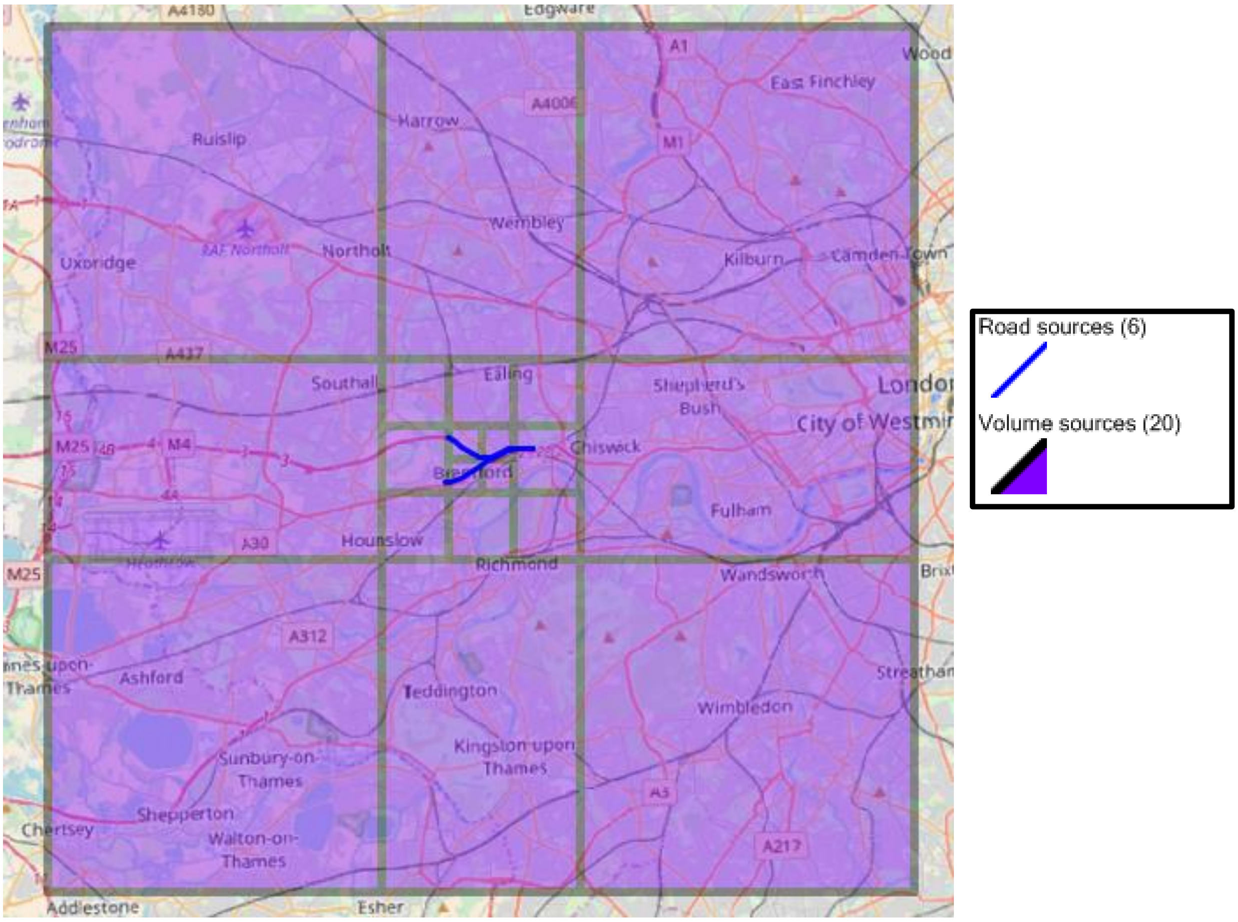


Figure 8 – Other local (volume) source locations at the Brentford site (© Openstreet Map)

HS010, located in Boston Manor Park, is approximately 7 m from the edge of the M4 motorway with an elevation of 1.7 m. HS5, located adjacent to the Chiswick flyover, is approximately 9 m from the edge of the M4, 4.5 m from the A4 and with an elevation of 2.5 m.

Figure 10 shows the location of the HS5 monitor from street level. In addition to the monitor's proximity to the A4 and M4, the presence of the row of buildings alongside the A4 influences pollutant dispersion from the A4. This became apparent during the initial stages of the evaluation exercise when inspecting the variation of concentrations with wind direction. Specifically, it was found that whilst model performance was good for wind directions between 0 and 100°, and 220° and 360°, for other wind directions, the model significantly under-predicted (refer to Figures 52 and 53 in the Appendix). This under-prediction by the model directly corresponds to meteorological conditions where the wind blows over the building towards the monitor, suggesting that the building generates a recirculation region that causes pollution to disperse in the opposite direction to the prevailing wind i.e. from the A4 towards the monitor. This effect can be modelled in ADMS-Roads using the advanced canyon module. Thus, this row of buildings has been represented in the model configuration by specifying this short segment of the A4 as an asymmetric street canyon, with building heights of 12 m.

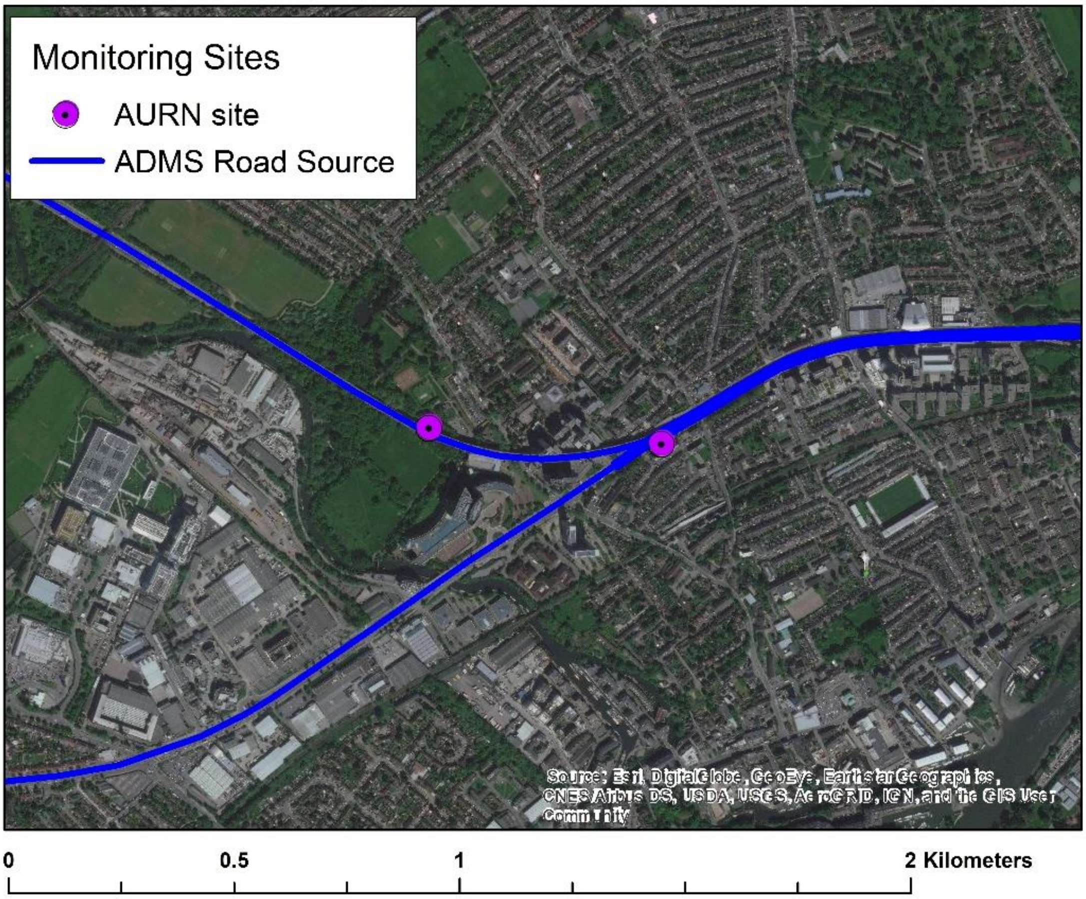


Figure 9 –Location of modelled roads and monitors at the Hounslow, Brentford site. Monitor HS10 to the west on the M4 only, monitor HS5 to the east, where the A4 and M4 are closely aligned. (Map data: ESRI *et al.*)

Figure 10 –Hounslow, Brentford HS5 air quality monitor (note the HS010 monitor cannot be seen using Google Street View. Google: Map data @ 2020)

4.4.3 Antwerp, Belgium

Table 3 summarises the Antwerp site dataset. The author of the paper describing this study, Martine van Poppel, helpfully provided a spreadsheet[6] containing meteorological and pollutant concentration measurement data. Data from the paper and spreadsheet have been used to configure ADMS-Roads.

The section of the R1 ring road of interest has been represented explicitly by a 3.5 km stretch of road, this includes a 1 km section at ground level and a 2.5 km section which is elevated at a height of 12 m. Along this stretch of the R1 ring road the width of the road varies from 14 m along the elevated portion to 22 m at ground level. Between the two sections of the motorway there is one approach and exit, influencing the AADT of the road. Figure 11 presents a map showing explicitly modelled roads and receptor locations.

There are two pairs of monitoring sites for this study. Ground level A which is 102 m from the kerbside on the northern side of the road, and ground level B which is 29 m from the kerbside on the southern side of the road. Flyover monitor A is situated 120 m to the north of the kerbside and flyover monitor B is located 60 m to the south of the kerbside. Figure 11 also displays the locations of all monitors with respect to the modelled roads. The specific coordinates of these receptors have not been supplied so this is a best estimate of their locations based on Google Earth and images in Poppel *et al.* (2014). The ground site measurements were recorded between 16:00 on the 6th February 2009 and 08:30 on the 13th March 2009. The elevated site measurements were recorded between 14:00 on the 18th March 2009 and 09:00 on the 15th April 2009.

[6] ‘Data for Analysis with Corrections.xls’

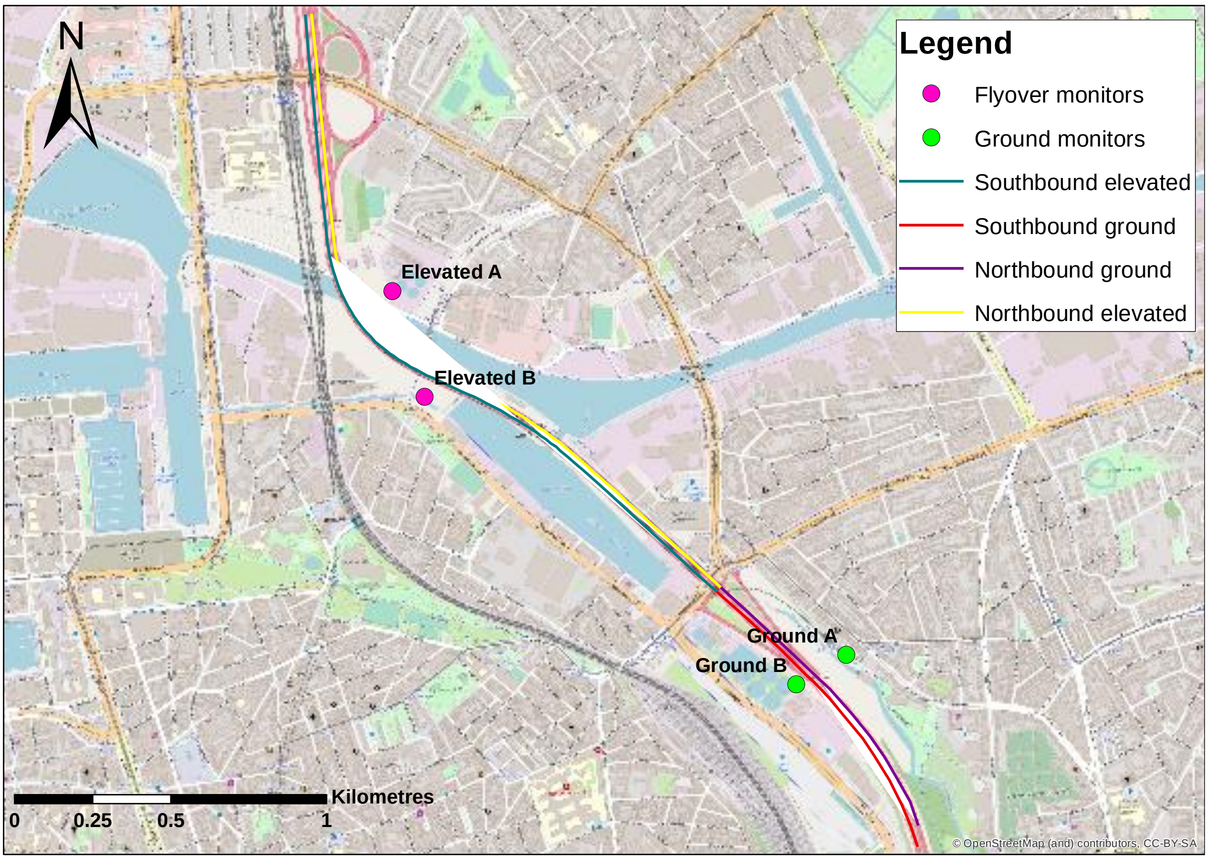


Figure 11 – Location of modelled roads and monitors at the Antwerp, Belgium site (© Openstreet Map)

Poppel *et al.* (2014) notes that the ground level section of the road can get very busy with up to 200,000 vehicles per day, which equates to approximately 8,333 cars per hour. It has been assumed that the elevated section has a reduced number of vehicles, which can be calculated using the ratios supplied in the paper for each of the total manual and traffic counted flows, giving a flow of 153,702 vehicles per day for the elevated section. A summary of traffic flow splits between vehicle type and segment of road is shown in Table 7**.** To achieve a better representation of the distribution of vehicles at a particular hour an hourly factor has been applied, this is presented in Figure 12. A speed of 80 kph has been used in the emissions calculations.

Table 7 – Summary of the traffic flow splits between vehicle type and segment of road.

<table>
<tr><th rowspan="2">Segment</th><th colspan="2">AADT</th><th colspan="2">Light-duty vehicle</th><th colspan="2">Heavy-duty vehicle</th></tr>
<tr><th>Total</th><th>Hourly</th><th>Split</th><th>Hourly AADT</th><th>Split</th><th>Hourly AADT</th></tr>
<tr><td>Ground</td><td>200,000</td><td>8,333</td><td>0.776</td><td>6,469</td><td>0.224</td><td>1,865</td></tr>
<tr><td>Elevated</td><td>153,702</td><td>6,404</td><td>0.739</td><td>4,735</td><td>0.261</td><td>1,669</td></tr>
</table>

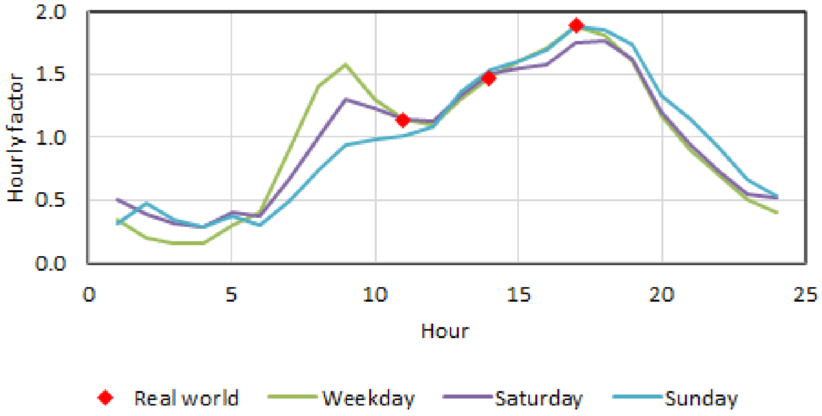


Figure 12 – Time-varying profile for Antwerp

The spreadsheet provides local wind speeds and directions, this data has been supplemented with meteorological data for the Deurne weather station (DS3505). The original study was split into measurements at the ground location between 06-02-2009 16:00 and 13-03-2009 08:30 and the elevated locations between 18-03-2009 14:00 and 15-04-2009 09:00. Both have a temporal resolution of 30 minutes. For the purpose of modelling four meteorological files were created; ground on the hour, elevated on the hour, ground on the half hour and elevated on the half hour. A summary of meteorological data used in the modelling is presented in Table 8**.**

Table 8 – Summary of the meteorological data for the Antwerp study; *a minimum wind speed of 0.75 m/s is used by the model.

Run	**% used**	**Wind Speed* (m/s)**			**Temperature (°C)**			**Cloud Cover (oktas)**		
		Min	**Max**	**Av**	**Min**	**Max**	**Av**	**Min**	**Max**	**Av**
Elevated (on the hour)	98.7	0.25	9.56	3.7	-1.9	23.4	9.8	0	8	4.3
Ground (on the hour)	99.6	0	10.1	3.8	-4.7	12.8	5.2	0	8	6.3
Elevated (on the half hour)	99.0	0.25	10.1	3.9	-1.9	23.4	9.2	0	8	4.3
Ground (on the half hour)	99.8	0.25	10.6	3.8	-4.7	12.8	5.2	0	8	6.3

5. Evaluation results

The method for evaluation for the sites with diffusion tube and automatic monitoring data differs from the evaluation where the focus is primarily on the measurements. Consequently, the discussion of the following sites:

- Diffusion tube data plus one automatic monitor – Birmingham, Oldbury
- Two automatic monitors – London, Hounslow

has been presented separately to the discussion of the analyses of the measurement campaign data:

- High temporal resolution monitoring data – Antwerp, Belgium

For these analyses, statistics relating to model performance are presented alongside period-average concentration comparisons where possible i.e. for reference monitors. Statistics presented are: the normalised mean square error (NMSE), correlation, proportion of points within a factor of two of the observed (Fac2) and the fractional bias (fb). Of these, the NMSE, correlation and Fac2 all relate to hourly values; NMSE has an ideal value of 0, whereas correlation and Fac2 have an ideal value of unity.

Source apportionment is useful for understanding the influence of different sources on overall concentrations, but the methodology is less robust for pollutants that are strongly influenced by non-linear processes over short temporal and spatial scales; consequently, source apportionment is straightforwardly valid for NOx, but less so for NO2 due the strong influence of rapid chemistry. Results from source apportionment calculations have been presented for the two UK studies, as overall totals and also binned according to wind direction. The approach for calculating NO2 source apportionment is as follows:

- Calculate 'total NO2' concentrations for each hour using the ADMS-Roads **Chemistry** module;
- Use the **Groups** option to run the model with all sources apart from one, e.g. the motorway;
- For all source types, calculate the source apportionment contribution as the 'total NO2' minus the result from the previous step;
- To calculate the final source apportionment total, include background concentrations of NO2;
- Sum all components over hours with valid monitoring and model data.

This method does not allow exactly for chemistry, so the overall total when calculated as a sum of each component is a few µg/m³ lower than the total annual average when all sources are modelled together. This highlights the importance of correctly accounting for chemistry when modelling NO2. NO2 source apportionment results presented in the following sections are described as 'indicative'.

Section 5.1 presents the results of the evaluation against measurements recorded Birmingham, Oldbury and London, Hounslow. Section 5.2 presents the study of measurement data from the Antwerp site, including associated modelling results.

5.1 Model evaluation at UK sites

The model evaluation at UK sites begins with comparing the annual average NOx and NO2 concentrations at each site modelled. Figure 13 shows the NOx and NO2 scatter plots of annual average concentrations for the Birmingham Oldbury site, with Tables 9 and 10 presenting the corresponding statistics. Model performance is good, with low values of fractional bias and high values of correlation and number of points within a factor of two of the observed for both NOx and NO2. There is very little difference in the model prediction at this site when the M5 section is modelled as elevated, compared to when it is modelled as flat. This is because the receptor is approximately 150 m away from the motorway, and the importance of accounting for the detailed source term definition decreases with distance from the road.

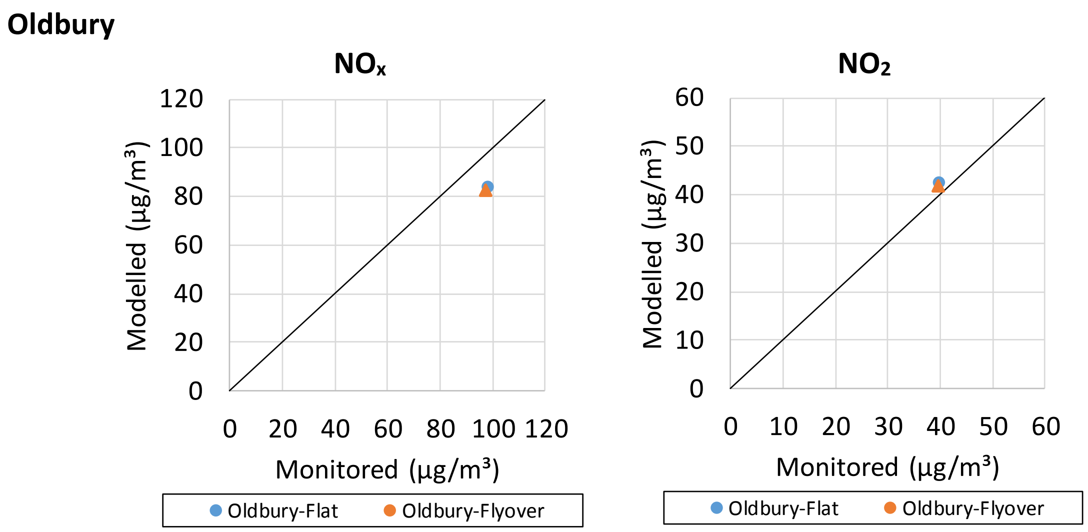


Figure 13 – NO_x and NO_2 annual average scatter plots for Birmingham Road reference monitor (2016)

Table 9 – Statistics from modelling M5 / Birmingham Road, Oldbury (NOx)

NO_x (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Flat	97.7	84.5	0.671	0.622	0.718	-0.145
Flyover	97.7	82.4	0.684	0.624	0.716	-0.170

Table 10 – Statistics from modelling M5 / Birmingham Road, Oldbury (NO2)

NO2 (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Flat	39.7	42.7	0.213	0.707	0.872	0.072
Flyover	39.7	41.7	0.209	0.705	0.871	0.049

Figure 16 a) presents the Birmingham Road, Oldbury source apportionment results for annual average NOx in terms of the concentration arising from: the explicitly modelled section of the M5; the other local (volume) sources representing urban emissions from surrounding areas (which may include some far-field contribution from the M5); Birmingham Road; and background concentrations. Figure 17 a) shows the corresponding 'indicative' plot for NO2 (recalling that it is not possible to undertake direct source apportionment for NO2 due to the non-linear influence of chemistry on concentrations). These source apportionment analyses demonstrate that the motorway is contributing relatively little to total concentrations at this distance from the road (less than 4 µg/m³ NO_2, from the 'Flyover' entry). Further source apportionment results from the reference monitor are presented in Figures 20 a) and 21 a), but are not discussed in detail here, as the motorway elevation does not impact significantly at this site; it is more interesting to evaluate modelled concentrations using diffusion tube measurements that are located in close proximity to the elevated section of road.

Figure 14 presents model predictions (vertical axis) against monthly measurements (horizontal axis) recorded by diffusion tubes deployed along, and in the vicinity of, Birmingham Road. The diffusion tube measurements are bias adjusted, but no 'adjustment factors' have been applied to the model results. Although there is a slight model over-prediction, performance is generally good, with 82% of values lying within 25% of the measurements; for a similar comparison using annual concentrations, all values lie within this range (Figure 15). Note that the four Highways England diffusion tubes do not have data for the full year: 3 tubes cover February to June and one January to June.

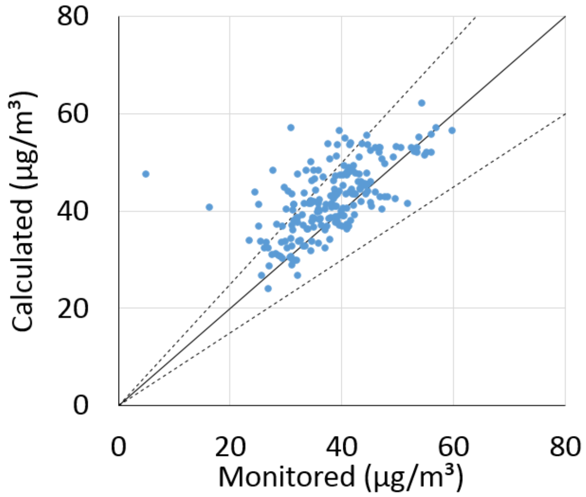


Figure 14 – Monthly average diffusion tube results showing +/- 25% error lines

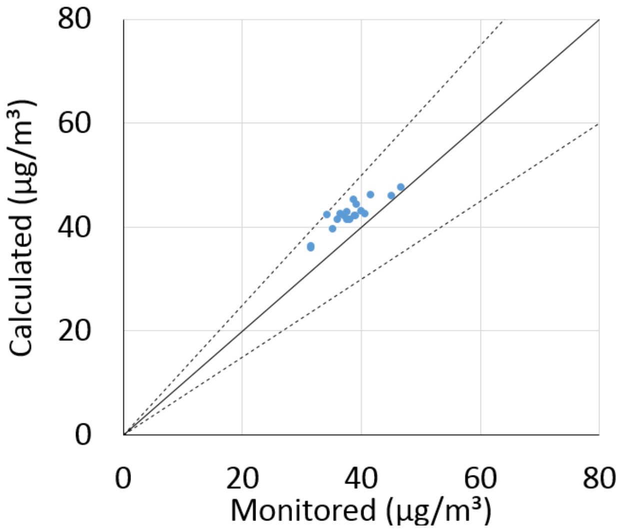
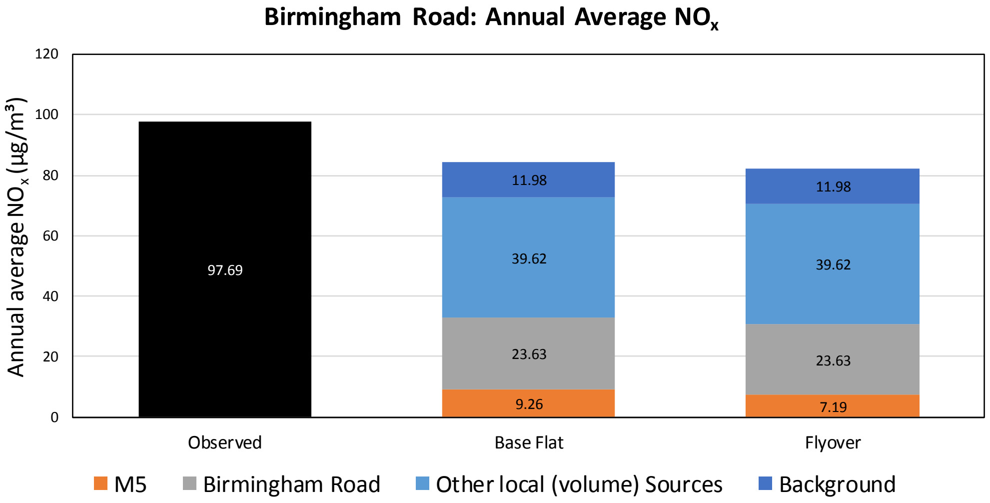
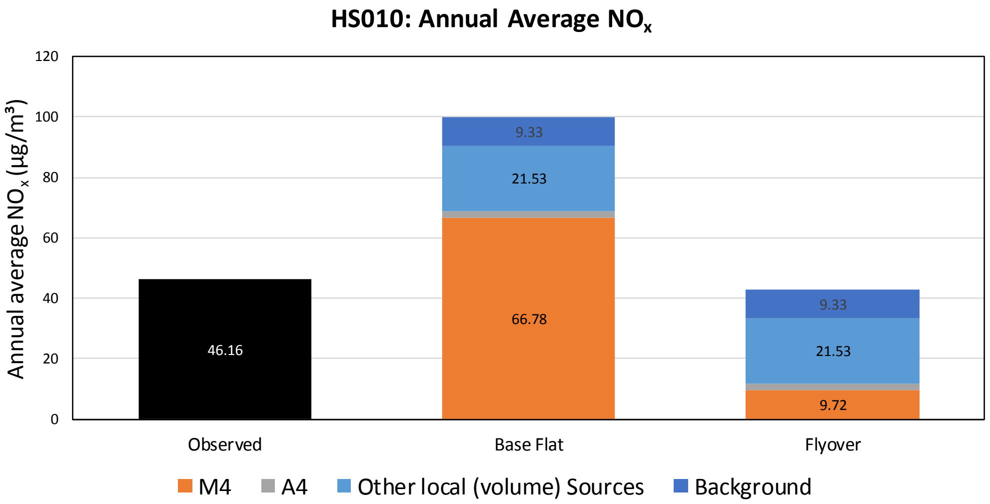


Figure 15 – Annual average diffusion tube results showing +/- 25% error lines

a) Birmingham Road, M5



b) Boston Manor Park, HS010, M4



c) Chiswick flyover, HS5, M4 / A4

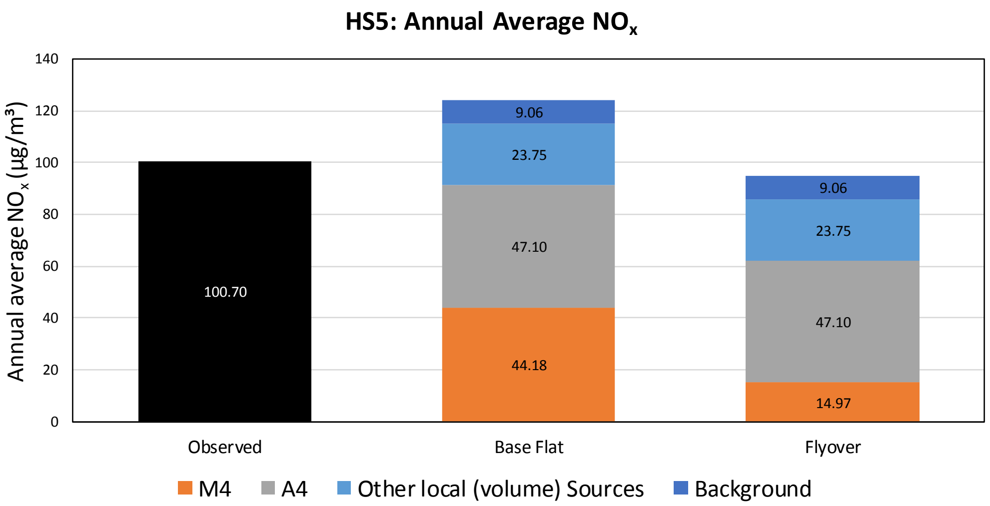
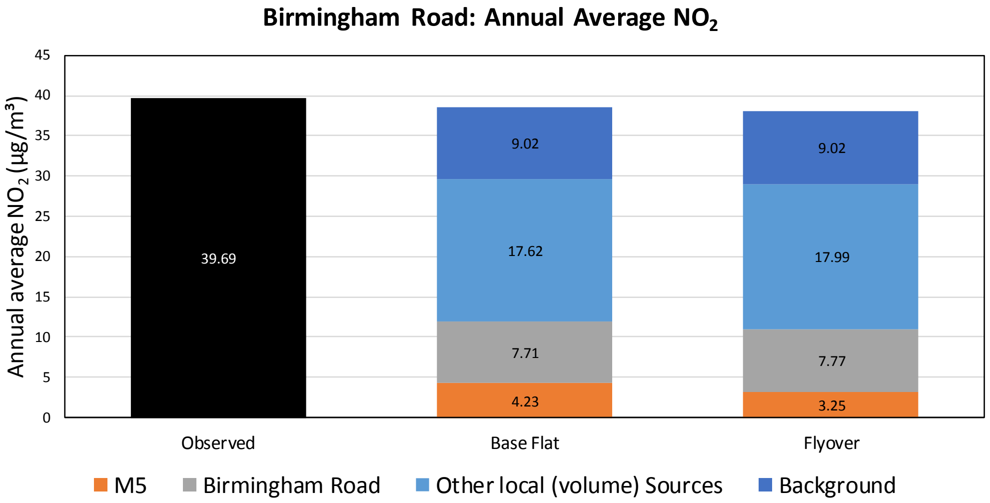
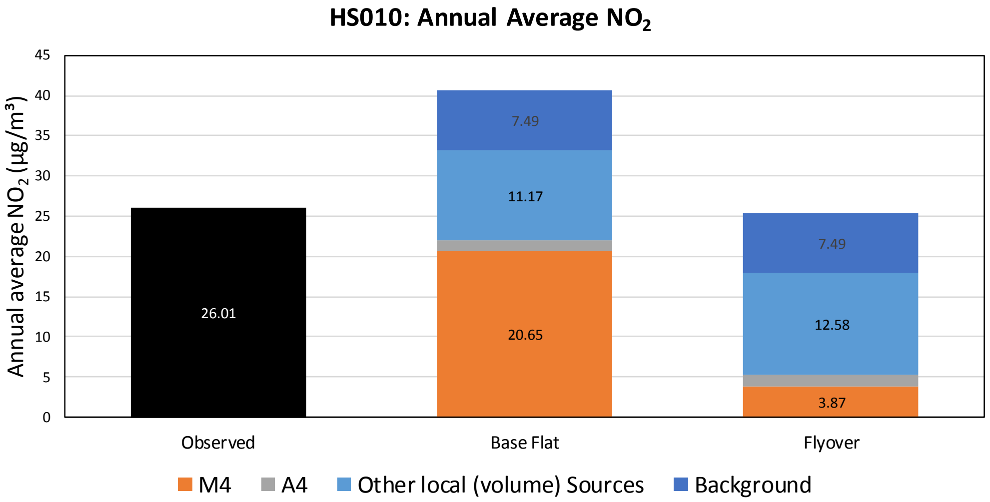


Figure 16 – NOx source apportionment plots for the monitors located adjacent to the motorways, with the elevated road section modelled as either a ground level source (‘Base Flat’) or a flyover

a) Birmingham Road, M5



b) Boston Manor Park, HS010, M4



c) Chiswick flyover, HS5, M4 / A4

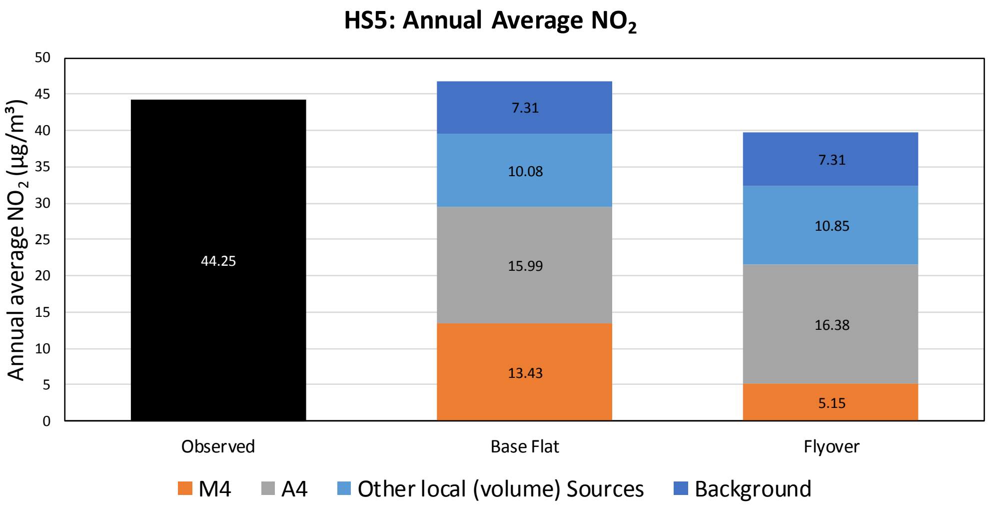


Figure 17 – NO2 indicative ‘source apportionment’ plots for the monitors located adjacent to the motorways, with the elevated road section modelled as either a ground level source or a flyover

Having demonstrated that the model is able to predict the measured concentration in the vicinity of the flyover accurately, 'indicative' source apportionment can be used to indicate the dominant sources of pollution in this location. Figure 18 shows the results of this analysis: period-average modelled and measured concentrations are shown on the left-hand vertical axis, and the perpendicular distance from the M5 is shown on the right-hand vertical axis; the reference monitor concentration ('Oldbury Bham Rd') is shown alongside the diffusion tube measurements. Concentrations are shown left to right with increasing distance from the M5. This figure shows the proportion of the NO2 concentration resulting from the motorway, which is smaller than the contribution from Birmingham Road at all locations, even at the diffusion tubes less than 50 m from the motorway. The contribution from the motorway decreases with distance, as expected. Note that site C6E is 50 m off Birmingham Road, on Stone Street.

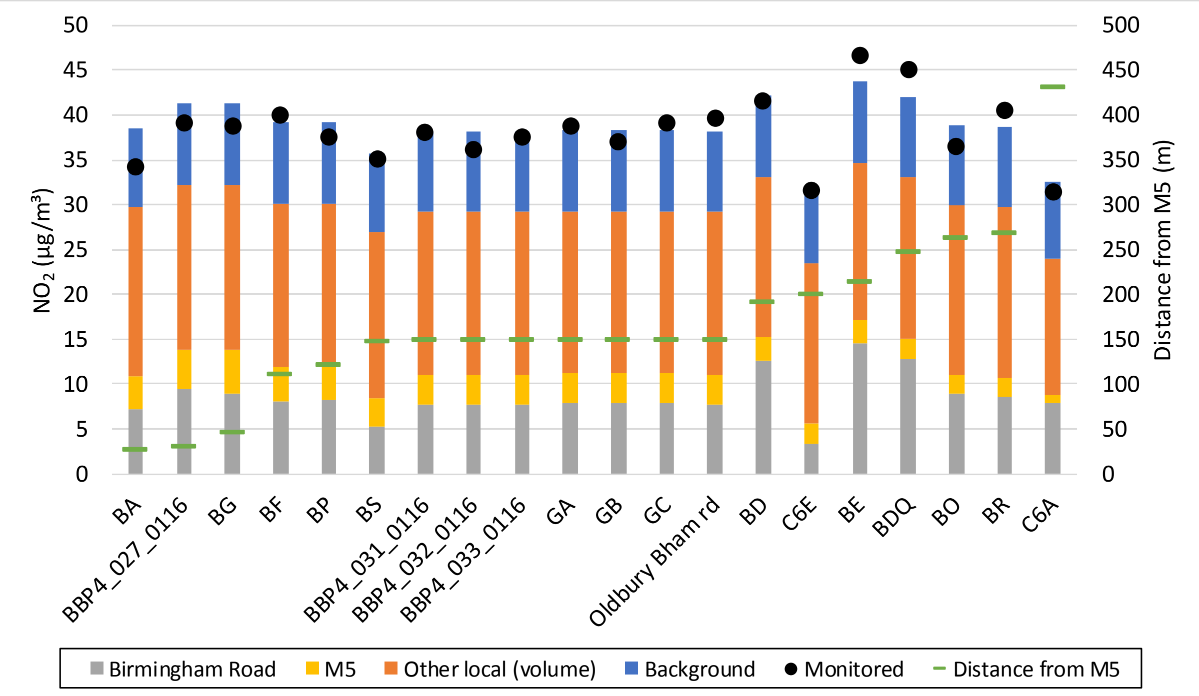


Figure 18 – NO2 indicative 'source apportionment' plots for the diffusion tube locations, modelling the M5 as a flyover

Figure 19 shows the NOx and NO2 scatter plots for both London Hounslow sites HS5 and HS10, with Tables 11 to 14 presenting the corresponding statistics for NOx and NO2. At this location, there is a much stronger influence of road elevation on measured concentrations due to the proximity of the monitoring sites to the elevated sections of road. Measured concentrations are much lower at HS10 compared to HS5 because of the additional road major sources located in the vicinity of HS5 (i.e. the A4).

Annual average NOx and NO2 concentrations are significantly over-predicted when the elevated sections of road are modelled at ground level (116% and 67% at HS10 and 23% and 18% at HS5 for NOx and NO2 respectively). The over-prediction is greater at HS10 compared to HS5 because the HS10 monitor is located closer to the motorway. Model performance is good when the elevated sections of road are modelled as flyovers, with low values of fractional bias and high values of correlation and number of points within a factor of two of the observed for both NOx and NO2. It is likely that the high values (i.e. demonstration of good performance) for correlation and Fac2 is due in part because of the use of hourly traffic data for the M4 sections, downloaded from WEBTRIS.

Figure 16 b) and c) presents the London Hounslow source apportionment results for annual average NOx in terms of the concentration arising from: the explicitly modelled section of the M4; the other local (volume) sources representing urban emissions from surrounding areas (and some far-field contribution of the M4); A4; and background concentrations. Figure 17 a) shows the corresponding 'indicative' plot for NO2. These source apportionment plots demonstrate the importance of accounting for elevation when modelling motorways. Specifically, at HS10, the model predicts the motorway contribution to be over 20 $\mu g/m^3$ NO2 when modelled at ground level, but less than 4 $\mu g/m^3$ when modelled as an elevated section.

The next stage of the evaluation is to assess model performance using wind-direction dependent source apportionment analyses. Theses analyses are shown in Figures 20 a) and 21 a) for NOx and indicative NO2 respectively for the Birmingham reference monitor; these results are not discussed further here, as the motorway elevation does not impact significantly at this site. The more interesting results relating to the London sites are shown in Figures 20 b), c) and 21 b), c) for HS10 and HS5. These plots demonstrate that the model is able to replicate the variation of concentrations with wind direction; this assists in understanding how the motorway and other sources influences the recorded concentrations. Specific points of interest include:

- As suggested by the plots shown in Figure 4, the highest impact from an elevated motorway on near-road ground level receptors is when the wind advects along the road rather than across it. Figures 20 b) and 21 b) demonstrate this: the motorway is aligned at an angle of approximately 110 degrees, and the high concentrations from the elevated section are when the wind advects in the range 70 to 160 degrees and 260 to 330 degrees. The contribution from the elevated road to the monitor when the wind advects directly across the road towards the monitor (an angle of 200 degrees) is minimal; this is because the plume is elevated above the monitor in the vicinity of the road.

- The A4 strongly influences concentrations at HS5 for all wind directions (Figures 20 c) and 21 c)). For an open road, when the wind advects from the monitor to the road, there is minimal contribution from the road to the concentrations recorded by the monitor. However, in the case of HS5, the buildings adjacent to the monitor form an asymmetric street canyon, leading to reverse flow in the vicinity of the monitor for wind directions in the range 120 to 200 degrees. This leads to the A4 emissions contributing to concentrations at the monitor for all wind directions, in contrast to the M4, which only contributes when the wind advects from the road to the monitor. This highlights one advantage of elevating roads in urban areas: the impact of ground level buildings on dispersion from elevated roads is minimal, unless the buildings are very tall and form canyons higher than the elevated road sections.

Hounslow

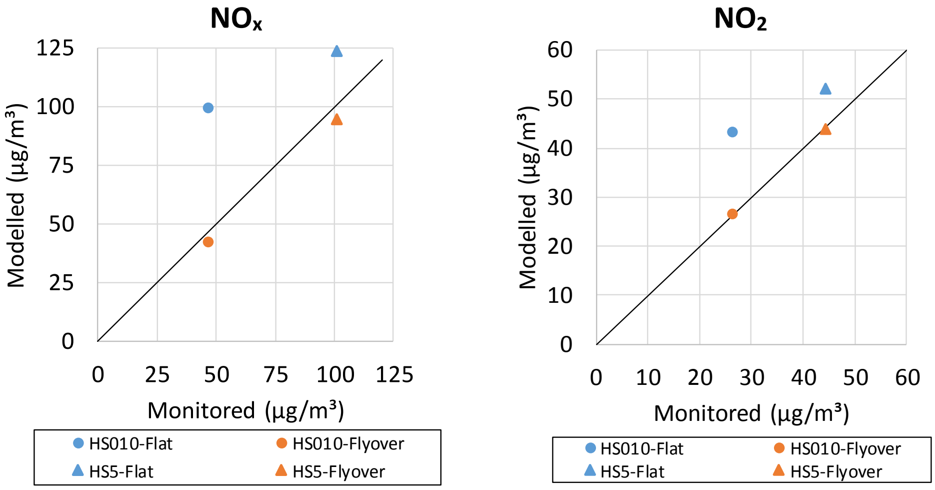


Figure 19 – NO_x and NO_2 annual average scatter plots for Hounslow reference monitors (2019)

Table 11 – Statistics from modelling M4 site Boston Manor Park, Hounslow, HS010 (NOx)

NO_x (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Flat	46.2	99.8	2.443	0.344	0.362	0.735
Flyover	46.2	42.8	1.285	0.557	0.708	-0.076

Table 12 – Statistics from modelling M4 site Boston Manor Park, Hounslow, HS010 (NO2)

NO2 (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Flat	26.0	43.5	0.872	0.496	0.584	0.503
Flyover	26.0	26.7	0.360	0.646	0.802	0.026

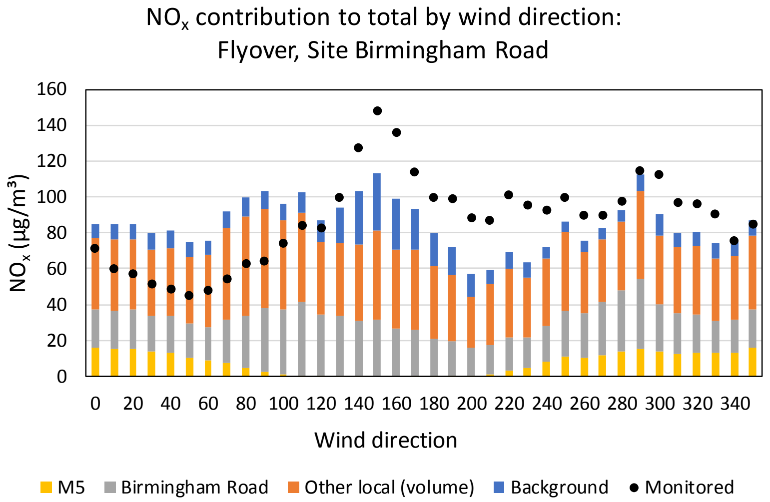
Table 13 – Statistics from modelling M4 /A4 Chiswick flyover site, HS5 (NOx)

NO_x (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Flat	100.7	124.1	0.617	0.662	0.802	0.208
Flyover	100.7	94.9	0.426	0.694	0.871	-0.059

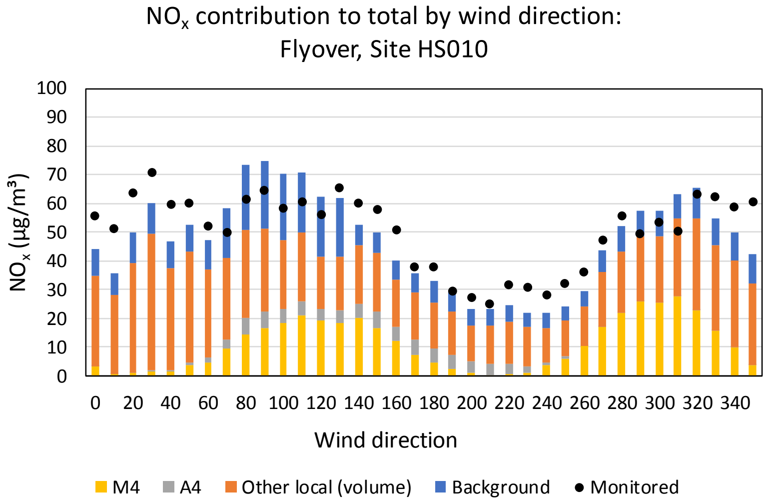
Table 14 – Statistics from modelling M4 /A4 Chiswick flyover site, HS5 (NO2)

NO2 (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Flat	44.3	52.1	0.306	0.677	0.868	0.163
Flyover	44.3	43.8	0.194	0.709	0.903	-0.010

a) Birmingham Road, M5



b) Boston Manor Park, HS010, M4



c) Chiswick flyover, HS5, M4 / A4

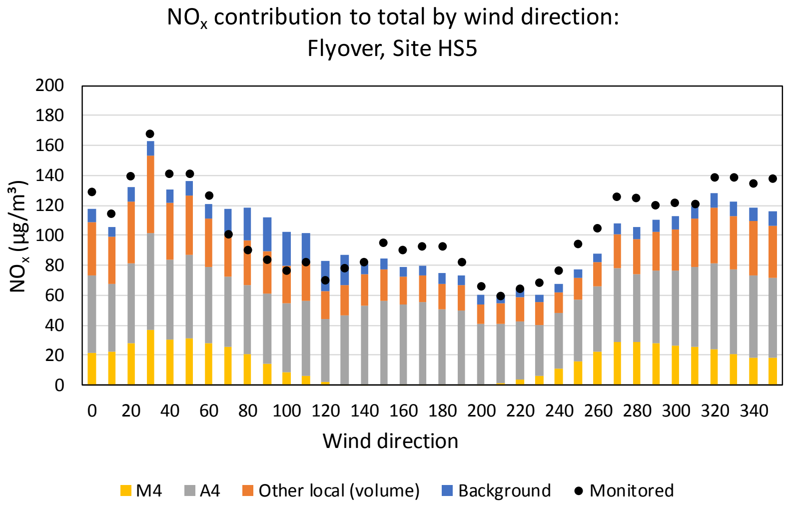
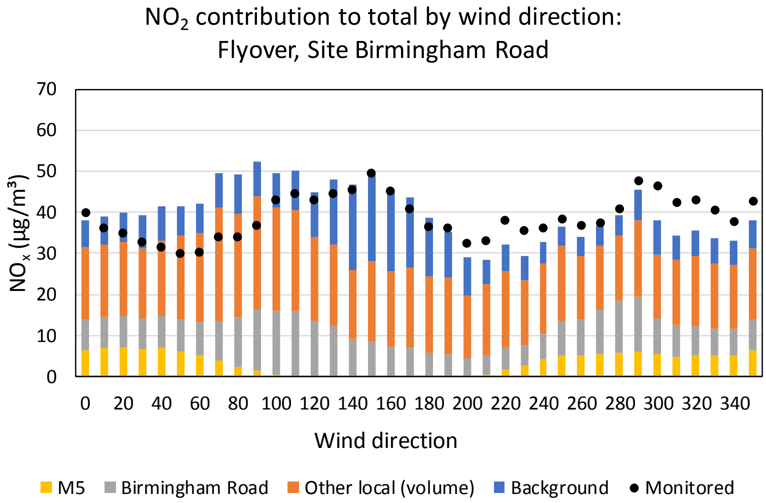
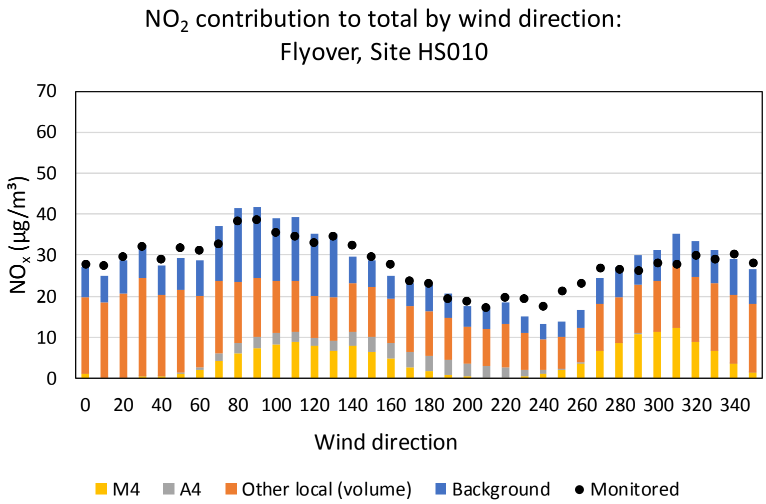


Figure 20 – NOx source apportionment plots by wind direction for the monitors located adjacent to the motorways, with the elevated road section modelled as a flyover

a) Birmingham Road, M5



b) Boston Manor Park, HS010, M4



c) Chiswick flyover, HS5, M4 / A4

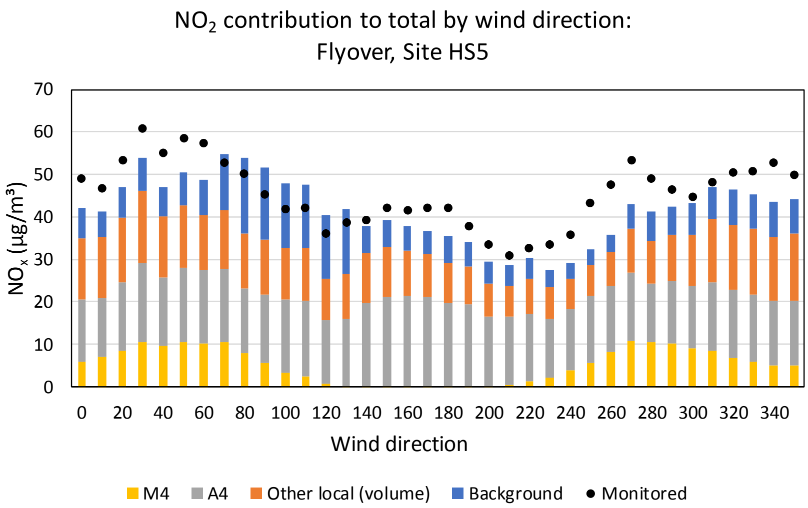


Figure 21 – NO2 indicative 'source apportionment' plots by wind direction for the monitors located adjacent to the motorways, with the elevated road section modelled as a flyover

The analyses above show that the model demonstrates good performance when predicting concentrations in the vicinity of elevated roads. This gives confidence in the use of the model to assess the spatial impact of pollutant dispersion from flyover-type elevated roads. Figures 22 and 23 shows NOx and NO2 contour plots for the Birmingham study respectively, with output height of 1.5 m. For each figure, the upper plot shows the total concentrations, and the lower plots show the impact of each explicitly modelled road separately. For NO2, single source calculations are, like the NO2 source apportionment discussed above, ‘indicative’ as it is not possible to perform direct source apportionment due to the non-linear influence of NOx chemistry.

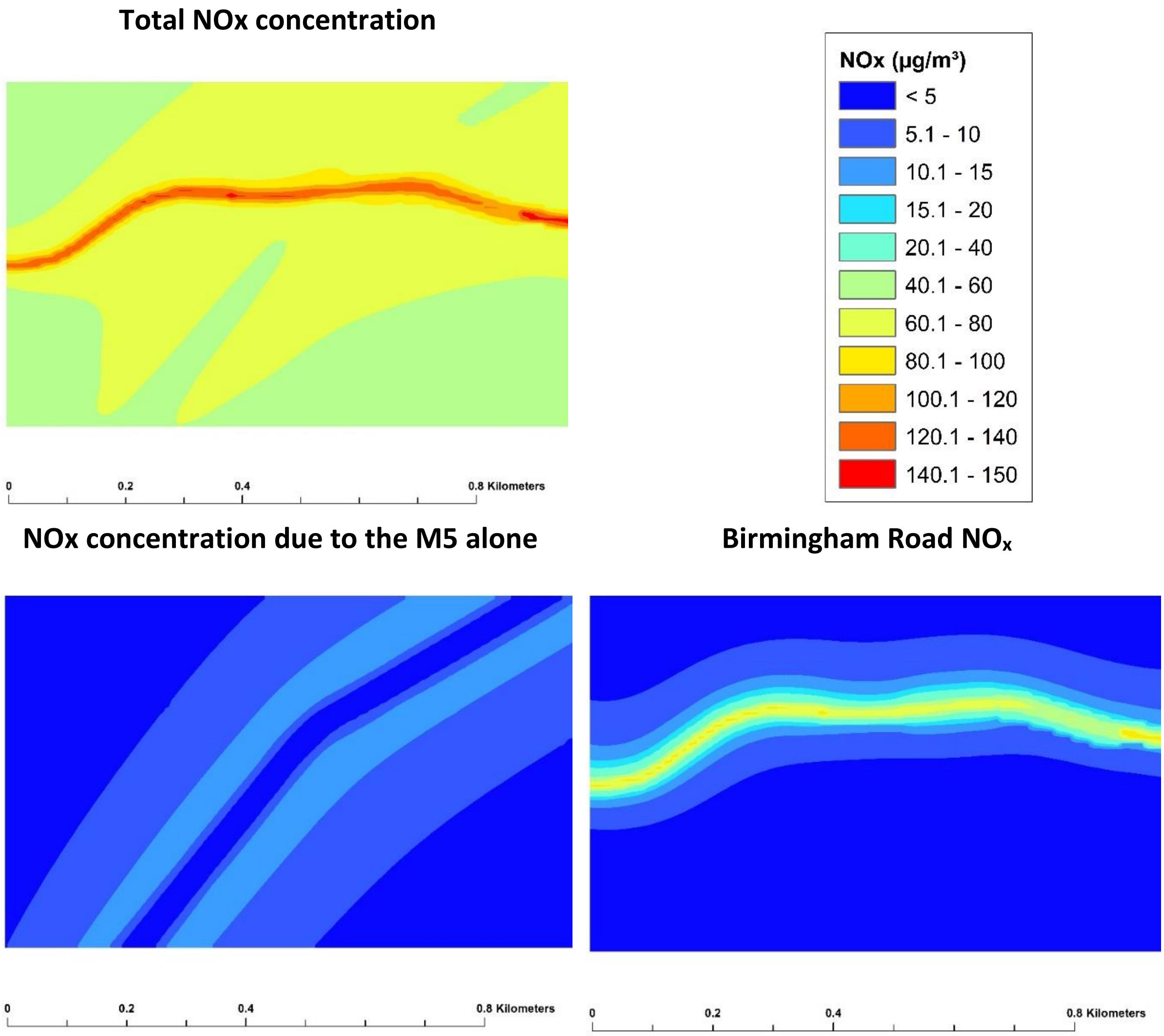


Figure 22 – Annual average contour plots of total NO_x and contributions from the M5 and Birmingham Road, all at a height of 1.5 m, at the Birmingham Road site

Of note in these plots is the strong signature of the local ground-based road and the relatively small signature from the elevated section. The maximum impact for the ground-based road is in the road centreline, whereas the maximum signature for the elevated road is two parallel concentrations peaks either side of the road.

Figures 24 and 25 show the corresponding plots for the London study site. These plots again show the relatively low contribution of the elevated road to total concentrations at 1.5 m.

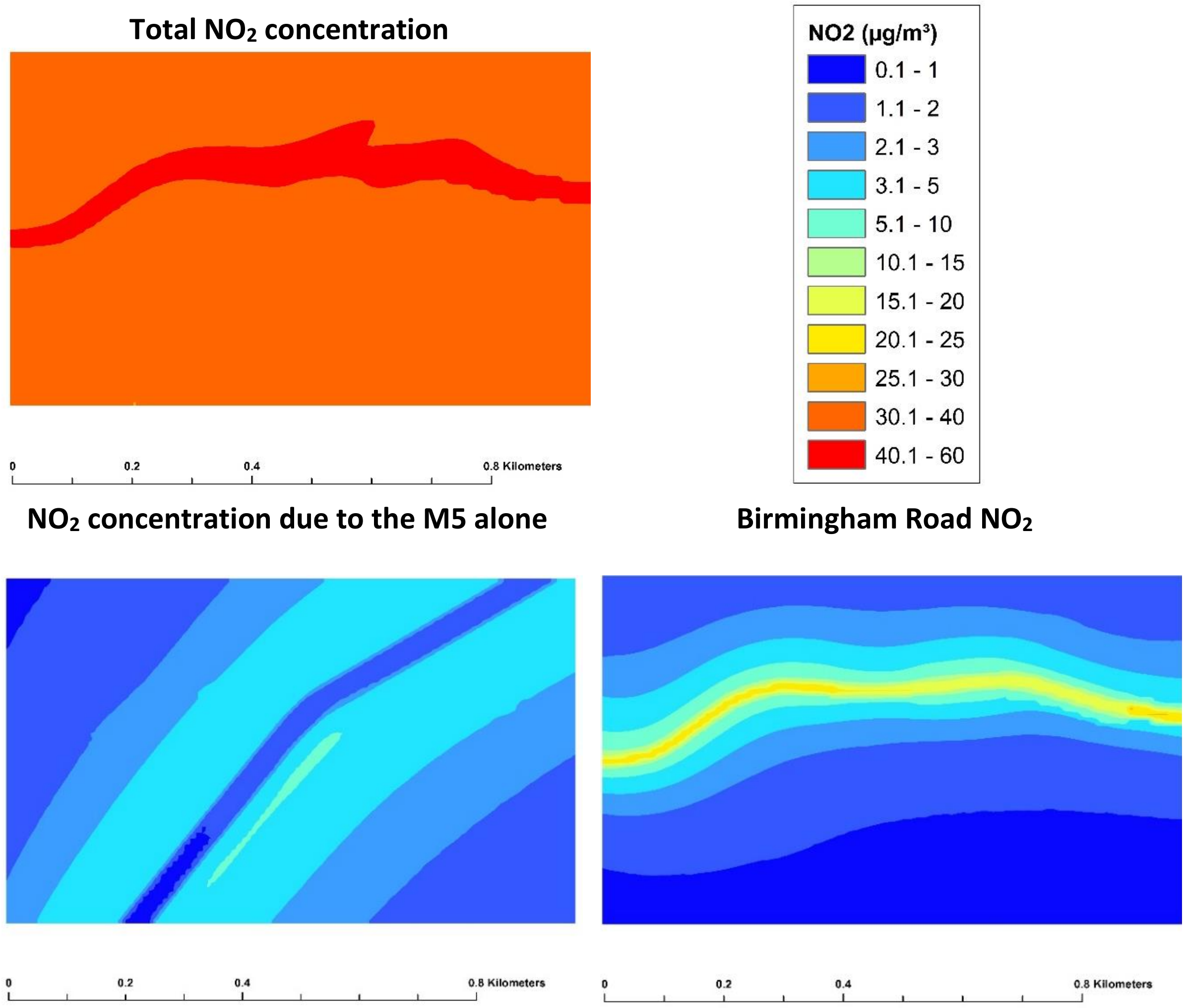


Figure 23 – Annual average contour plots of total NO_2 and contributions from the M5 and Birmingham Road, all at a height of 1.5 m, at the Birmingham Road site

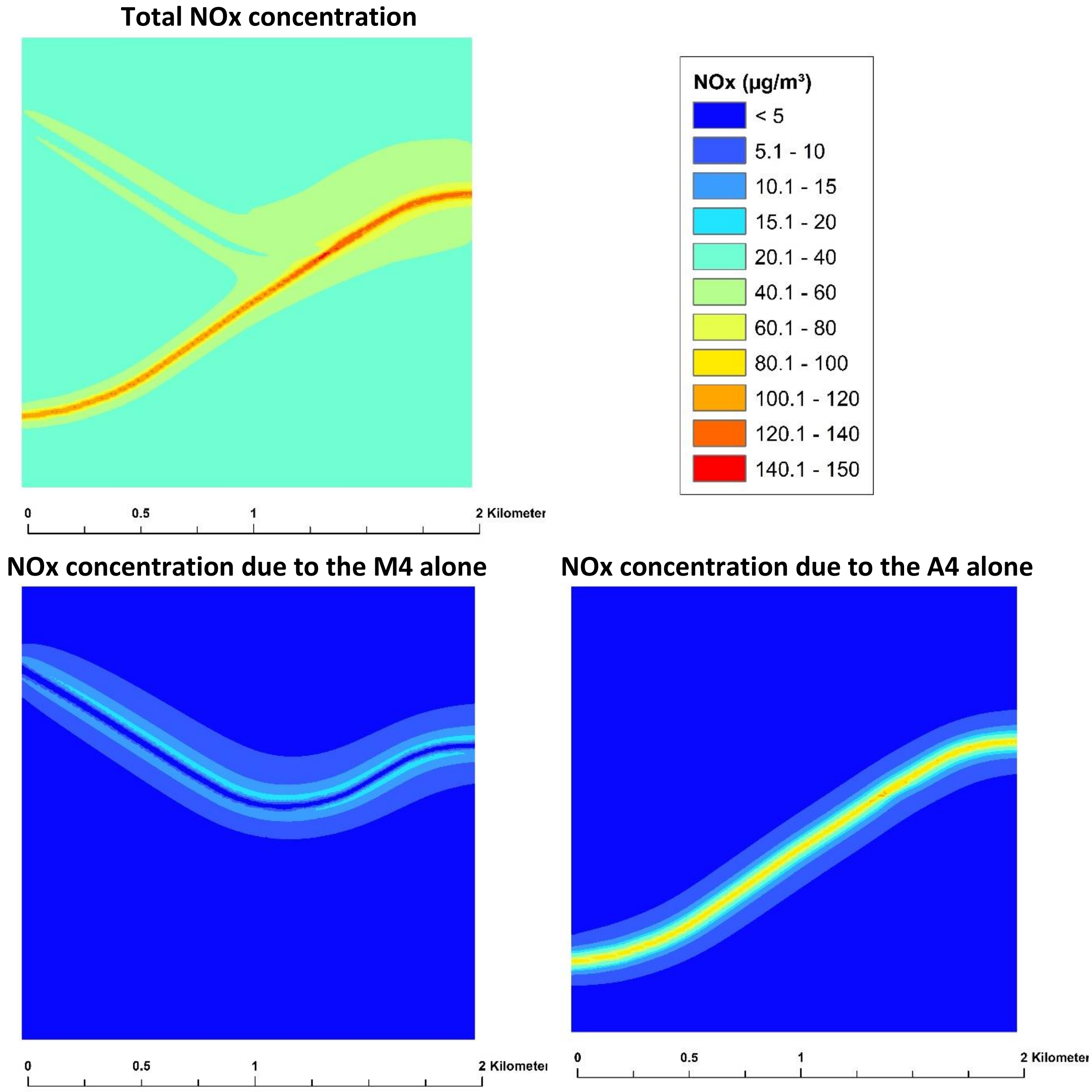


Figure 24 – Annual average contour plots of total NO_x and contributions from the M4 and A4, all at a height of 1.5 m, at the London, Hounslow site.

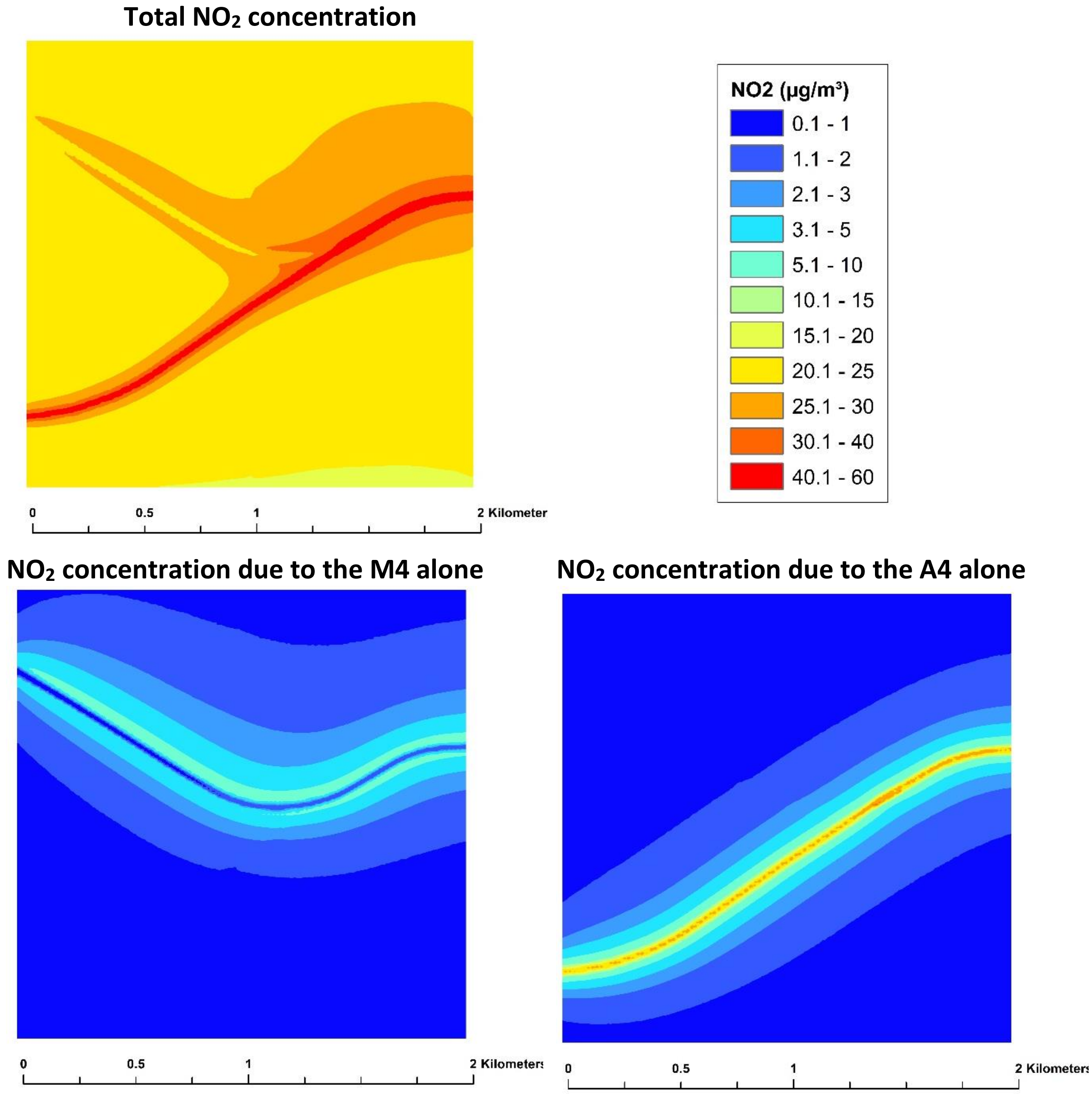


Figure 25 – Annual average contour plots of total NO_2 and contributions from the M4 and A4, all at a height of 1.5 m, at the London, Hounslow site.

5.2 Measurement analysis and model evaluation for non-UK site

This section describes the measurement analyses and model evaluation that has been undertaken using the data from the Poppel *et al.* (2012) Antwerp measurement campaign. This dataset is useful because pollutant concentrations have been recorded at receptor locations on both sides of a ground level section and an elevated section of a busy road in the centre of Antwerp. However, there are some aspects of the study that make the dataset difficult to use directly, specifically: the measurements recorded in the vicinity of the ground level and elevated roads were for a different time period; and the receptors were placed at different distances from the road in each case.

Pollutant concentrations are a result of many factors including: local emissions, meteorology, chemistry, source term description, urban morphology, source-to-receptor distance and long-range pollutant transport. When comparing two or more concentration datasets, it is important to ensure that a 'like-for-like' comparison is being undertaken. **Table 15** summarises the confounding factors that have been considered when analysing the Antwerp dataset.

Table 15 – Summary of approach to accounting for confounding factors for the Antwerp dataset

Confounding factor	Explanation of why this factor needs to be considered	How this factor is accounted for in the Antwerp dataset measurement analyses
Variation in traffic flow	Pollutant emissions have a near-linear impact on pollutant concentrations. Each section of road has a different traffic flow.	The concentrations must be normalised by the traffic flow on an hourly basis, to give a 'per vehicle' impact of the road.
Different time periods	Atmospheric conditions impact on dispersion, and different periods have different distributions of atmospheric conditions.	Pollutant concentrations have been binned according to dominant meteorological parameters: wind speed and atmospheric stability.
Different source to receptor differences	There is a strong near-road concentration gradient.	Use modelling results from a ground-level model configuration to adjust the ground level receptor concentrations to be at the same distances from the road as the receptors close to the elevated section.
Long-range pollutant transport	The influence of long-range pollutant transport is different for different time periods.	Use the upwind receptor to represent long-range pollutant transport.

The results of the measurement analyses are presented in Section 5.2.1.

Some modelling work was necessary in order to proceed with the measurement analyses, specifically, adjusting concentrations to allow for the distance to the carriageway edge. This modelling work was extended to generate results for both the elevated and ground level monitors; results from the modelling work are presented in Section 5.2.2.

5.2.1 Measurement analysis

The first part of the results section analyses the measurements using NO_x concentration polar plots. Polar plots are a useful graphical tool for visually assessing the influence of wind speed and direction on concentrations; NOx (rather than NO2) concentrations are presented with the aim of identifying the influence of elevation on dispersion processes, without the complications of chemistry. Figure 26 presents a polar plot of mean NO_x concentrations at both the ground level monitoring sites and Figure 27 shows measurements at both the elevated monitoring sites; all plots are presented using the same colour scale. In these plots, concentration magnitude is indicated by colour, wind speed is on the radial axis, and wind direction variation shown clockwise from north. It should be noted that the minimum number of points allowed in the wind speed and direction bin is three, chosen due to the measurements spanning over an approximate one-month period.

The influence of the highway on the concentrations recorded at the ground level monitors is clear in terms of the wind sectors that show high concentrations. 'Ground A' high concentrations range from the south clockwise to the north west, whereas 'Ground B' has high concentrations from the north west clockwise to the east; it is not possible to assess concentration levels in the south east sector due to the lack of cases when wind prevails from that direction. Comparing the ground level receptors, the 'Ground A' site to the north east of the highway records lower NO_x concentrations as it is situated much further away from the road than the 'Ground B' receptor to the south west (102 m compared to 29 m).

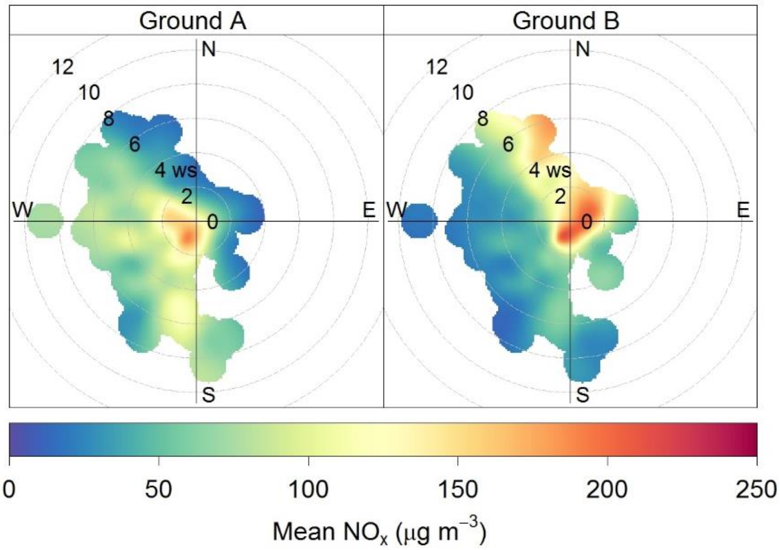


Figure 26 – Polar plots of mean NO_x at the ground level receptors to the north east ('Ground A', left) and south west ('Ground B', right) of the highway; minimum number of points allowed in the wind speed and direction bin is three.

The pollutant concentrations recorded adjacent to the elevated road receptors are much lower. Further, it is much more difficult to distinguish a clear wind sector influence. This is likely in part because the road is elevated but also because these plots show *total* concentrations so the influence of adjacent ground-based roads are indistinguishable from concentrations that are a direct result of dispersion of emissions from the highway. **In subsequent analyses, the impact**

of adjacent roads is removed by considering *road increments* rather than total concentrations.

The 'Elevated A' receptor has fairly uniform concentrations across all wind directions although concentrations corresponding to southeasterly directions are higher; this is likely related to the longer-range impact of the road, which is aligned in that direction. The 'Elevated B' receptor shows a clear indication of the presence of the road, with higher concentrations between the north west clockwise to south east.

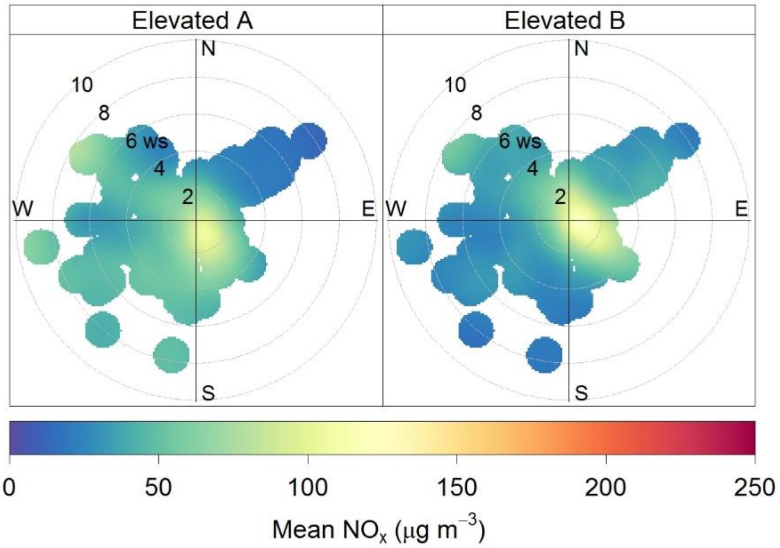


Figure 27 – Polar plots of mean NO_x at the receptors close to the elevated section to the north east ('Elevated A', left) and south west ('Elevated B', right) of the highway; minimum number of points allowed in the wind speed and direction bin is three.

Analyses accounting for confounding factors

The concentrations in the dataset have been processed to remove the influence of confounding factors by:

- Calculating road concentration increments by subtracting the NO_x concentration at the upwind receptor from the downwind receptor (note that no other roads lie between the receptor and the highway for any of the monitors);
- Normalising the road concentration increments by using the number of vehicles that travel on each portion (ground or elevated) every half hour, resulting in a concentration per vehicle;
- Binning concentrations according to meteorological parameters: (1) wind speed and (2) stability (H/L_{MO}) in order to remove the influence of seasonal and daily meteorology on the concentrations (different for the ground and elevated measurement campaigns); and
- Adjusting the ground level receptor concentrations to account for the difference in the road-to-carriageway distances ('Ground A' is moved from 120 m to 102 m, and 'Ground B' is moved from 29 m to 60 m). This was done by configuring ADMS-Roads to present the ground level receptors and roads, and including two additional receptors located at the 'elevated section' distances from the road. Hourly ratios of NOx concentration decay were calculated and applied to the 120 m and 29 m normalised road increment concentrations. Full details of the model configuration is given in Section 5.2.2.

Figures 28 to 30 present boxplots binned by wind speed for the Ground, Elevated and Ground adjusted datasets respectively. Each figure includes the number of values in each bin and the 25th and 75th inter-quartile (IQR) ranges are shown; outliers are not displayed. The expected trend of decreasing measured concentrations with increasing wind speed is clearly shown in these plots, with the exception of the highest wind speed bin (> 8 m/s), which shows a slightly higher concentration; this anomalous result for the highest wind speed may be unrepresentative because of the relatively low number of values included within this bin.

Figures 29 and 30 demonstrate the relatively lower concentrations recorded by the receptors adjacent to the elevated road compared to the ground level monitors. Median values for each wind speed category shown in these plots are summarised in Table 16, and the last row in the table gives the ratio of the concentration at the elevated road receptors compared to the ground level receptors. **The elevated road concentrations are always lower than the ground level concentrations, with the ratio between binned concentrations ranging from 0.50 to 0.85.** The general trend is that the difference between the elevated road and ground level road concentrations decreases with an increase in wind speed; this is likely related to an increase in mixing for higher wind speed, reducing the influence of the location of the source on downwind concentrations.

Figures 49 to 51 (in the Appendix) and Table 17 present the results of the corresponding analyses by atmospheric stability, categorised by H/L_{MO}. Atmospheric stability has been binned according to stable ($H/L_{MO} > 1$), neutral ($-1 \leq H/L_{MO} < 1$) and convective conditions ($H/L_{MO} < -1$). As expected, the results show that measured concentrations are higher in stable meteorological conditions; concentrations for neutral and convective conditions appear similar. **The elevated road concentrations are always lower than the ground level road concentrations, with the ratio between binned concentrations ranging from 0.51 to 0.68.** These results have also been calculated for individual receptors, and are presented in Tables 22 to 25 in the Appendix.

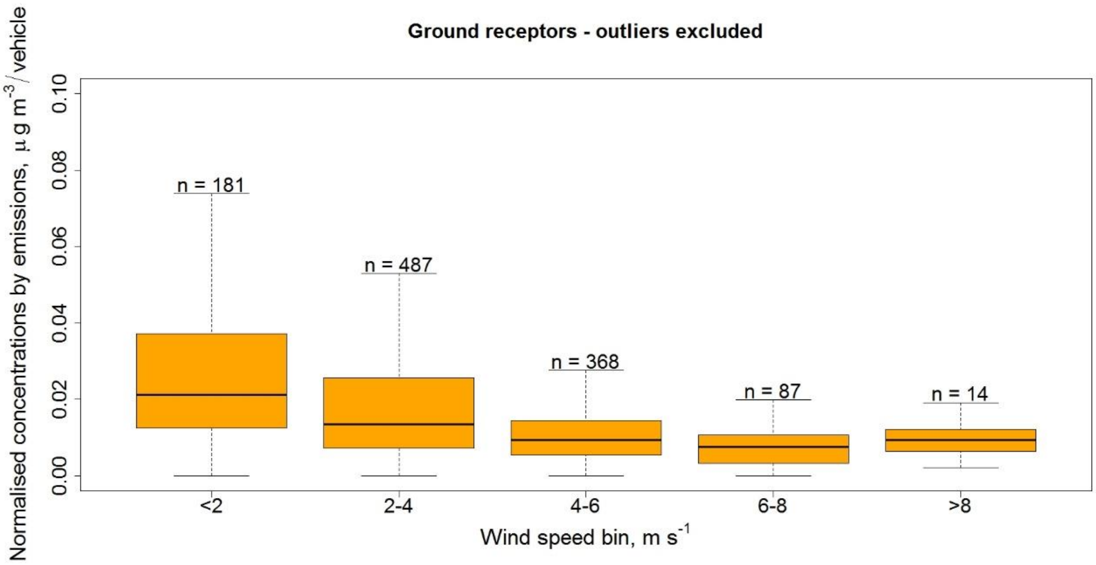


Figure 28 – Box plots of road increment concentrations normalised by emissions, categorised according to wind speed for ground receptors; 25th and 75th IQR and number of values in each bin shown

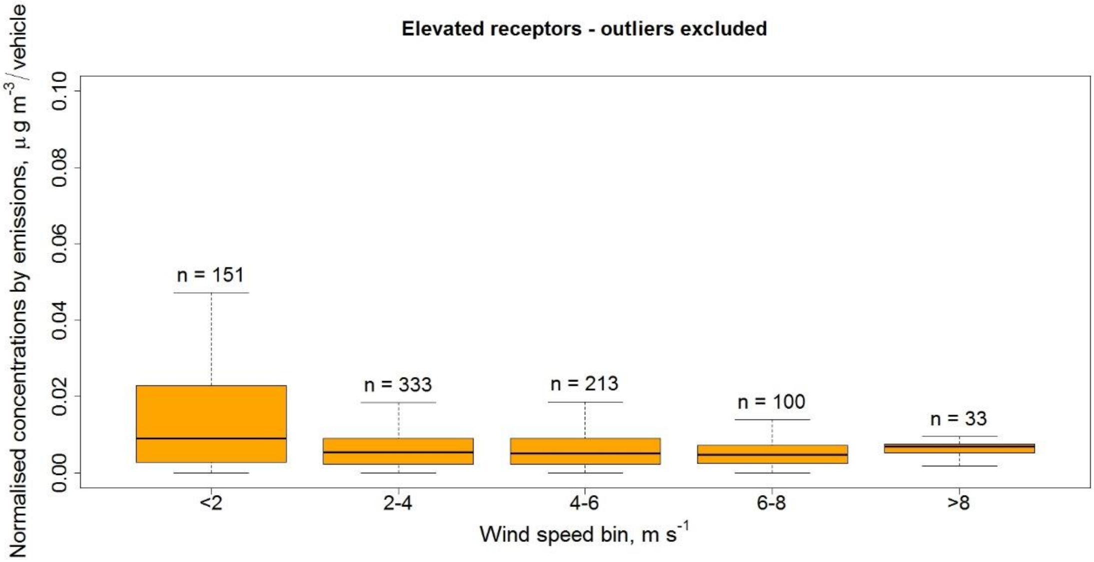


Figure 29 – Box plots of road increment concentrations normalised by traffic flow, categorised according to wind speed for the receptors close to the elevated section; 25th and 75th IQR and number of values in each bin shown

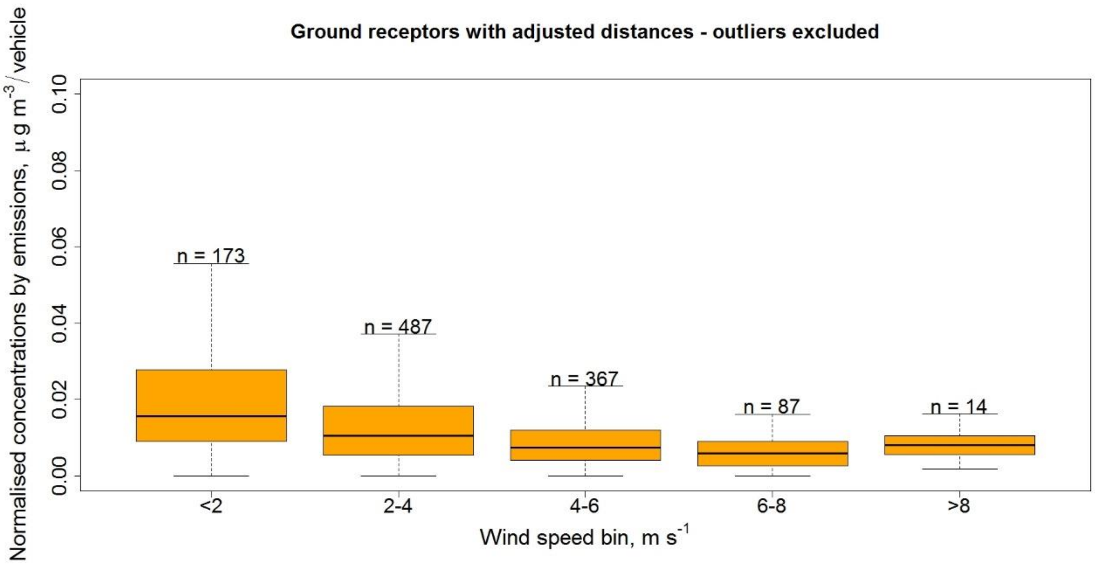


Figure 30 – Box plots of road increment concentrations normalised by traffic flow, categorised according to wind speed for ground level receptors adjusted to be the same distance from the road as the receptors close to the elevated section; 25th and 75th IQR and number of values in each bin shown

Table 16 – Median NOx road increment concentrations normalised by traffic flow (µg/m³/vehicle) categorised according to wind speed for the ground, elevated and adjusted ground receptors

Dataset	Wind speed (m/s)				
	<2	2 to 4	4 to 6	6 to 8	>8
Ground	0.0211	0.0134	0.0092	0.0074	0.0093
Elevated	0.0090	0.0053	0.0050	0.0047	0.0068
Ground adjusted	0.0156	0.0105	0.0073	0.0059	0.0080
Elevated / Ground adjusted	**0.58**	**0.50**	**0.68**	**0.80**	**0.85**

Table 17 – Median NOx road increment concentrations normalised by traffic flow (µg/m³/vehicle), categorised according to stability (H/L_{MO}) for the ground, elevated and adjusted ground receptors.

Dataset	Stability H/L_{MO} (-)		
	< -1 Convective	Between -1 and 1 Neutral	> +1 Stable
Ground	0.0100	0.0102	0.0154
Elevated	0.0038	0.0054	0.0067
Ground adjusted	0.0075	0.0080	0.0111
Elevated / Ground adjusted	**0.51**	**0.68**	**0.60**

5.2.2 Model evaluation

There are two separate measurement periods, so the model evaluation results have been split into these two periods: ‘Ground’ and ‘Elevated’ results. Subsectors of wind directions are considered for each receptor. Figure 31 presents a schematic diagram of both the flyover and ground level sections of road. Taking each of the half-hourly data records in turn, the wind direction allows definition of an upwind receptor (used to quantify background concentrations) and a downwind receptor which can be used to calculate the road concentration increment.

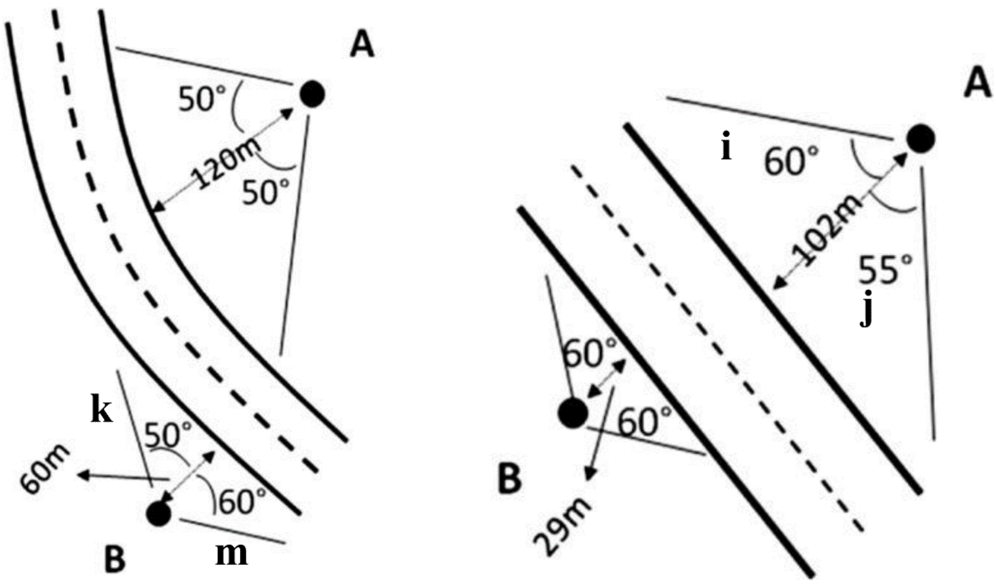


Figure 31 – Schematic of road layout for the flyover (left) and ground (right) level portions of the road (from Poppel *et al.*, 2012).

The ground portion of the road aligns north west to south east (141 degrees). Figure 31 shows that the Ground A receptor is considered as downwind when wind directions fall between 171 and 286 degrees; Ground B receptor is downwind when the wind direction is between 351 and 111 degrees. All other wind directions are disregarded and removed from the dataset.

The elevated portion of the road segment differs in comparison to the ground road as the flyover bends slightly (between around 124 and 150 degrees). For receptor Elevated A the road alignment is taken as 330 degrees and for Elevated B, the alignment is taken as 124 degrees. The Elevated A receptor is considered as downwind when wind directions fall between 190 and 290 degrees; Elevated B receptor is downwind when the wind direction is between 344 and 94 degrees. All other wind directions are disregarded and removed from the dataset.

Evaluating how well the model has performed in comparison to the observed data involves the comparison of a range of statistics. Four model configurations have been evaluated:

- Receptors in the vicinity of the **ground level section** of road (Ground A and Ground B), with the elevated section of the road modelled at ground level;
- Receptors in the vicinity of the **ground level section** of road (Ground A and Ground B), with the elevated section of the road modelled as a flyover;
- Receptors in the vicinity of the **elevated section** of road (Elevated A and Elevated B), with the elevated section of the road modelled at ground level; and
- Receptors in the vicinity of the **elevated section** of road (Elevated A and Elevated B), with the elevated section of the road modelled as a flyover.

Figure 32 shows the mean NO_x scatter plot for the both receptors adjacent to the ground level road; the mean concentrations predicted by the model when the flyover section of the road is modelled as elevated are graphically indistinguishable from the results when the flyover section is modelled at ground level, because the ground level receptors are approximately 0.5 km from the start of the elevated section. Statistics for the ground level model set up are presented in Table 18; the number of valid data points is also presented in this table. All statistics are calculated using the 30-minute values.

Model performance is very good at the Ground A receptor (102 m away from the highway) with a correlation exceeding 0.72 and over 88% of the points within a factor of two of the observed. Although correlation and number of points within a factor of two of the observed are still high for the Ground B receptor (0.63 and 76% respectively), the model over-predicts average NOx by over 50%. The most likely explanation for this model over-prediction is an over-prediction of the background concentrations from the use of the Ground A receptor due to its proximity to another road to the north east of the monitor i.e. it cannot be considered a reliable ‘background’ site; the other three monitors appear to be in locations less influenced by adjacent roads.

Figure 33 shows the mean NO_x scatter plot for the elevated portion of the road, with the road modelled as elevated and at ground level; Table 19 presents the corresponding statistics. When the flyover is modelled with elevation, the model demonstrates much better performance in terms of both the period average concentration and statistics compared to when the road is modelled at ground level; the correlation and number of points within a factor of two of the observed are very high when the road is modelled as elevated (0.88 / 0.90 and 91% / 91% at

Elevated A / Elevated B). When the elevated section of road is modelled at ground level, the model over-predicts concentrations by 45% at the Elevated A receptor and by over 100% at the Elevated B receptor. The difference in modelled concentrations is more significant at the Elevated B receptor due to this monitor being situated closer to the road i.e. the need for a precise specification of source term geometry reduces with distance from the road.

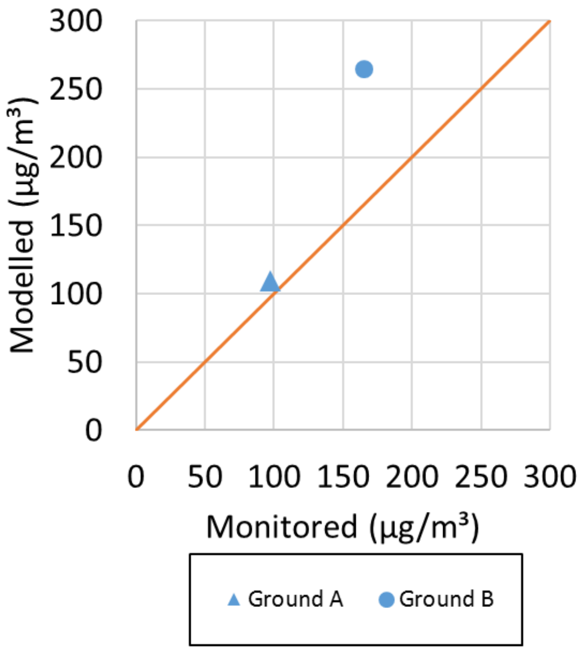


Figure 32 – NO_x annual average scatter plots for ground reference monitors

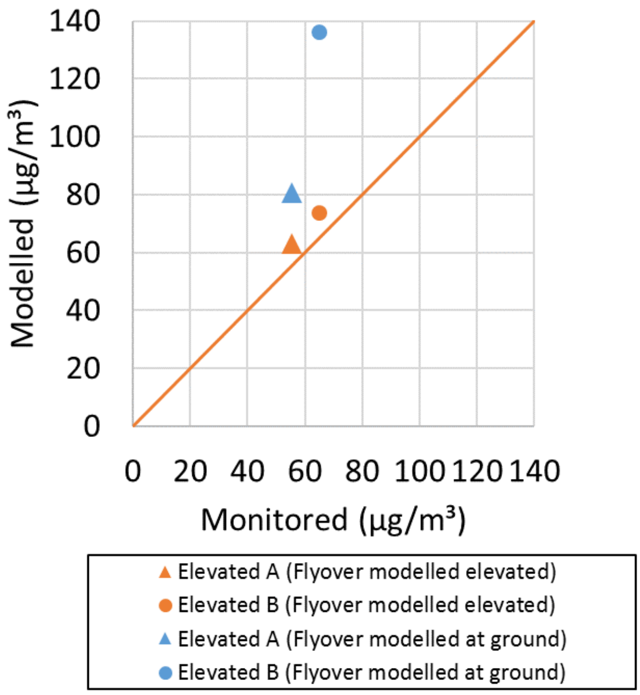


Figure 33 – NO_x annual average scatter plots for elevated reference monitors, showing modelling results with flyover effects included and omitted

Table 18 – Statistics from modelling the ground level portion of the road, Antwerp, Belgium (NO_x)

Receptor	Valid data points	Monitored mean (µg/m³)	Modelled Mean (µg/m³)	NMSE	Correlation	Fac2	fb
Ground A (Flyover elevated)	999	97.2	109.3	0.303	0.724	0.888	0.117
Ground A (Flyover at ground level)	999	97.2	109.7	0.304	0.723	0.887	0.120
Ground B (Flyover elevated)	160	165.0	264.6	0.600	0.625	0.763	0.464
Ground B (Flyover at ground level)	160	165.0	264.8	0.601	0.625	0.763	0.464

Table 19 – Statistics from modelling the elevated portion of the road, Antwerp, Belgium (NO_x)

Receptor	Valid data points	Monitored mean (µg/m³)	Modelled Mean (µg/m³)	NMSE	Correlation	Fac2	fb
Elevated A (Flyover elevated)	476	55.5	63.1	0.146	0.879	0.905	0.128
Elevated A (Flyover at ground level)	476	55.5	80.5	0.330	0.820	0.756	0.367
Elevated B (Flyover elevated)	359	65.0	73.8	0.172	0.899	0.905	0.127
Elevated B (Flyover at ground level)	359	65.0	136.2	0.967	0.714	0.457	0.708

5.3 Sensitivity testing

Results from some sensitivity testing involving assessing the impact of elevating a road on ground level concentrations were presented in the feasibility study report[4]. This sensitivity testing is extended here in order to compare against data from the Antwerp field campaign study described above.

The model configuration for the elevated section of the M4 adjacent to the HS10 monitor has been used for this sensitivity testing. Near ground (2 m) annual average concentrations of NOx and NO2 due to the elevated road section only are presented in Figure 35; in these plots, output points have been located on a line perpendicular to the motorway centreline, and passing below the elevated section. Predicted concentrations where the road is elevated to a height of 6 m, 8 m, 10 m and 12 m are compared to concentrations for a ground level road source. Note that in the evaluation study presented in Section 5.1, the road elevation is fixed at the real-world height i.e. 6 m. In this sensitivity testing, height variations are considered in order to understand the influence of road elevation on ground level concentrations; HS10 is chosen as a typical motorway site. A 2 m receptor height has been selected in order to allow comparison with the Antwerp field campaign dataset.

The cross-sectional profiles clearly show the influence of the prevailing wind direction, with the concentrations higher to the north east of the motorway. As would be expected, the concentrations when the elevated section of road is present ‘dip’ under the elevated section, compared to the large peak that is seen for the ground level source, where the receptors are ‘in’ the road. Concentrations reach a local maximum either side of the elevated section, for example, for the 6 m motorway, the NO2 concentrations peak at 6.3 µg/m³ at a distance of 36 m to the north west of the road centreline, and at 4.9 µg/m³ 26 m to the south west of the road centreline, but these concentrations are much lower than for the ground level source. Concentrations for cases where the road is elevated to a higher level (8 m, 10 m. 12 m) result in lower concentrations at constant 2 m receptor height, as expected. The location of the maximum concentration relative to the road centreline varies with road elevation, with the maximum being further away from the road for higher elevations; this is unsurprising as pollutants have further to travel to reach ground level when the road is higher (see Figure 4).

The relative reduction in near-ground concentrations compared to elevated concentrations with distance from the road centreline is of interest when considering road elevation as a pollutant mitigation option. Figure 36 shows the ratio of the elevated road concentration to the ground level concentration with distance from the road for the 6 m, 8 m, 10 m and 12 m elevated sections. The results are as expected: higher elevations lead to ground level concentrations being a smaller proportion of the equivalent ground-based road concentration; and the impact of road elevation decreases quickly with distance from the road, with elevated road concentrations being almost 80% of ground based road concentrations by 250 m from the road centreline for this London model configuration.

The road source geometry and meteorological conditions will influence this ratio of the elevated to ground based road concentrations. To help put this into context, the ratios derived from the Antwerp flyover measurements have been presented on Figure 36 (blue circles). Here, ratios have been calculated for both the data binned by wind speed, as well by stability; weighted average values have been calculated in each case, using the minimum number of values within each wind speed / stability bin to ensure the most robust result. The modelled ratios compare well with measured values (note that the 'by wind speed' and 'by stability' ratios give approximately the same result for the point further away from the road centreline). This comparison provides further evidence that the model is performing well in terms of its ability to predict near-elevated road concentrations.

The NO2 ratio plot corresponding to Figure 36 is shown in Figure 37. This diagram (and associated dataset) can be used to answer the question 'when is it worth considering road elevation in a modelling study?' Specifically, the following aspects need to be taken into consideration:

- How high is the elevated section of road?
- At what distance from the road are concentrations of interest?

For this particular model configuration, which could be considered broadly representative of an SRN motorway section, Figure 34 shows the relationship between road elevation and the distance at which the impact of the elevation reduces to within 10% of the concentration resulting from a ground-based road. As expected, low elevations (less than 4 m) have little impact on concentrations past around 100 m from the carriageway edge, but higher elevations (greater than around 8 m) impact significantly even beyond 0.5 km.

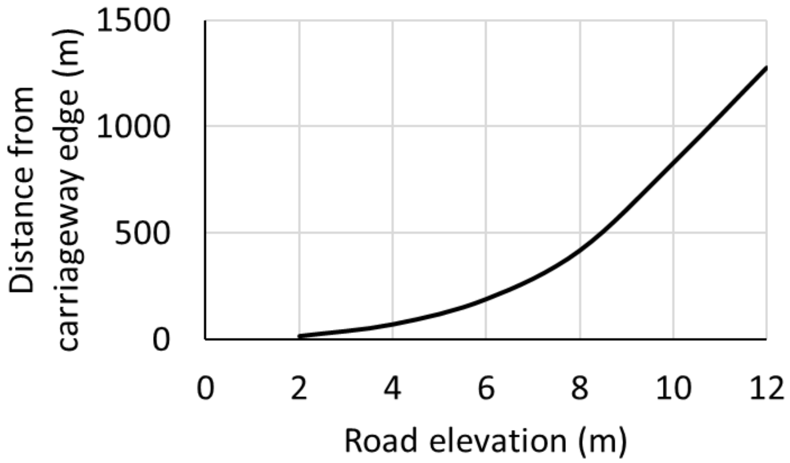


Figure 34 – Typical distance from carriageway edge to a location where the elevated road annual average NO_2 concentration has reached 90% of the concentration value from an equivalent ground level road; values shown are sensitive to road orientation, road width and background concentrations

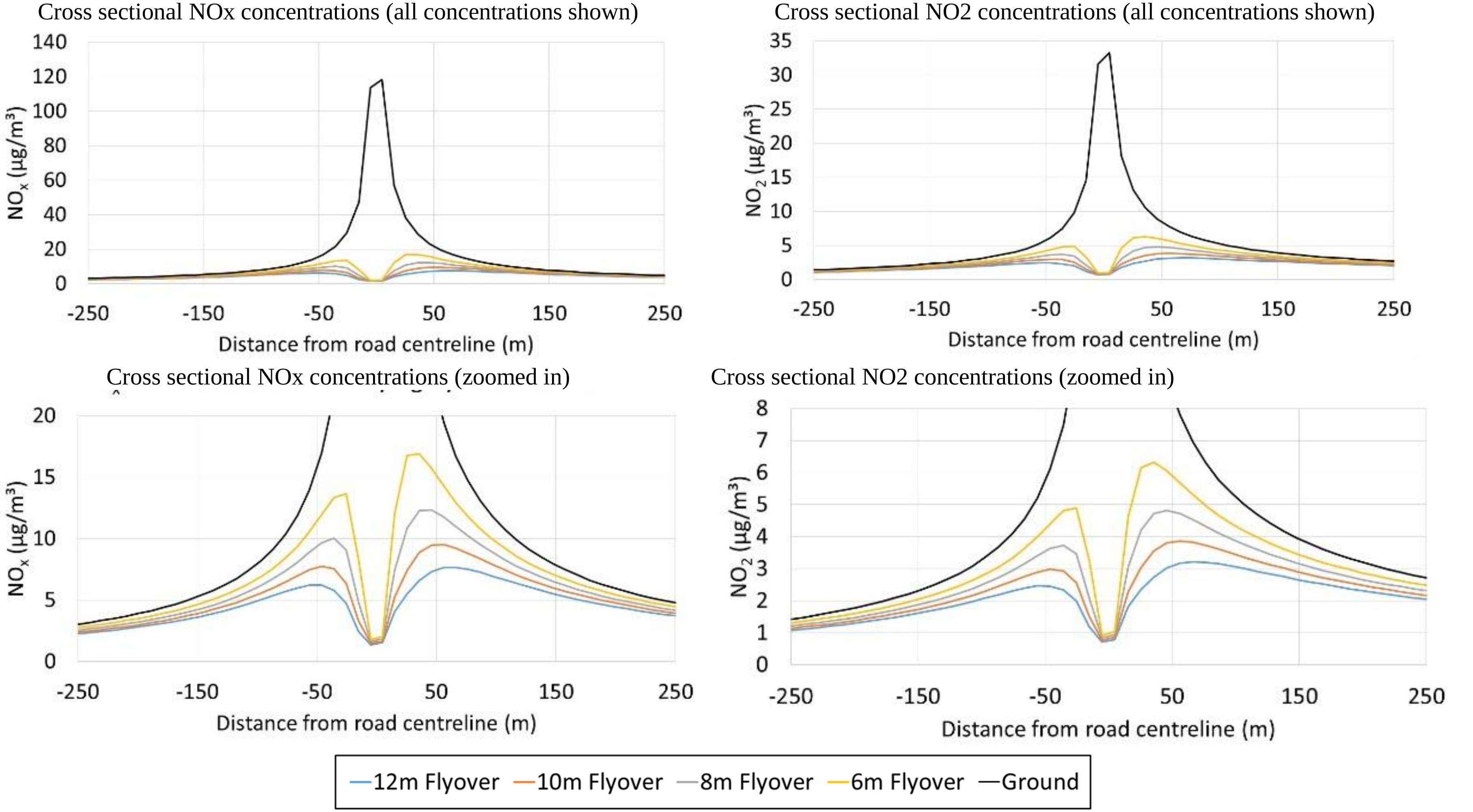


Figure 35 – Predictions of annual average NOx (left) and NO2 (right) showing concentrations at 2 m above ground in µg/m³ (vertical axis) against distance from road centreline in m (horizontal axis), an elevated road section compared to a non-elevated road (black line); lower plots show detail of upper plots for low concentrations; negative distance corresponds to south west of the motorway, positive to the north east.

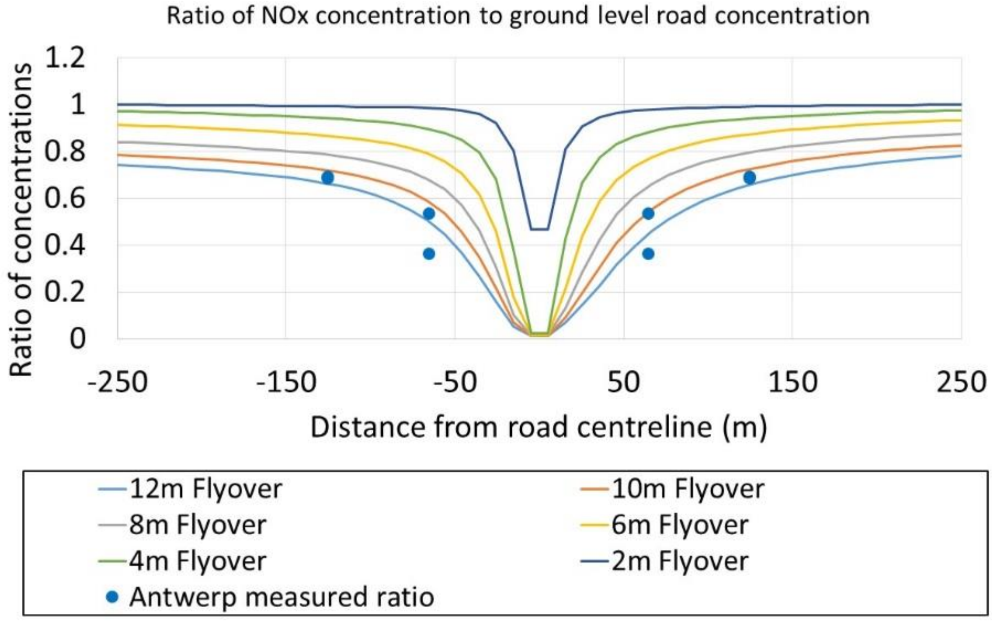


Figure 36 – Ratio of annual average flyover to ground-based road NOx concentrations for the HS10 London monitor configuration, modified to demonstrate the impact of road elevation *for the road increment only*; ratios corresponding to measurements from the Antwerp study shown as blue dots (flyover height 12 m)

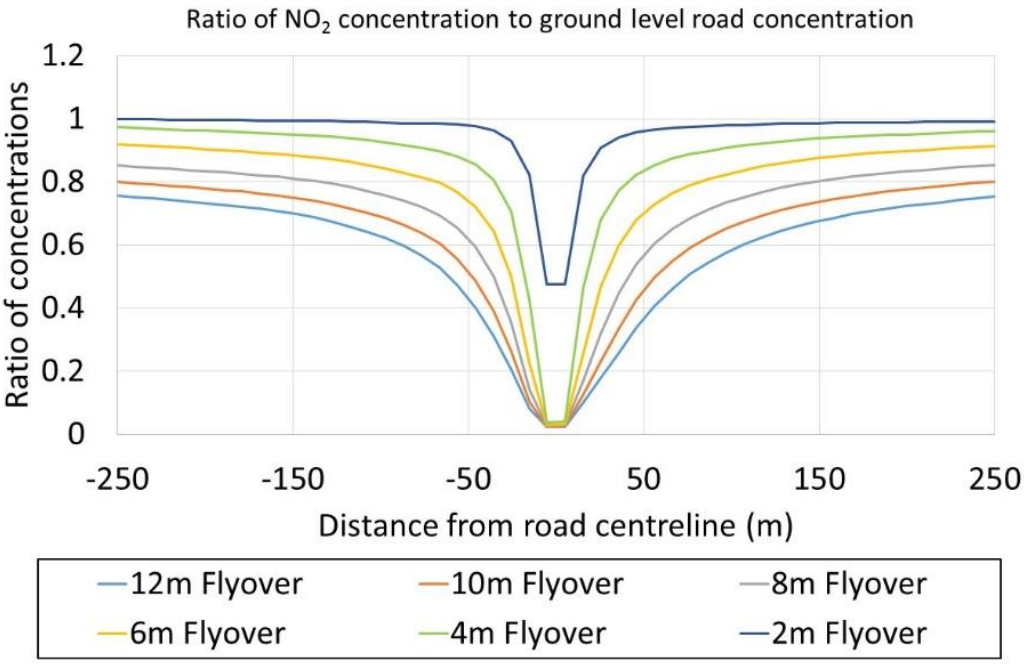


Figure 37 – Indicative ratio of annual average flyover to ground-based road NO_2 concentrations for the HS10 London monitor configuration, modified to demonstrate the impact of road elevation *for the road increment only*.

6. Guidance

This section provides practical guidance on how ADMS-Roads should be used to model a variety of different elevated road scenarios.

6.1 Standard flyover

A 'standard' flyover is considered to be a road located above ground level with constant elevation along its full length; air can flow above and below the elevated road largely unimpeded (see schematic in Figure 38, left, and example photo in Figure 39).

This scenario should be modelled in ADMS-Roads using the **Flyovers** option, as described in Section 3.2, with road heights as indicated in Figure 38 (right).

Figure 38 – Schematic of a standard flyover (left) and corresponding road heights as would be entered into ADMS-Roads (right). Green line – ground-level road source (into page); blue line – flyover road source (into page).

Figure 39 – Real-world example of a standard flyover modelling scenario. Google: Map data @ 2020.

6.2 Bridge over a cutting

When modelling in the vicinity of a road that passes over another road within a cutting, i.e. one that sits beneath the more general local ground level, and where the receptor(s) are on the level of the non-cutting road (see schematic in Figure 40, left, and example photo in Figure 41), it is advised to model both roads at ground level. However, the width of the road in the cutting should be extended to be the width of the top of the cutting (see Figure 40, right).

This approach should work moderately well for shorter cuttings; for wider cuttings, the influence of air flow both above and below the central section of the bridge will have a stronger influence on dispersion of emissions and resultant pollutant concentrations.

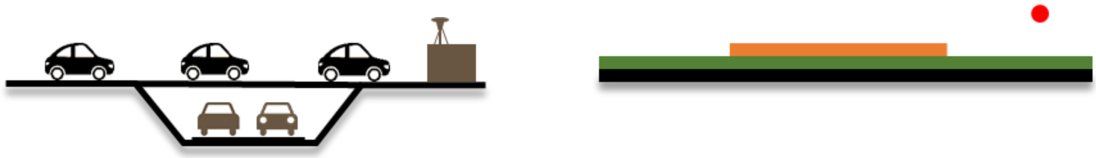


Figure 40 – Schematic of a road over a cutting (left) and corresponding road heights as would be entered into ADMS-Roads (right). Green line – ground-level road source above cutting; orange line – ground-level road source inside cutting (into page); red dot - receptor.

Figure 41 – Real-world example of a road over a cutting modelling scenario. Google: Map data @ 2020.

6.3 Bridge over a valley

In contrast to the above scenario, when a bridge crosses a larger valley (see schematic in Figure 42, left, and example photo in Figure 43), the influence of air flow above and below the elevated road will have a significant impact on dispersion and thus concentrations at receptors on the valley floor. In this case, the valley floor should be treated as ground level and the bridge as a piecewise series of elevated roads (using the **Flyovers** option) to account for the varying distance between the ground and the bridge along its length (see Figure 42, right). Smaller road sections should be used near the edges of the valley to capture the sharper gradients. Any roads on the valley floor should be modelled as standard ground-level road sources.

It is also advised to use the **Complex terrain** option to capture flow variations in the valley. Note that the **Complex terrain** option can only be used if the sides of the valley are not too steep (no more than around a 1 in 3 gradient).

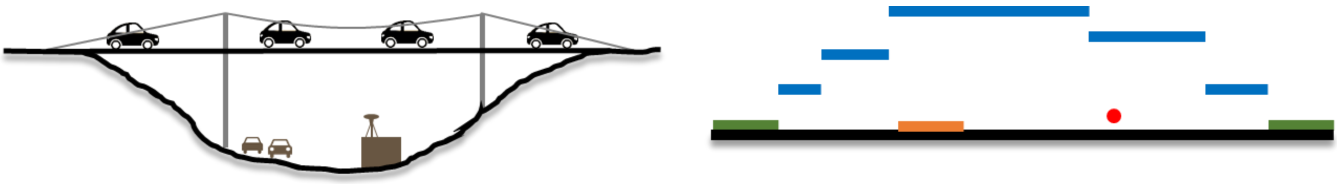


Figure 42 – Schematic of a bridge over a valley (left) and corresponding road heights (relative to ground level) as might be entered into ADMS-Roads (right). Green lines – ground-level road sources at start and end of the bridge; blue lines – flyover road sources representing elevated part of the bridge; orange line – ground level road source on valley floor (into page); red dot – receptor.

Figure 43 – Real-world example of a bridge over a valley modelling scenario. Google: Map data @ 2020.

6.4 Bridge over a road: ground-level receptors

When modelling in the vicinity of a road bridge with embankments that passes over another ground-level road, the model setup guidance depends on whether the receptor(s) are at ground level or on the bridge itself. For ground-level receptors (see schematic in Figure 44, left, and example photo in Figure 45), it is advised to model the constant-elevation section of the bridge as an elevated road source (using the **Flyovers** option), but the embankment sections as ground-level road sources due to the fact that air cannot flow under the embankments (see Figure 44, right).

This approach should work moderately well for longer bridges; for shorter bridges, end effects (where the constant-elevation section joins the embankments) may have a stronger influence on air flow and hence dispersion of emissions and resultant pollutant concentrations.

Figure 44 – Schematic of a bridge over a road with ground-level receptors (left) and corresponding road heights as would be entered into ADMS-Roads (right). Green lines – Ground-level road sources representing embankment sections of the bridge; Blue line – Flyover road source representing constant-elevation section of the bridge; orange line – ground-level road source under the bridge (into page); red dot – receptor.

Figure 45 – Real-world example of a bridge over a road (ground-level receptor) modelling scenario. Google: Map data @ 2020.

6.5 Bridge over a road: bridge-level receptors

In contrast to the previous modelling scenario, if the receptors are instead located at bridge-level (see schematic in Figure 46, left, and example photo in Figure 47), it is advised to model all road sections at ground level (see Figure 46, right). This is because emissions from the embankment sections are likely to be significant at the receptor(s), and so it is important that the receptor(s) are located at the correct height relative to both the constant-elevation section and embankment sections of the bridge.

This approach should work moderately well for shorter bridges; for longer bridges, the influence of air flow both above and below the central section of the bridge will have a stronger influence on dispersion of emissions and resultant pollutant concentrations. Note that this setup is likely to give conservative estimates of (i.e. over-predict) concentrations at the receptor(s) due to the closer proximity of the road source under the bridge.

Figure 46 – Schematic of a bridge over a road with bridge-level receptors (left) and corresponding road heights as would be entered into ADMS-Roads (right). Green line – ground-level road source representing full length of bridge; orange line – ground-level road source under bridge (into page); red dot - receptor.

Figure 47 – Real-world example of a bridge over a road (bridge-level receptor) modelling scenario. Google: Map data @ 2020.

7. Discussion

This report presents the outcomes of the project to develop a 'Tool to assess air quality impacts of elevated roads within the Strategic Road Network'. This project has been successful.

The elevated road sub-model developed as part of the feasibility study has been fully integrated within ADMS-Roads. Complexities resolved during this integration process included ensuring compatibility with the complex terrain module and the deposition module. Consequences of these developments include: elevated road sections can be modelled within ADMS-Roads while also accounting for hilly terrain; and deposition calculations can be performed accurately in the vicinity of elevated roads, which is important for habitats assessments. The elevated roads module is very easy to use. A new version of ADMS-Roads is now available for use by Highways England (version 5.0.1.1), and the model will be released more generally in July 2020 to approximately 200 organisations holding valid licences of ADMS-Roads and its sister models ADMS-Urban and ADMS-Airport.

The exercise to collate suitable datasets to allow evaluation of the elevated roads model was successful. After discussions with Highways England, three different types of elevated road site were specified: sites with a dense network of diffusion tube measurements; sites which would allow measurement data analyses; and sites where reference monitors recording hourly concentration values are located in the vicinity. A comprehensive inspection of available measurement data from the UK and a short literature search resulted in two or three site options for each site type. Within each site type, one site was selected as preferable for evaluation, and the remainder were kept in reserve should the primary site not be suitable for some reason. Datasets were collated for 7 sites in total, prior to the evaluation study. Highways England provided data for UK sites. The measurement campaign data associated with the Antwerp (Belgium) study was kindly provided for use by Martine van Poppel (VITO). As the evaluation exercise using the primary sites was successful, it was unnecessary to include any of the reserve sites in the study.

The evaluation exercise produced results that demonstrate ADMS-Roads' ability to represent the dispersion processes associated with emissions from elevated roads. Highlights include:

- Good agreement between modelled NO2 concentrations and monthly diffusion tube measurements recorded at a series of locations along the local road that passes under an elevated section of the M5. By applying an 'indicative' source apportionment approach, the modelled concentrations have been split between: contributions from the elevated motorway section; the local road; other emissions in the vicinity; and background concentrations. Of interest is that the contribution of the local road to the NO2 levels is almost twice that of the elevated motorway, even at less than 50 m from the motorway.

- The model demonstrates that road elevation has a large impact on concentrations in the vicinity of the elevated section, but this drops off within 150 m or so (depending on the road elevation and other site considerations). For the Birmingham site, which includes a number of emissions sources in addition to the M5, road elevation has negligible impact on concentrations at the location of the reference monitor approximately 150 m from the M5; in contrast, at the London site, the road elevation has a large impact because the monitors are much closer to the motorway (a difference of 16.8 µg/m³ of NO2 at one reference monitor located 7 m from the motorway edge, and 8.3 µg/m³ at the other located 9 m from the motorway edge).

- The detailed UK model evaluation studies highlighted the need to account not only for road elevation, but also for the influence of urban morphology on pollutant dispersion on the local roads. The stretch of the A4 in London adjacent to the HS5 monitor is also bordered by a terrace of relatively tall houses (12 m); it was clear from the wind-direction analyses of measured concentrations that these houses were causing a reverse flow region i.e. an asymmetric street canyon, and including this feature in the model configuration significantly improved modelled / measured agreement. Similarly, when modelling the near-motorway diffusion tube locations at the Birmingham site, it became apparent that the monitor closest to the motorway was unaffected by the buildings which formed a street canyon along Birmingham Road, whereas the majority of other monitors along the road were inside the canyon; accounting for this in the model configuration led to better model performance.

- The typical pattern of near-ground concentrations arising from dispersion of emissions from an elevated section of road has been demonstrated by presenting contour plots for the London evaluation study, and by showing results of sensitivity tests. The studies show how concentrations peak either side of the road; the distance of these peaks from the road centreline is dependent on the road geometry and meteorological conditions, with the peak being further away from the road for higher elevations due to longer source to receptor pathways. The sensitivity study suggests that peak ground level concentrations are located between 20 – 40 m from the road centreline for a 6 m high motorway, and between 50 – 70 m for a 12 m high motorway.

- A number of confounding factors had to be accounted for when undertaking evaluation of the measurement dataset, in order to compare measurements recorded in the vicinity of elevated and ground-based sections of a highway in Belgium. As the elevated road measurements were recorded during a different period to the ground-based measurements, it was necessary to categorise the concentration data according to the meteorological parameters that dominate dispersion processes i.e. wind speed and direction, and atmospheric stability. In addition, the influence of the magnitude of hour-by-hour road emissions was allowed for and also, by using results from an ADMS-Roads model configuration, an adjustment was made to compensate for the different road-to-receptor distances. Having allowed for the most important confounding factors, the measurement analyses clearly demonstrate that concentrations in the vicinity of elevated roads are significantly lower than those close to ground-based roads. Further, the magnitude of the concentration reduction is in line with that predicted by the model.

- Prior to these developments, it was possible to model elevated line and road sources using ADMS-Roads. However, the default dispersion modelling approach was to allow pollutants to disperse downwards underneath the road i.e. no account was made of the shielding effect of the road structure. It is useful to assess the level of improvement in modelled concentrations using the new version of the elevated source algorithms compared to the default approach. Tables 20 and 21 are copies of Tables 12 and 14 relating to the London, Hounslow study, but comparing the results of modelling using the default elevated source approach (indicated as ‘Base elevated’) to modelling as a flyover. Unsurprisingly, at both monitors, the model predicts lower concentrations for the new flyover option, because they are located close to the elevated section. The flyover approach demonstrates better performance at both monitors, although differences are more noticeable at the HS10 monitor, which does not have the complications of being close to any other major roads.

The treatment of flyover-type elevated roads in the ADMS-Roads model will enable more accurate assessment of air quality impacts when elevated sections of roads are to be modified or added to the SRN. Adding this method to the Highway England ‘toolbox’ of assessment methods should assist in making informed decisions regarding road layout and design.

The new module will also assist with the modelling of a number of different road layouts involving bridges:

- Bridges that pass over cuttings containing road sources, where receptors are on the level of the elevated section of road;
- Bridges over valleys;
- Bridges over roads supported on either side by embankments, where receptors of interest are either:
    - at ground level; or
    - on the level of the elevated section.

Guidance on how to model these road layouts has been provided.

The new module has been extensively evaluated during this project, and CERC are confident in its application for flyover-type elevated roads. In terms of model limitations, further work is required to: fully develop the embankments module that was tested in Phase 1; account for end effects where bridges meet embankments; and implement a cuttings module, the technical specification for which has already been written by CERC.

Following the Phase 1 feasibility project, the elevated roads sub-model was at Technology Readiness Level (TRL) 5 (‘technology validated in relevant environment’) and is now at TRL 8 (‘System complete and qualified’). Following the general release of the model, the system will move to TRL 9 (‘Actual system proven in operational environment’).

Table 20 – Statistics from modelling M4 site Boston Manor Park, Hounslow, HS010 (NO_2)

NO2 (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Elevated	26.0	29.6	0.387	0.628	0.785	0.130
Flyover	26.0	26.7	0.360	0.646	0.802	0.026

Table 21 – Statistics from modelling M4 /A4 Chiswick flyover site, HS5 (NO_2)

NO2 (µg/m³)	Monitored mean	Modelled Mean	NMSE	Correlation	Fac2	fb
Base Elevated	44.3	45.5	0.204	0.709	0.902	0.029
Flyover	44.3	43.8	0.194	0.709	0.903	-0.010

Appendix A – Gantt chart

	Work Packages and Tasks
1.	**WP1 - PROJECT MANAGEMENT AND MEETINGS**
2.	T1.1 - Inception meeting
3.	T1.2 - Monthly teleconferences with Highways England
4.	T1.3 - Quarterly meetings with Innovate UK Monitoring Officer
5.	M1.1 – Gateway meeting with HE, MO
6.	M1.2 - Training workshop at Highways England Offices
7.	T1.4 - Final meeting
8.	**WP2 - INTEGRATION OF SUB-MODEL INTO ADMS-ROADS**
9.	T2.1 - Integration of elevated roads sub-model within ADMS-Roads
10.	M2.1 - Beta version of ADMS-Roads including elevated roads available testing
11.	T2.2 - Code modifications
12.	D2.1 - Release version of ADMS-Roads
13.	**WP3 - TESTING AND EVALUATION**
14.	T3.1 - Specify evaluation database requirements
15.	M3.1 - Evaluation database requirements documented
16.	T3.2 - Collate evaluation databases
17.	M3.2 – Evaluation databases collated
18.	T3.3 - Evaluate elevated roads sub-model
19.	M3.3 - Scientific evaluation complete
20.	D3.1 - Documented record of elevated roads model evaluation
21.	**WP4 - USER DOCUMENTATION AND REPORTING**
22.	T4.1 - Quarterly reports
23.	T4.2 - User documentation
24.	T4.3 - Training material preparation
25.	D4.1 - Updated ADMS-Roads User Guide including new option
26.	D4.2 - Technical specification for modelling elevated roads
27.	D4.3 - Final report
28.	D4.4 - Summary presentation
29.	**WP5 - PUBLICITY AND MARKETING**
30.	T5.1 - Promote new elevated roads tool at relevant trade events
31.	M5.1 - Presentation of scientific results at UK meeting (e.g. DMUG April 2020)
32.	M5.2 - Publicizing new option via CERC Website, CERC Newsletters
33.	M5.3 - Promotional advert in trade journals (Air Quality News, Air Quality Bulletin)
34.	M5.4 - Providing material to CERC's overseas partners for their publicity
35.	M5.5 - Promoting new option to Local Authorities (e.g. at ADMS-Roads User Group Meeting)

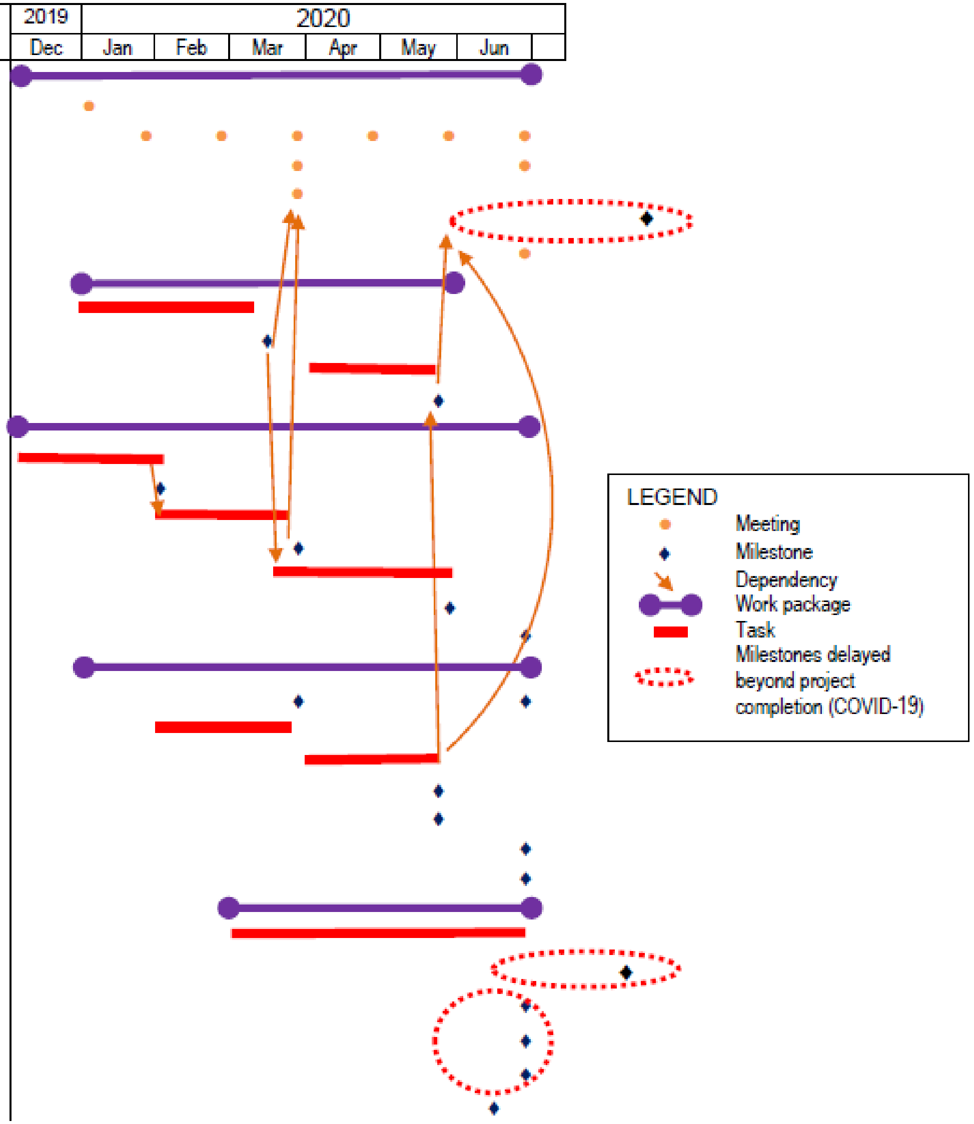


Figure 48 – Gantt chart

Appendix B – Normalised concentrations by stability class

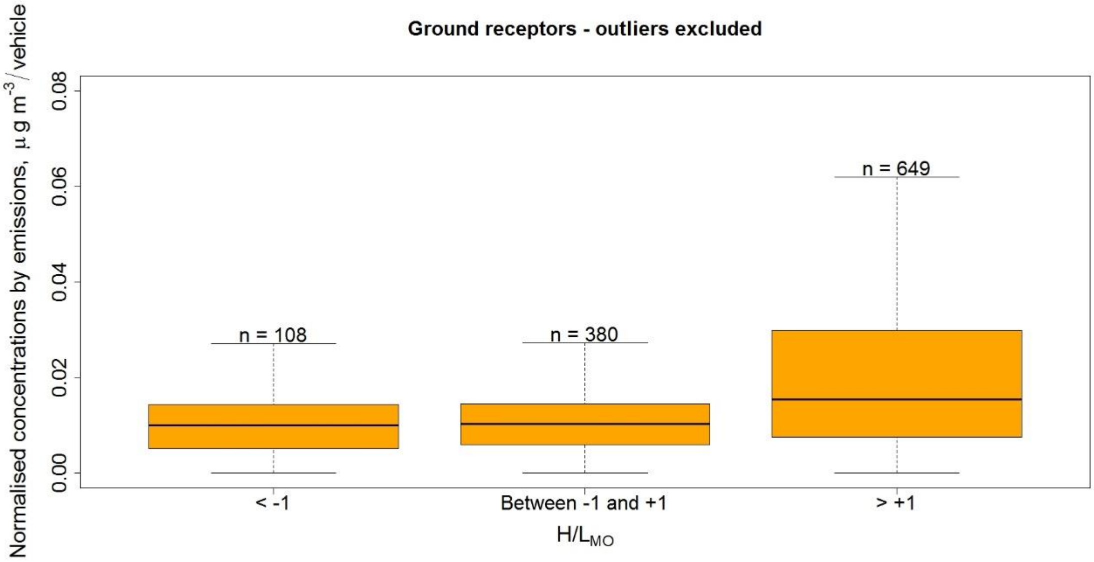


Figure 49 – Box plots of road increment concentrations normalised by traffic flow, categorised according to atmospheric stability (H/L_{MO}) for ground receptors; 25th and 75th IQR and number of values in each bin shown. The stability categories correspond to convective (H/L_{MO} <-1), neutral (H/L_{MO} between -1 and +1) and stable conditions (H/L_{MO} >+1).

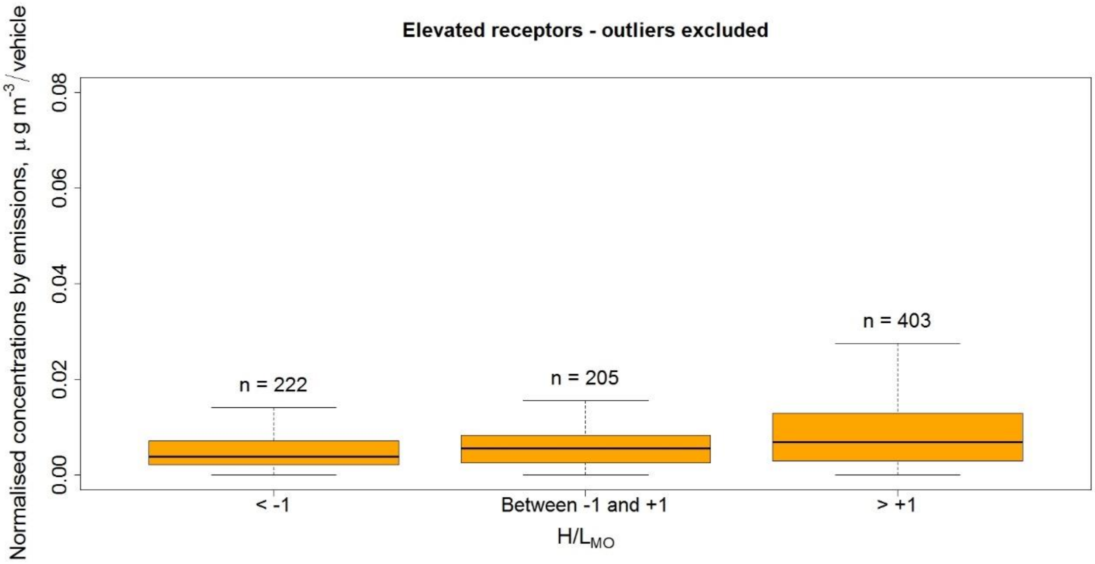


Figure 50 – Box plots of road increment concentrations normalised by traffic flows, categorised according to atmospheric stability (H/L_{MO}) for receptors close to the elevated section of road; 25th and 75th IQR and number of values in each bin shown. The stability categories correspond to convective (H/L_{MO} <-1), neutral (H/L_{MO} between -1 and +1) and stable conditions (H/L_{MO} >+1).

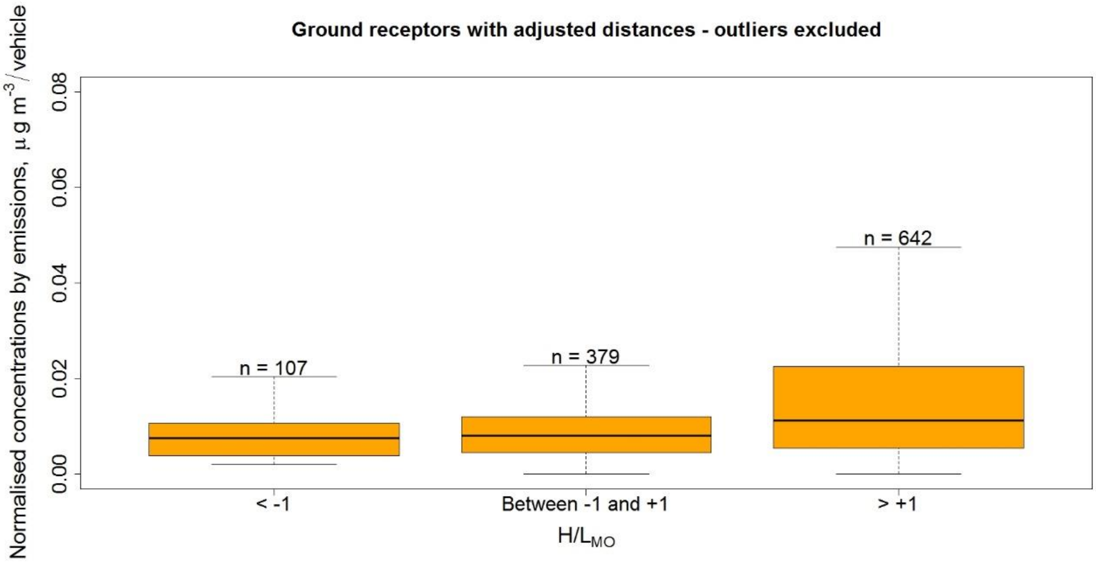


Figure 51 – Box plots of road increment concentrations normalised by traffic flows, categorised according to atmospheric stability (H/L_{MO}) for ground level receptors adjusted to be the same distance from the road as the receptors close to the elevated section of road; 25th and 75th IQR and number of values in each bin shown. The stability categories correspond to convective (H/L_{MO} <-1), neutral (H/L_{MO} between -1 and +1) and stable conditions (H/L_{MO} >+1).

Table 22 – Median NOx road increment normalised concentrations (µg/m³/vehicle), categorised according to wind speed for the ground, elevated and adjusted ground receptors – Receptor A

Dataset	**Wind speed (m/s)**				
	<2	**2 to 4**	**4 to 6**	**6 to 8**	**>8**
Ground	0.0175	0.0113	0.0090	0.0074	0.0093
Elevated	0.0047	0.0053	0.0057	0.0052	0.0072
Ground adjusted	0.0145	0.0087	0.0071	0.0059	0.0080
Elevated / Ground adjusted	**0.32**	**0.61**	**0.81**	**0.87**	**0.90**

Table 23 – Median NOx road increment normalised concentrations (µg/m³/vehicle), categorised according to wind speed for the ground, elevated and adjusted ground receptors – Receptor B; a '-' indicates where the wind speed bin does not contain any data points

Dataset	**Wind speed (m/s)**				
	<2	**2 to 4**	**4 to 6**	**6 to 8**	**>8**
Ground	0.0275	0.0286	0.0219	-	-
Elevated	0.0149	0.0054	0.0036	0.0033	0.0035
Ground adjusted	0.0178	0.0178	0.0140	-	-
Elevated / Ground adjusted	**0.83**	**0.31**	**0.25**	**-**	**-**

Table 24 – Median NOx road increment normalised concentrations (µg/m³/vehicle), categorised according to stability (H/L_{MO}) for the ground, elevated and adjusted ground receptors – Receptor A

Dataset	**Stability H/L_{MO} (-)**		
	< -1 Convective	**Between -1 and 1 Neutral**	**> +1 Stable**
Ground	0.0067	0.0094	0.0121
Elevated	0.0028	0.0058	0.0065
Ground adjusted	0.0059	0.0078	0.0088
Elevated / Ground adjusted	**0.49**	**0.74**	**0.74**

Table 25 – Median NOx road increment normalised concentrations (µg/m³/vehicle) categorised according to stability (H/L_{MO}) for the ground, elevated and adjusted ground receptors – Receptor B

Dataset	**Stability H/L_{MO} (-)**		
	< -1 Convective	**Between -1 and 1 Neutral**	**> +1 Stable**
Ground	0.0162	0.0226	0.0302
Elevated	0.0043	0.0035	0.0071
Ground adjusted	0.0089	0.0150	0.0195
Elevated / Ground adjusted	**0.48**	**0.23**	**0.36**

Appendix C – Advanced canyon modelling justification

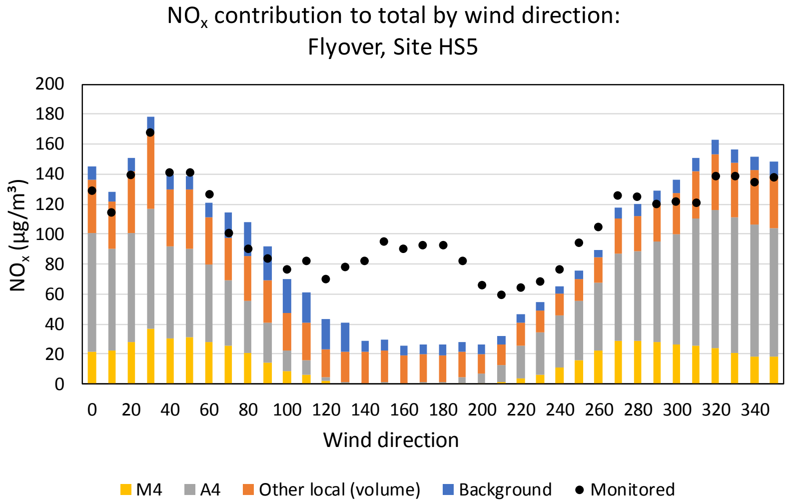


Figure 52 – NOx source apportionment plots by wind direction for the monitors located adjacent to the motorways, with the elevated road section modelled as a flyover; no asymmetric street canyon modelled

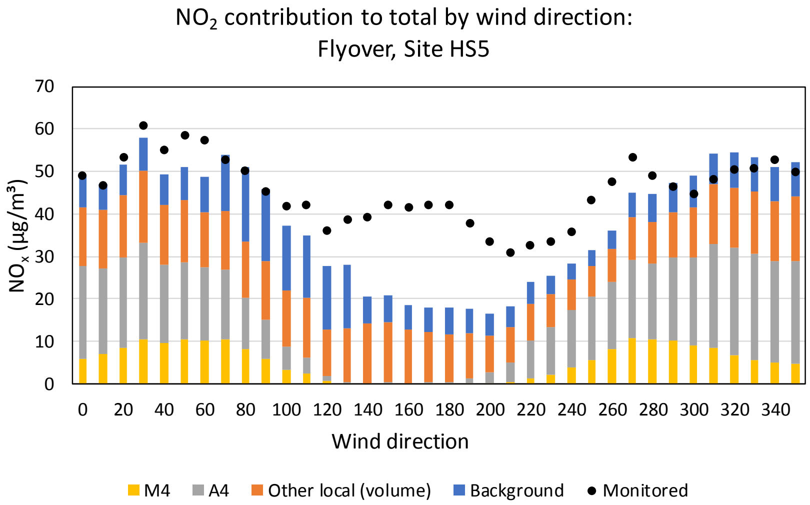


Figure 53 – NO2 source apportionment plots by wind direction for the monitors located adjacent to the motorways, with the elevated road section modelled as a flyover; no asymmetric street canyon modelled