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Detailed modelling of NO_2 at Market Hill AQMA, Maldon

Draft Report

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CERC

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Contents

1 Summary

Maldon District Council (MDC) recently declared an Air Quality Management Area (AQMA) at Market Hill, Maldon. To this end, Chelmsford City Council, on behalf of Maldon District Council, commissioned Cambridge Environmental Research Consultants Ltd (CERC) to carry out air quality modelling to support the Air Quality Action Plan (AQAP) for the new AQMA. To support the AQAP, detailed source apportionment and baseline modelling was required, plus modelling a number of scenarios to assist with identifying appropriate mitigation measures.

Pollutant emissions from vehicles were calculated using automatic traffic count data provided by the council at two locations on Market Hill. To take account of the uncertainty of emission rates from diesel vehicles, emission factors were adjusted based on real-world remote sensing data. The steep gradient on Market Hill was accounted for by adjusting emission factors of HGVs, based on Defra Technical Guidance TG (16).

Emissions data from other sources were taken from the National Atmospheric Emissions Inventory.

Modelling was carried out using the ADMS-Urban model (version 4.2) using meteorological data from Southend and background pollutant data from Rochester Stoke rural monitoring site.

Model verification was carried out, comparing modelled concentrations with measured data for 2018. Initial model verification showed general underprediction of concentrations at the monitoring sites, even after increasing the emissions by accounting for the road gradient and adjusting for real-world conditions. Further investigation showed that this was likely to be due to underestimation of emissions; to take account of this and improve the verification, the modelled average speed of vehicles travelling up the hill was reduced to 10 km/hr. With this change, the modelled concentrations showed generally good agreement with the measured data with the majority being within 25% of the measured data and no systematic under or over prediction of concentrations.

Modelling for 2018 showed exceedences of the annual and hourly average NO_2 limit values along the sections of Market Hill with canyon properties, including locations with potential public exposure.

Source apportionment showed that the major contribution to annual average NO_x concentration is from cars with significant contributions from buses, LGVs and rigid HGVs.

Note that there is some uncertainty in the source apportionment results. Changing the uphill vehicle speed to 10 km/hr increases emissions from all vehicle types, however, the reason for the underestimate in emissions is unclear. It could be, for instance, that the gradient adjustments for light or heavy vehicles are not appropriate in this case, or that there is a significant amount of stop-start driving giving rise to increased emissions, or that the national vehicle fleet composition used is not representative of the local vehicle fleet. Each of these could affect emissions from each vehicle type in different ways.

2 Introduction

Maldon District Council (MDC) recently declared an Air Quality Management Area (AQMA) at Market Hill, Maldon due to high annual average NO_2 concentrations. To this end, Chelmsford City Council, on behalf of Maldon District Council, commissioned Cambridge Environmental Research Consultants Ltd (CERC) to carry out air quality modelling to support the Air Quality Action Plan (AQAP) for the new AQMA. To support the AQAP, detailed source apportionment and baseline modelling was required, plus modelling a number of scenarios to assist with identifying appropriate mitigation measures.

The air quality targets, with which the calculated concentrations are compared, are presented in Section 3. An overview of the area and details of measured data are given in Section 4. The emissions data is summarised in Section 5, and the detailed model set-up is summarised in Section 6. The model verification for 2018 is presented in Section 7, and the results of detailed modelling for 2018 are presented in Section 8. Source apportionment from the modelling is provided in Section 9 and discussion of the results is provided in Section 10. Finally, a description of the ADMS-Urban model is provided in Appendix A.

3 Air quality standards

The EU *Ambient Air Quality Directive* (2008/50/EC) sets binding limits for concentrations of air pollutants, which take into account the effects of each pollutant on the health of those who are most sensitive to air quality. The Directive has been transposed into English legislation as the *Air Quality Standards Regulations 2010*[1], which also incorporates the provisions of the *Fourth Daughter Directive* (2004/107/EC).

The Air Quality Standards Regulations 2010 include limit values and target values. Local authorities are required to work towards air quality objectives. In doing so, they assist the Government in meeting the limit values. The limit values are presented in Table 3.1.

Table 3.1: Air quality limit values for NO_2

	Value ($\mu g/m^3$)	Description of standard
NO_2	200	Hourly mean not to be exceeded more than 18 times a calendar year (modelled as 99.79th percentile)
	40	Annual average

The short-term objectives, i.e. those measured hourly or over 24 hours, are specified in terms of the number of times during a year that a concentration measured over a short period of time is permitted to exceed a specified value. For example, the concentration of NO_2 measured as the average value recorded over a one-hour period is permitted to exceed the concentration of 200 $\mu g/m^3$ up to 18 times per year. Any more exceedences than this during a one-year period would represent a breach of the objective.

It is convenient to model objectives of this form in terms of the equivalent percentile concentration value. A percentile is the concentration below which lie a specified percentage of concentration measurements. For example, consider the 98th percentile of one-hour concentrations over a year. Taking all of the 8760 one-hour concentration values that occur in a year, the 98th percentile value is the concentration below which 98% of those concentrations lie. Or, in other words, it is the concentration exceeded by 2% (100 – 98) of those hours, that is, 175 hours per year. Taking the NO_2 objective considered above, allowing 18 exceedences per year is equivalent to not exceeding for 8742 hours or for 99.79% of the year. This is therefore equivalent to the 99.79th percentile value. It is important to note that modelling exceedences of short term averages is generally not as accurate as modelling annual averages.

[1] http://www.legislation.gov.uk/uksi/2010/1001/contents/made

4 Site information

4.1 Site location

In December 2018, Maldon District Council (MDC) declared an AQMA at Market Hill, Maldon for annual average and 1-hour average nitrogen dioxide (NO_2) concentrations. This AQMA incorporates the stretch of road and properties between Anchorage Hill and Bull Lane.

4.2 Air quality monitoring

Along Market Hill, NO_2 is measured using 10 diffusion tubes at 8 sites, including co-located tubes MD22A, B and C. Monitoring along Market Hill at site MD20 has been discontinued as the location of the diffusion tube did not comply with Defra Technical Guidance TG(16).

Monitoring at sites MD23, MD24, MD25, MD26, MD27 and MD28 commenced in April 2018. Seasonal adjustment factors was calculated following Defra guidance TG(16) and applied to the measured, bias-adjusted concentrations. The seasonal adjustment factors are shown Table 4.1.

Table 4.1: Seasonal adjustments for incomplete monitoring data

ID	Site Name	Measured, bias adjusted concentration (µg/m³)	Seasonal adjustment factor	Final concentration (µg/m³)
MD23	59-63 Market Hill	32.6	1.14	37.1
MD24	32 Market Hill	45.4	1.02	**46.3**
MD25	1 Hillside	29.4	1.05	30.9
MD26	18 Market Hill	36.6	1.07	39.1
MD27	6 Market Hill	57.7	1.07	**61.8**
MD28	21 Market Hill	27.0	1.07	28.9

Table 4.2 presents the annualised and bias-adjusted annual average NO_2 concentrations for all the diffusion tubes and Figure 4.1 presents the locations of the diffusion tubes along Market Hill. Exceedences of the air quality standard of 40 µg/m³ are highlighted in **bold.**

Table 4.2: Annual average NO_2 concentrations at diffusion tube sites in 2018 (µg/m³)

ID	Site Name	X (m)	Y (m)	Height (m)	In AQMA?	Concentration (µg/m³)
MD6	High Street (Market Hill Jn)	585072.4	207079.9	2.5	Yes	26.9
MD22A	10 Market Hill	585061.7	207159.9	2.5	Yes	**57.1**
MB22B						**58.3**
MD22C						**59.9**
MD23	59-63 Market Hill	585055	207324	2.5	Yes	37.1
MD24	32 Market Hill	585044.5	207272.2	2.5	Yes	**46.3**
MD25	1 Hillside	585015.4	207241.2	2.5	Yes	30.9
MD26	18 Market Hill	585045	207186	2.5	Yes	39.1
MD27	6 Market Hill	585074.1	207132.4	2.5	Yes	**61.8**
MD28	21 Market Hill	585067	207116.2	2.5	Yes	28.9

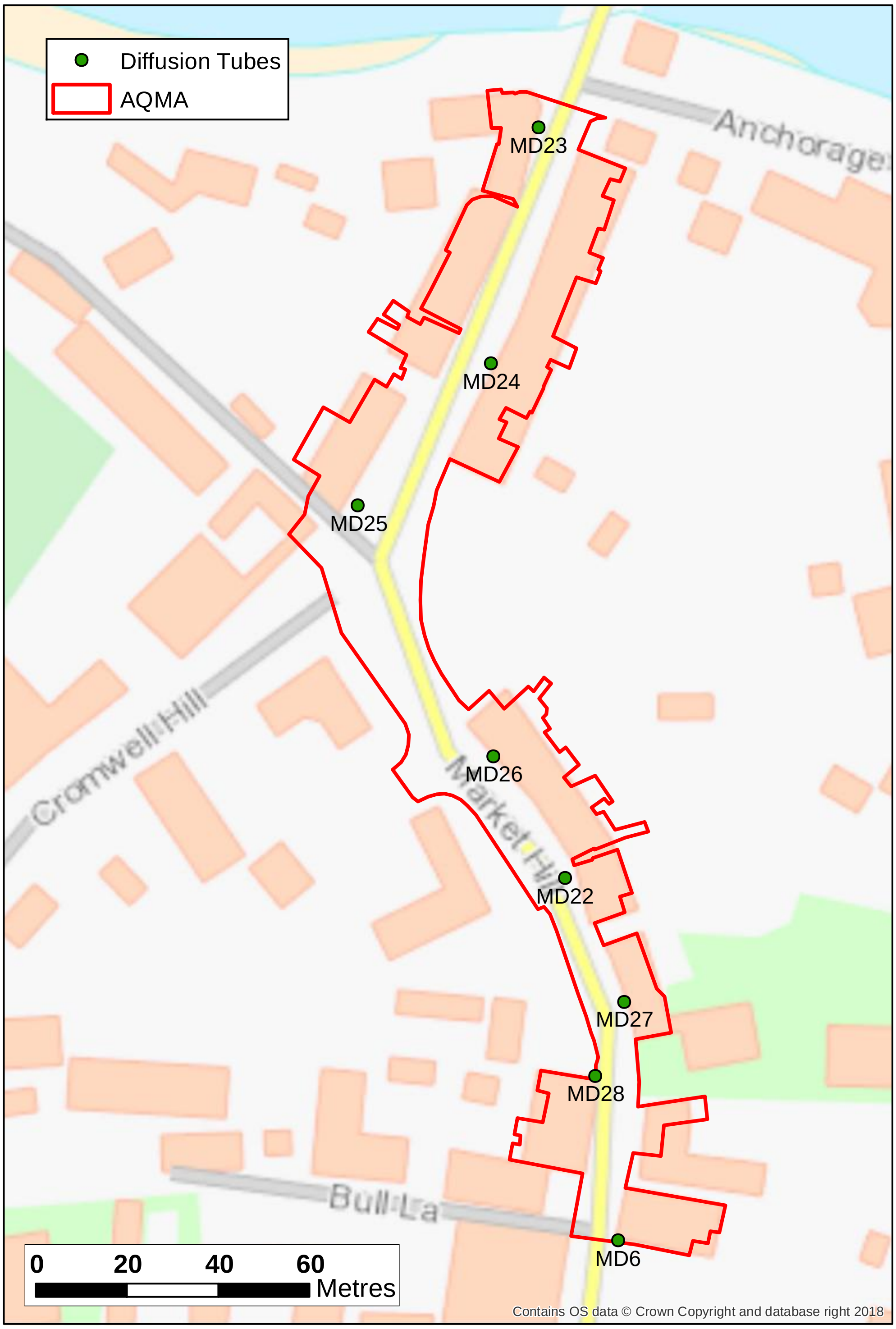

Figure 4.1: Location map of the AQMA and diffusion tubes along Market Hill, Maldon

5 Emissions data

An emissions inventory was compiled for Maldon and the surrounding area for 2018 using CERC's emissions inventory toolkit (EMIT), version 3.6.0.

5.1 Traffic emissions

Emissions from road vehicles are calculated using traffic data and speed-dependent emission factors. The traffic data used in this modelling was taken from automatic traffic counts at two locations on Market Hill provided by Maldon District Council. The traffic count data is summarised in Table 5.1. The traffic count data comprised of northbound and southbound flows split into ten vehicle categories. The vehicle categories did not exactly match the eleven categories used for emissions calculations, for instance there was no split between cars, taxis and LGVs (Light Goods Vehicles), or between HGVs (Heavy Goods Vehicles) and buses. These splits were in the first instance calculated using the national data for a typical minor urban road[2]. This report provides an update, where the split between HGVs and buses is based on the bus counts derived from local timetables[3].

Table 5.1: Modelled traffic data based on automatic traffic count for Market Hill

Location	Direction	Average 12-hour weekday Speed (kph)	% Motor-cycle	% Car	% LGV	% Bus	% Rigid HGV	% Artic HGV	AADT
South Market Hill	Southbound	30	1.2	79.1	14.7	1.1	3.9	0.2	8372
	Northbound	37	1.0	79.9	14.9	1.1	3.1	0.1	8192
North Market Hill	Southbound	41	0.9	79.1	14.7	1.1	4.1	0.1	8148
	Northbound	40	1.3	78.6	14.5	1.1	4.4	0.1	8155

5.1.1 Traffic speeds

The automatic traffic count data included a fifteen minute breakdown of speeds. On the northbound (downhill) portion of Market Hill, 12-hour average weekday speeds were used, as summarised in Table 5.1. Initial model verification showed underprediction of concentrations, in particular at the monitors close to the uphill side of the road. To improve the model verification, and to account for emission uncertainties associated with steep road gradients, for the southbound (uphill) portions of the road the speed was set to 10km/h.

[2] https://www.gov.uk/government/statistical-data-sets/road-traffic-statistics-tra
[3] http://www.essexbus.info/map.html accessed 14th May 2019

5.1.2 Emission factors

5.1.2.1 Speed-related emission factors

Traffic emissions of NO_x, NO_2, and VOCs were calculated from traffic flows using the Emission Factor Toolkit[4]. The EfT emission factors include speed-emissions data for NO_x based on the COPERT 5 software tool[5]. The emissions data include primary NO_2 emission factors for each vehicle type resulting in accurate road-by-road NO_x and NO_2 emission rates.

Note that there is uncertainty surrounding the current emissions estimates of NO_x from all vehicle types, in particular diesel vehicles, in these factors; refer to for example an AQEG report from 2007[6] and a Defra report from 2011[7]. In order to address this discrepancy, the NO_x emission factors were modified based on recently published Remote Sensing Data (RSD)[8] for vehicle NO_x emissions. Scaling factors were applied to each vehicle category and Euro standard.

5.1.2.2 Gradient-related emission factors

Road gradient can have a significant effect on vehicle emissions, increasing the power demanded from the vehicle engine when travelling uphill, particularly for HGVs. The opposite occurs for vehicles going down the hill and emissions decrease. Since Market Hill has a steep gradient (up to 14%), the calculated vehicle emissions were adjusted based on Defra Technical Guidance TG (16)[9], which provides gradient and speed-dependent adjustment factors for older HGVs. The guidance assumes that there is no significant effect on emissions from motorcycles, cars, taxis, LGVs or new HGVs.

The general equation for the amended EF for vehicles going up a hill is:

$$\mathbf{EF_2 = EF_1\,(1+ G \times [C1 \times V + C2])}$$

For vehicles going down a hill the amended (reduced) EF is:

$$\mathbf{EF_2 = EF_1\,(1- G \times [C1 \times V + C2])} \text{ for gradients } \leq 2.5\%\text{; and}$$
$$\mathbf{EF_2 = EF_1\,(1- 0.025 \times [C1 \times V + C2])} \text{ for gradients } > 2.5\%$$

Where:

EF_1 = emission factor for vehicles travelling at the speed V on a level road (grams per vehicle km);
EF_2 = revised emission factor for vehicles travelling at the same speed V (grams per vehicle km);

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[4] https://laqm.defra.gov.uk/review-and-assessment/tools/emissions-factors-toolkit.html
[5] http://copert.emisia.com/
[6] Trends in primary nitrogen dioxide in the UK
[7] Trends in NOx and NO2 emissions and ambient measurements in the UK
[8] Carslaw, D and Rhys-Tyler, G 2013: New insights from comprehensive on-road measurements of NO_x, NO_2 and NH_3 from vehicle emission remote sensing in London, UK. *Atmos. Env.* **81** pp 339–347.
[9] https://laqm.defra.gov.uk/documents/LAQM-TG16-February-18-v1.pdf

V = vehicle speed (km per hour);
G = the gradient of the hill, expressed as a decimal fraction; and
C1 and C2 = gradient coefficients, which differ according to the HDV type, the emission standard and the pollutant of concern. These coefficients are given in Table 5.2 below for specific vehicle weight categories.

Table 5.2: Road Gradient Emission Coefficients

NO_x by Vehicle Category	Gradient Coefficients			
	Old Vehicles (pre 2014)		New Vehicles (from 2014)	
Vehicle weight category	C1	C2	C1	C2
Small rigid HGVa	0.29	10.74	0	0
Medium rigid HGVb	0.48	10.81	0	0
Articulated trucks	0.62	12.44	0	0
Urban buses and coaches	0.48	7.41	0	0
a All rigid HGV is defined as up to 14 tonnes. b Medium rigid HGV is defined as 14 tonnes and over.				

5.1.3 Time-varying emissions profiles

The variation of traffic flow on Market Hill during the day was taken into account by applying a set of diurnal profiles to the road emissions. Traffic data provided by MDC included a southbound and northbound vehicle count at fifteen minute intervals for the two automatic traffic sites on Market Hill. Averages for each hour across the two directions and traffic sites were used to create the profiles shown in Figure 5.1. The profiles were applied to Market Hill road and grid sources, representing other emissions aggregated on 1-km square basis, described in Section 5.2.

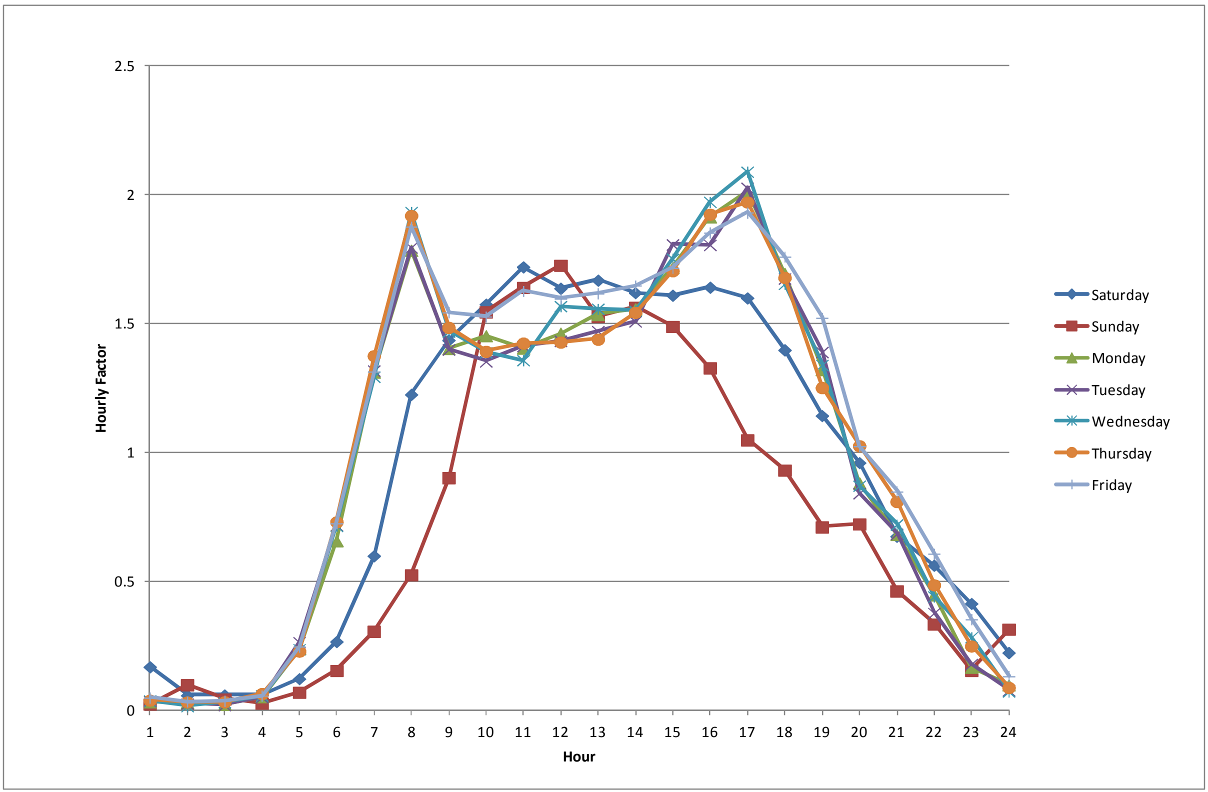

Figure 5.1: Diurnal profiles used for Market Hill road

5.2 Other emissions

Spatially-diffuse emissions from sources other than explicitly modelled road data were represented by a set of 1-km square grid sources with a depth of 10 m. Gridded emissions data for 2016 from the NAEI[10] were used to represent these sources.

Industrial emissions were included in the NAEI gridded emissions and not modelled explicitly as no significant point sources emitting NO_x or particulates were identified within 5 km of the modelled area.

[10] http://naei.defra.gov.uk/

6 Model set-up

Modelling was carried out using the ADMS-Urban[11] model (version 4.2.0). The model uses the detailed emissions inventory described in Section 5 together with a range of other input data to calculate the dispersion of pollutants. This section summarises the data and assumptions used in the modelling.

6.1 Surface roughness

A length scale parameter called the surface roughness length is used in the model to characterise the assessment area in terms of the effects it will have on wind speed and turbulence, which are key factors in the modelling. A value of 0.5 m was used to represent Maldon, representing the built-up nature of the area.

6.2 Monin-Obukhov length

In urban and suburban areas a significant amount of heat is emitted by buildings and traffic, which warms the air within and above an urban area. This is known as the urban heat island and its effect is to prevent the atmosphere from becoming very stable. In general, the larger the urban area the more heat is generated and the stronger the effect becomes.

In the ADMS-Urban model, the stability of the atmosphere is represented by the Monin-Obukhov parameter, which has the dimension of length. In very stable conditions it has a positive value of between 2 metres and 20 metres. In near neutral conditions its magnitude is very large, and it has either a positive or negative value depending on whether the surface is being heated or cooled by the air above it. In very convective conditions it is negative with a magnitude of typically less than 20 metres.

The effect of the urban heat island is that, in stable conditions, the Monin-Obukhov length will never fall below some minimum value; the larger the urban area, the larger the minimum value. A value of 10 m was used in the modelling.

[11] http://www.cerc.co.uk/environmental-software/ADMS-Urban-model.html

6.3 Meteorological data

Meteorological data from Southend for the year 2018 were used in the modelling. A summary of the data is given in Table 6.1. Figure 6.1 shows a wind rose giving the frequency of occurrence of wind from different directions for a number of wind speed ranges. A value of 0.2 metre was used for the surface roughness for the met site.

Table 6.1: Hours of meteorological data used in the modelling

Year	Percentage used	Parameter	Minimum	Maximum	Mean
2018	97.1	Temperature (°C)	-8	32	11.5
		Wind speed (m/s)	0	17.5	4.2
		Cloud cover (oktas)	0	8	3.0

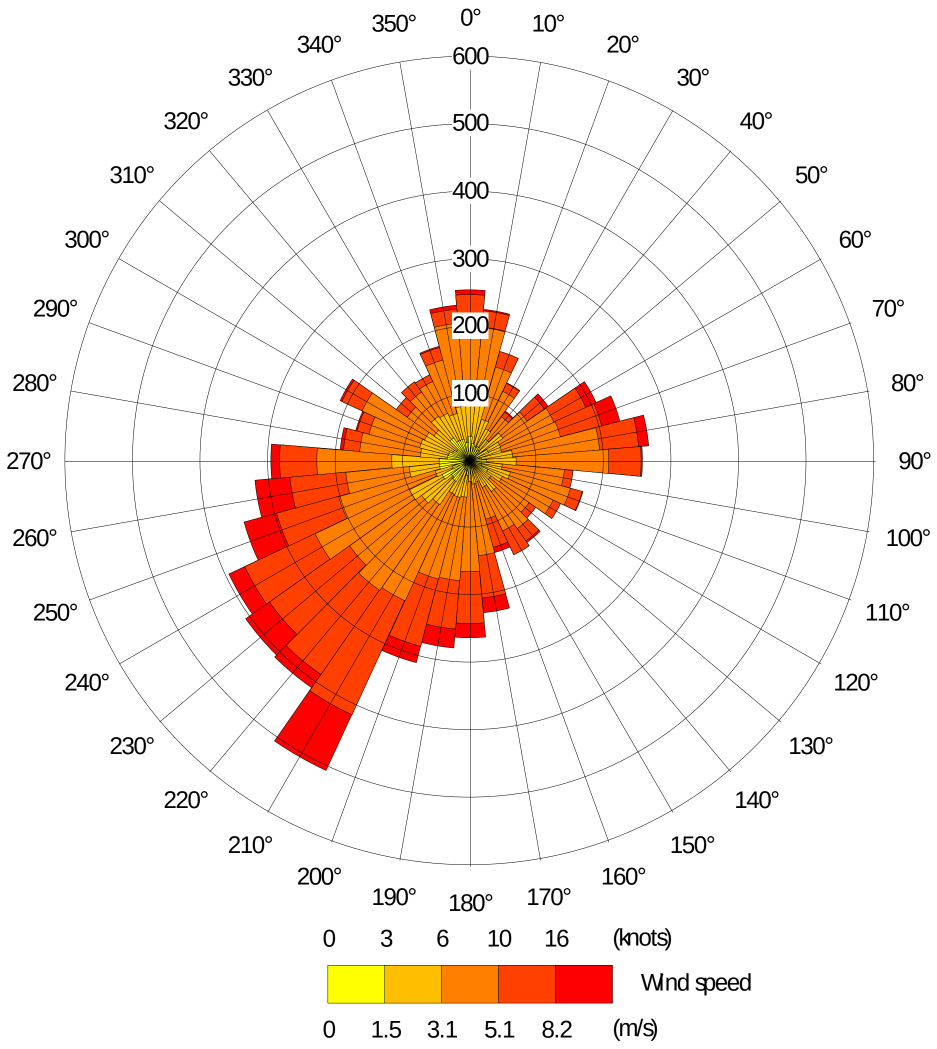

Figure 6.1: Wind rose for Southend 2018

6.4 Background concentrations

Nitrogen dioxide (NO_2) results from direct emissions from combustion sources together with chemical reactions in the atmosphere involving NO_2, nitric oxide (NO) and ozone (O_3). The combination of NO and NO_2 is referred to as nitrogen oxides (NO_x).

The chemical reactions taking place in the atmosphere were taken into account in the modelling using the Generic Reaction Set (GRS) of equations. These use hourly average background concentrations of NO_x, NO_2 and O_3, together with meteorological and modelled emissions data to calculate the NO_2 concentration at a given point.

Background concentrations of NO_x, NO_2, and O_3 were obtained from Rochester Stoke rural background monitoring site, located approximately 30 km south of Maldon. Hourly background data for these pollutants were input to the model to represent the concentrations in the air being blown into Maldon.

Table 6.2 summarises the annual statistics of the resulting background concentrations used in the modelling for 2018.

Table 6.2: Background concentrations for 2018 (μg/m^3)

	NO_x	NO_2	O_3
Annual average	16.8	13.1	54.5
99.79th percentile of hourly average	130.9	58.2	154.0

6.5 Street canyons

The presence of buildings either side of a road can introduce street canyon effects that result in pollutants becoming trapped, leading to increased pollutant concentrations. Street canyon effects were taken into account using the ADMS Advanced Canyon option, which makes use of detailed information for roadside buildings. Street canyon parameters were calculated from OS Mastermap buildings data. The road was divided into sections which had constant gradient and canyon properties. Different street canyon data were calculated for each of these road sections. The locations of the monitoring sites were refined so that the modelled locations were the correct distance from the modelled roads and within the appropriate street canyons.

7 Model verification

The first stage of a modelling assessment is to verify that the input data and model setup are representative for the area. This is carried out by calculating annual average concentrations of NO_2 at the monitoring sites at which they are measured and, if necessary, adjusting model input parameters within realistic ranges to improve agreement between the modelled and measured concentrations.

Following adjustment of the road emissions to account for road gradients and real-world engine performance, initial model verification showed underprediction of roadside concentrations compared to the measured data, particularly at the monitors next to the southbound (uphill) side of the road. Further investigation showed that these discrepancies were unlikely to be due to uncertainties in the dispersion calculations, but more likely to be due to underestimation of emissions or uncertainty in the measured data. To improve the agreement, and take account of possible uncertainty in the gradient emissions adjustments, the average speed of vehicles travelling uphill was set to 10 km/h.

Table 7.1 and Figure 7.1 show the measured and modelled annual average NO_2 concentrations for 2018 taking into account these changes.

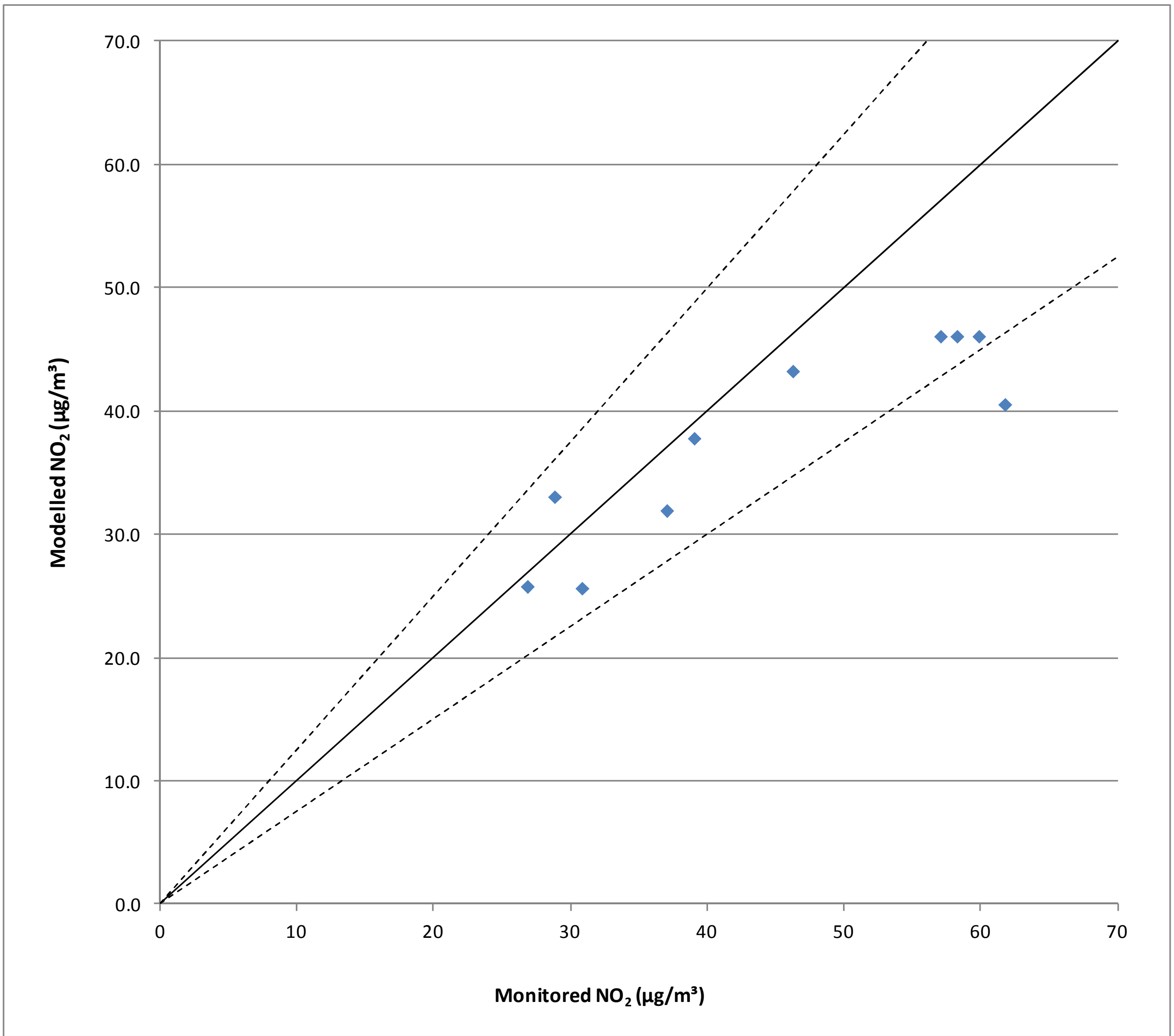

Figure 7.1: Measured and modelled annual average NO_2 concentrations

Table 7.1: Measured and modelled annual average NO_2 concentrations (µg/m³)

ID	Site Name	Measured	Modelled	Modelled %
MD6	High Street (Market Hill Junction)	26.9	25.7	96
MD22A	10 Market Hill, Maldon	**57.1**	**46.0**	81
MB22B		**58.3**		79
MD22C		**59.9**		77
MD23	59-63 Market Hill, Maldon	37.1	31.9	86
MD24	32 Market Hill	**46.3**	**43.2**	93
MD25	1 Hillside, Maldon	30.9	25.6	83
MD26	18 Market Hill, Maldon	39.1	**37.8**	97
MD27	6 Market Hill, Maldon	**61.8**	**40.5**	66
MD28	21 Market Hill, Maldon	28.9	33.0	114

The modelled concentrations show generally good agreement with the measured data with no consistent under or over-prediction. The modelled concentrations are within 25% of the measured data at 9 of the 10 sites considered; 3 sites are within 10% of the measured data.

The main difference is underpredicting at site MD27; this could be due to traffic queuing from the pedestrian crossing near the High Street. Queuing data were not available and so could not be modelled explicitly without potentially overestimating concentrations at other locations on Market Hill.

8 NO_2 concentrations

Ground level concentrations of NO_2 were calculated on a regular grid of receptor points, with additional points added along Market Hill road, in order to more accurately capture roadside concentrations. Concentrations were calculated to allow comparison against the air quality standards presented in Section 3, and presented in the form of coloured contour maps. The contour maps are presented showing areas with concentrations exceeding the air quality standards shown in yellow and red and areas with concentrations below the standards shown in green and blue.

Figure 8.1 and Figure 8.3 show the modelled annual average and the modelled 99.79th percentile of hourly average NO_2 concentrations for 2018.

The modelled concentrations show exceedences of the annual average NO_2 limit value of 40 µg/m³ along the sections of Market Hill with street canyons. The exceedences here, which are shown in more detail in Figure 8.2, could extend to the properties lining the roads.

The modelled concentrations show exceedences of the hourly average NO_2 limit value of 200 µg/m³. The extent of these exceedences are similar to the extent of the exceedences of the annual average limit value.

Figure 8.1: Annual average NO_2 concentrations (µg/m³) along Market Hill, Maldon

Figure 8.2: Modelled exceedences of annual average NO_2 standard along Market Hill, Maldon

Figure 8.3: Modelled 99.79th percentile of hourly average NO_2 concentrations (µg/m³) along Market Hill Maldon

9 NO_x source apportionment

Using the results of the baseline ADMS-Urban modelling for 2018, source apportionment was carried out for Market Hill to determine the contribution of different sources types to concentrations of NO_x.

The contribution of different source groups to the total NO_2 concentration cannot be determined due to the non-linearity of the chemical reactions which take place in the atmosphere, therefore the total NO_x concentration is calculated and presented in this section.

The contribution of different source groups to total NO_2 concentrations will be related to the contribution of each group to total NO_x concentrations and the proportion of NO_x emissions emitted as NO_2, known as 'primary NO_2'. Therefore percentage primary NO_2 emissions for road traffic emissions are also provided.

Figure 9.1 shows the contribution of each source group to the total NO_x emissions, for the year 2018. The contribution of these sources to the total NO_x concentrations at the set of receptor locations is shown in Figure 9.2.

Source apportionment of NO_x concentrations at the receptor locations along Market Hill, for the year 2018, is summarised in Table 9.1.

Table 9.1: Summary of NO_x source apportionment for Market Hill, 2018 (μg/m³)

Source Group	MD6	MD22	MD23	MD24	MD25	MD26	MD27	MD28
Background	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
NAEI	7.1	7.1	7.2	7.1	7.0	7.1	7.1	7.1
Motorcycle	0.0	0.2	0.1	0.1	0.0	0.1	0.1	0.1
Car	10.3	33.2	19.2	30.7	9.9	21.3	26.7	15.4
LGV	5.5	17.8	10.4	16.6	5.4	11.0	14.3	8.0
Bus and Coach	3.1	13.3	3.9	9.1	2.9	12.1	10.3	8.3
Rigid	5.1	22.6	6.6	15.3	4.8	20.8	17.4	14.2
Articulated	0.3	1.5	0.2	0.5	0.2	1.4	1.2	1.0

Note that there is some uncertainty in the relative contributions of each type of vehicle. In particular, the speed of vehicles travelling uphill was set to 10 km/hr which took into account underestimate of emissions detected during the model verification. However, the reason for this underestimate of emissions is unclear, it could be for instance that the gradient adjustments for light or heavy vehicles are not appropriate in this case, or that there is a significant amount of stop-start driving giving rise to increased emissions, or that the national vehicle fleet composition used is not representative of the local vehicle fleet. Each of these could affect the source apportionment in different ways.

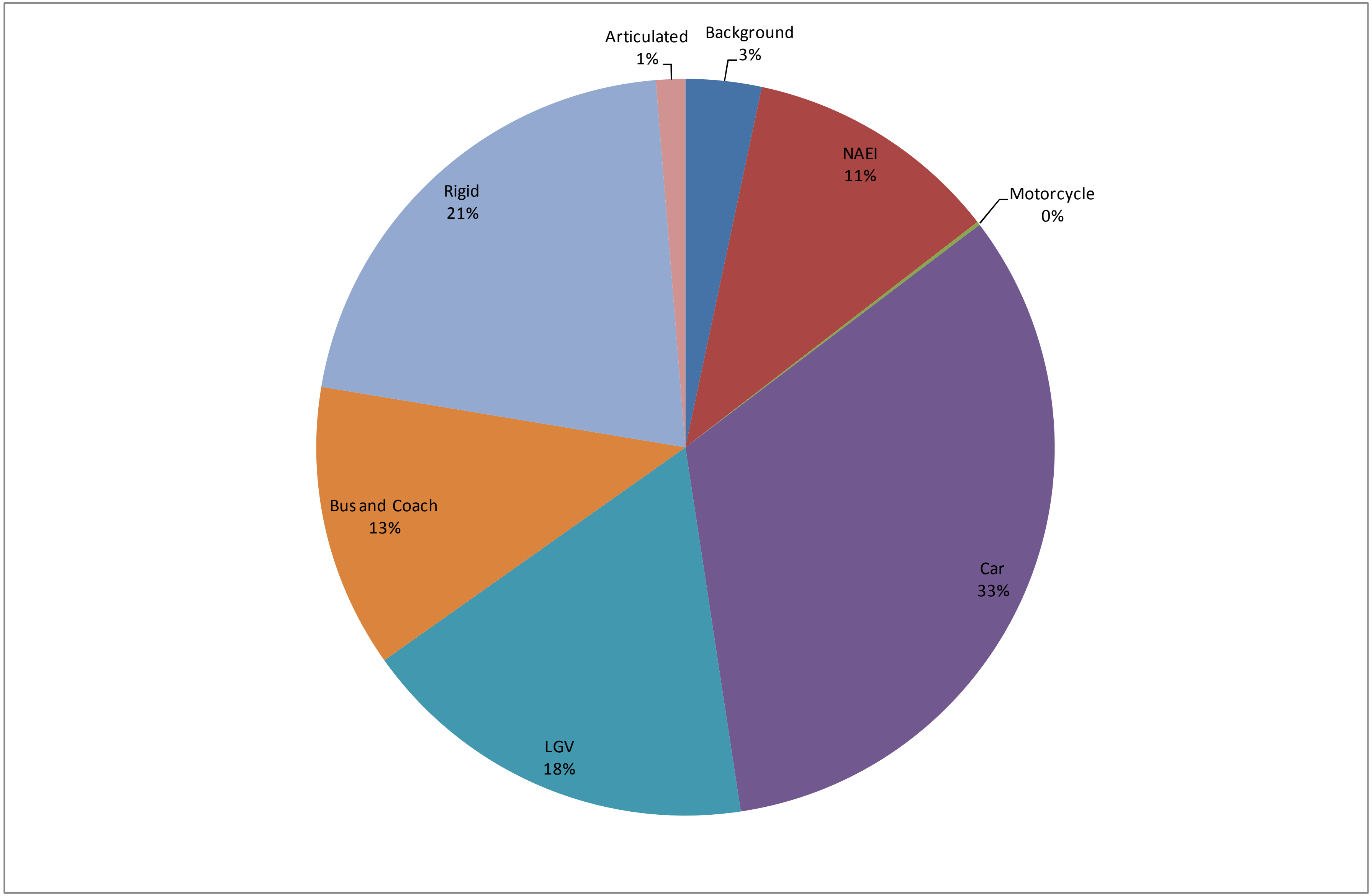

Figure 9.1: Market Hill NO_x emissions by source type, 2018

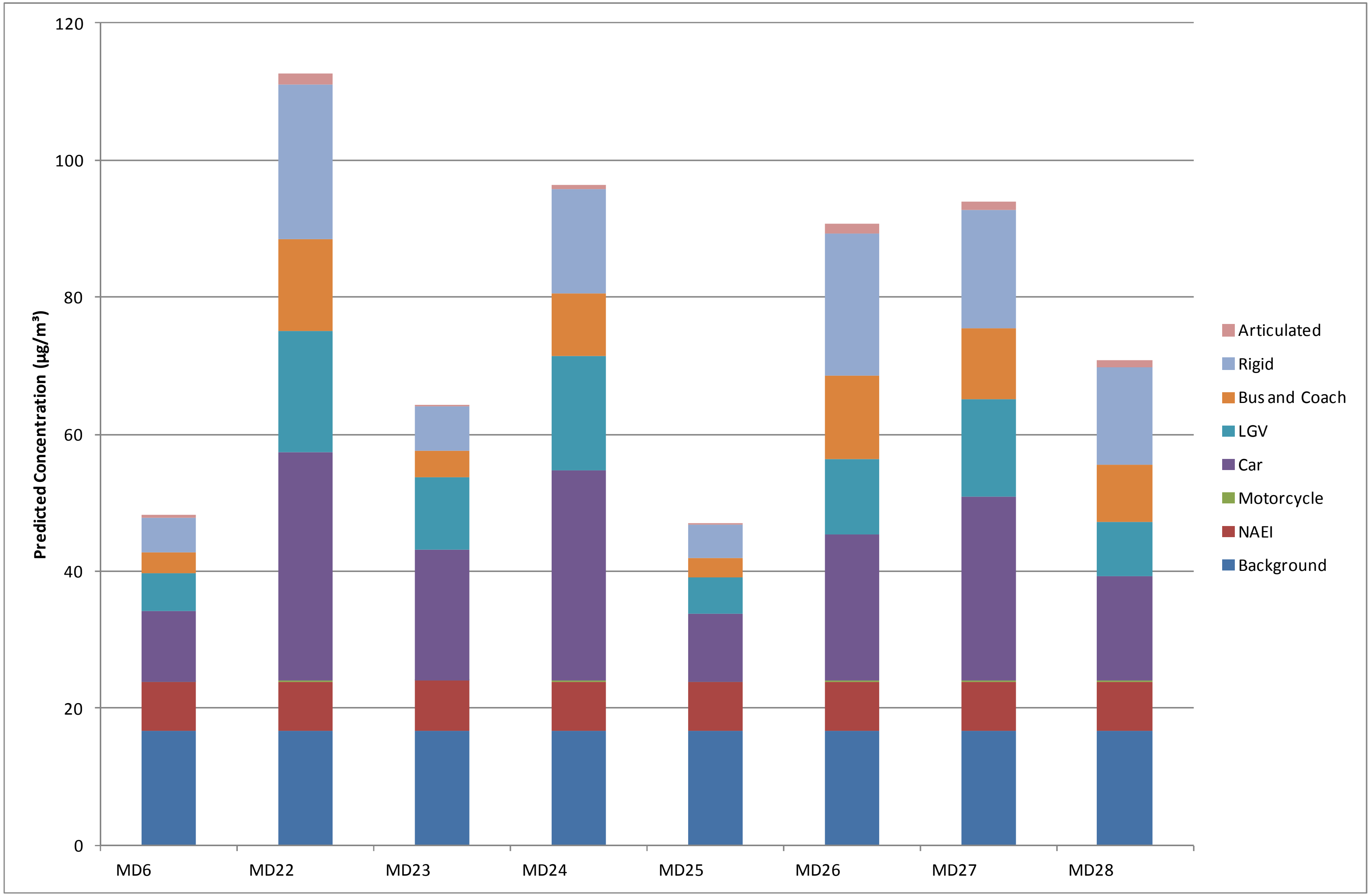

Figure 9.2: NO_x source apportionment by source type, 2018 (µg/m³)

10 Discussion

Air quality modelling was carried out for baseline conditions in 2018 for Market Hill using ADMS-Urban (version 4.2). Detailed source apportionment and baseline modelling was required to support the Quality Action Plain (AQAP) for the new AQMA at Market Hill, Maldon.

Pollutant emissions from vehicles were calculated using automatic traffic count data provided by the council at two locations on Market Hill. Vehicle emissions were calculated using speed-dependent emission factors from the EFT. To take account of the uncertainty of emission rates from diesel vehicles, emission factors were adjusted based on real-world remote sensing data. The steep gradient on Market Hill was accounted for by adjusting emission factors of HGVs, based on Defra Technical Guidance TG (16). Emissions data from other sources were taken from the National Atmospheric Emissions Inventory.

The advanced street canyon option in ADMS-Urban model was used to account for the effect of buildings in detail. The road was split into sections with constant gradient and canyon properties; street canyon data were calculated separately for each of these road sections. The street canyon inputs for Market Hill were fully reviewed as part of model verification to insure that the model inputs are representative.

Model verification was carried out, comparing modelled concentrations with measured data for 2018. Initial model verification showed underprediction of roadside concentrations, particularly at monitors adjacent to the east (uphill) side of the road. Further investigation showed that the underprediction was unlikely to be due to the dispersion calculations, but more likely to be either due to underestimation of vehicle emissions, or uncertainties in the monitoring data.

To improve the model verification, and take account of the likely underestimation of emissions, the average speed of vehicles travelling uphill was set to be 10 km/hr. After this adjustment, the modelled concentrations showed generally good agreement with the measured data with the majority of modelled concentrations within 25% of the measured data and no systematic under or overprediction of concentrations.

Note that the reason for the underestimation of emissions is not clear. It could be, for instance, that the gradient adjustments for light or heavy vehicles are not appropriate in this case, or that there is a significant amount of stop-start driving giving rise to increased emissions, or that the national vehicle fleet composition used is not representative of the local vehicle fleet. Each of these could affect emissions from each vehicle type in different ways, whereas changing the average speed to 10 km/hr increases emissions from all vehicle types. There is therefore some uncertainty in the relative contributions of each vehicle type to the total NO_x concentrations.

Modelling for 2018 showed exceedences of the annual and hourly average NO_2 limit values along the sections of Market Hill with street canyon properties, including locations with potential public exposure.

Source apportionment showed that the major contribution to annual average NO_x concentrations is from cars with significant contributions from LGVs, buses and rigid HGVs.

APPENDIX A: Summary of ADMS-Urban

ADMS-Urban is a scientifically advanced but practical air pollution modelling tool, which has been developed to provide high resolution calculations of pollution concentrations for all sizes of study area relevant to the urban environment. The model can be used to look at concentrations near a single road junction or over a region extending across the whole of a major city. ADMS-Urban has been extensively used for the Review and Assessment of Air Quality carried out by Local Authorities in the UK and for a wide range of planning and policy studies across the world. The following is a summary of the capabilities and validation of ADMS-Urban. More details can be found on the CERC web site at www.cerc.co.uk.

ADMS-Urban is a development of the Atmospheric Dispersion Modelling System (ADMS), which has been developed to investigate the impacts of emissions from industrial facilities. ADMS-Urban allows full characterisation of the wide variety of emissions in urban areas, including an extensively validated road traffic emissions model. It also includes a number of other features, which include consideration of:

- the effects of vehicle movement on the dispersion of traffic emissions;
- the behaviour of material released into street-canyons;
- the chemical reactions occurring between nitrogen oxides, ozone and Volatile Organic Compounds (VOCs);
- the pollution entering a study area from beyond its boundaries;
- the effects of complex terrain on the dispersion of pollutants; and
- the effects of a building on the dispersion of pollutants emitted nearby.

Further details of these features are provided below.

Studies of extensive urban areas are necessarily complex, requiring the manipulation of large amounts of data. To allow users to cope effectively with this requirement, ADMS-Urban runs in Windows 10, Windows 8, Windows 7 and Windows Vista environments. The manipulation of data is further facilitated by the possible integration of ADMS-Urban with a Geographical Information System (GIS) (MapInfo, ArcGIS, or the ADMS-Mapper) and the CERC Emissions Inventory Toolkit, EMIT.

Dispersion Modelling

ADMS and ADMS-Urban use boundary layer similarity profiles to parameterise the variation of turbulence with height within the boundary layer, and the use of a skewed-Gaussian distribution to determine the vertical variation of pollutant concentrations in the plume under convective conditions.

The main dispersion modelling features of ADMS-Urban are as follows:

- ADMS-Urban is an **advanced dispersion model** in which the boundary layer structure is characterised by the height of the boundary layer and the Monin-Obukhov length, a length scale dependent on the friction velocity and the heat flux at the surface. This method supersedes methods based on Pasquill Stability Categories, as used in, for example, Caline and ISC. Concentrations are calculated hour by hour and are fully dependent on prevailing weather conditions.
- For convective conditions, a **non-Gaussian vertical profile of concentration** allows for the skewed nature of turbulence within the atmospheric boundary layer, which can lead to high concentrations near to the source.
- A **meteorological pre-processor** calculates boundary layer parameters from a variety of input data, typically including date and time, wind speed and direction, surface temperature and cloud cover. Meteorological data may be raw, hourly averaged or statistically analysed data.

Emissions

Emissions into the atmosphere across an urban area typically come from a wide variety of sources. There are likely to be industrial emissions from chimneys as well as emissions from road traffic and domestic heating systems. To represent the full range of emissions configurations, the explicit source types available within ADMS-Urban are:

- **Roads**, for which emissions are specified in terms of vehicle flows and the additional initial dispersion caused by moving vehicles is also taken into account.
- **Industrial points**, for which plume rise and stack downwash are included in the modelling.
- **Areas**, where a source or sources is best represented as uniformly spread over an area.
- **Volumes**, where a source or sources is best represented as uniformly spread throughout a volume.

In addition, sources can also be modelled as a regular grid of emissions. This allows the contributions of large numbers of minor sources to be efficiently included in a study while the majority of the modelling effort is used for the relatively few significant sources.

ADMS-Urban can be used in conjunction with CERC's Emissions Inventory Toolkit, EMIT, which facilitates the management and manipulation of large and complex data sets into usable emissions inventories.

Presentation of Results

The results from the model can be based on a wide range of averaging times, and include rolling averages. Maximum concentration values and percentiles can be calculated where appropriate meteorological input data have been input to the model. This allows ADMS-Urban to be used to calculate concentrations for direct comparison with existing air quality limits, guidelines and objectives, in whatever form they are specified.

ADMS-Urban can be integrated with the ArcGIS or MapInfo to facilitate both the compilation and manipulation of the emissions information required as input to the model and the interpretation and presentation of the air quality results provided.

Complex Effects - Street Canyons

ADMS-Urban incorporates two methods for representing the effect of street canyons on the dispersion of road traffic emissions: a basic canyon method based on the *Operational Street Pollution Model (OSPM)*[12], developed by the Danish National Environmental Research Institute (NERI); and an advanced street canyon module, developed by CERC. The basic canyon model was designed for simple symmetric canyons with height similar to width and assumes that road traffic emissions originate throughout the base of the canyon, i.e. that the emissions are spread across both the road and neighbouring pavements.

The advanced canyon model[13] was developed to overcome these limitations and is our model of choice. It represents the effects of channelling flow along and recirculating flow across a street canyon, dispersion out of the canyon through gaps in the walls, over the top of the buildings or out of the end of the canyon. It can take into account canyon asymmetry and restricts the emissions area to the road carriageway.

Complex Effects - Chemistry

ADMS-Urban includes the *Generic Reaction Set (GRS)*[14] atmospheric chemistry scheme. The original scheme has seven reactions, including those occurring between nitrogen oxides and ozone. The remaining reactions are parameterisations of the large number of reactions involving a wide range of Volatile Organic Compounds (VOCs). In addition, an eighth reaction has been included within ADMS-Urban for the situation when high concentrations of nitric oxide (NO) can convert to nitrogen dioxide (NO_2) using molecular oxygen.

In addition to the basic GRS scheme, ADMS-Urban also includes a trajectory model[15] for use when modelling large areas. This permits the chemical conversions of the emissions and background concentrations upwind of each location to be properly taken into account.

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[12] Hertel, O., Berkowicz, R. and Larssen, S., 1990, 'The Operational Street Pollution Model (OSPM).' *18th International meeting of NATO/CCMS on Air Pollution Modelling and its Applications.* Vancouver, Canada, pp741-749.

[13] Hood C, Carruthers D, Seaton M, Stocker J and Johnson K, 2014. *Urban canopy flow field and advanced street canyon modelling in ADMS-Urban.* 16th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Varna, Bulgaria, September 2014. http://www.harmo.org/Conferences/Proceedings/_Varna/publishedSections/H16-067-Hood-EA.pdf

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

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

Complex Effects - Terrain

As well as the effect that complex terrain has on wind direction and, consequently, pollution transport, it can also enhance turbulence and therefore increase dispersion. These effects are taken into account in ADMS-Urban using the FLOWSTAR[16] model developed by CERC.

Data Comparisons – Model Validation

ADMS-Urban is a development of the Atmospheric Dispersion Modelling System (ADMS), which is used throughout the UK by industry and the Environment Agency to model emissions from industrial sources. ADMS has been subject to extensive validation, both of individual components (e.g. point source, street canyon, building effects and meteorological pre-processor) and of its overall performance.

ADMS-Urban has been extensively tested and validated against monitoring data for large urban areas in the UK and overseas, including London, Birmingham, Manchester, Glasgow, Riga, Cape Town, Hong Kong and Beijing, during projects supported by local governments and research organisations. A summary of published model validation studies is available at www.cerc.co.uk/Validation, with other publications available at www.cerc.co.uk/publications.

[16] Carruthers D.J., Hunt J.C.R. and Weng W-S. 1988. 'A computational model of stratified turbulent airflow over hills – FLOWSTAR I.' Proceedings of Envirosoft. In: *Computer Techniques in Environmental Studies*, P. Zanetti (Ed) pp 481-492. Springer-Verlag.