Specialist Professional and Technical Services (SPATS) Framework

Task 61 – Lot 2
Geographical Pilot Study – Manchester M60

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Geographical Pilot Study – Manchester M60
Lot 1 SPaTS Framework

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APPENDICES

Appendix A – Spatial Patterns in Diffusion Tube Measurements
1. Setting the Scene

Introduction

The M60 is a 36 mile-long orbital motorway around Manchester. As well as connecting conurbations within the Greater Manchester district it forms an important part of the main east-west transport corridor, linking Merseyside and Greater Manchester with Yorkshire and the Humber; it also serves both national and international traffic movements, forming part of Euro Route 22, which links Siberia to Dublin. Traffic flows on sections of the M60 are reported to reach up to 180,000 vehicles per day\(^1\). As a consequence, it suffers from heavy congestion and unpredictable journey times, especially during peak periods. Annual mean nitrogen dioxide (\(\text{NO}_2\)) concentrations above the Air Quality Strategy (AQS) objective of 40 \(\mu\text{g/m}^3\) have been measured at a number of locations near to the M60 in Manchester in recent years. As several Highways England (HE) road improvement schemes (“smart motorways”) are currently being considered in this area, for which elevated annual mean \(\text{NO}_2\) concentrations could represent a potential constraint, HE wishes to investigate in detail the factors which influence \(\text{NO}_2\) concentrations adjacent to the M60. The intention is that, with an improved understanding of these factors, mitigation measures could potentially be developed to reduce annual mean \(\text{NO}_2\) concentrations in certain areas (for instance, as part of the proposed road improvement schemes).

Study Area

This pilot study focusses on the western section of the M60 in Manchester, between M60 Junction 9 and 15 (as shown in Figure 1). This area was selected primarily due to the quantity and extent of available air quality monitoring data as well as the presence of residential dwellings adjacent to either side of the motorway. The Environmental Assessment Report (EAR) for the M60 Junction 8 to M62 Junction 20 smart motorway scheme\(^2\), which is currently under construction, states that “congestion, journey delays, and disruption are inherent problems on these sections of the highway network attributable to: high volumes of strategic and local traffic; weaving and conflict between merging and diverging, strategic and local traffic movements; low speeds; vehicle queuing; and close junction spacing.” These characteristics are likely to influence roadside annual mean \(\text{NO}_2\) concentrations.

Areas of Interest

Monitoring results at the Salford M60 Continuous Monitoring Station (CMS), which is located adjacent to the M60, suggest that whilst the annual mean AQS objective was exceeded at this location in all years between 2004 and 2016, annual mean \(\text{NO}_2\) concentrations have reduced substantially in recent years (from 61.5 \(\mu\text{g/m}^3\) in 2013 to 45.5 \(\mu\text{g/m}^3\) in 2016 – a 26% reduction). Reductions in \(\text{NO}_2\) concentrations of this magnitude have not been observed at other CMS sites in the wider study area, which suggests that this reduction is potentially associated with a reduction in the contribution from the M60. Determining if this is indeed the case and understanding which factors may have caused this reduction could be highly informative with regard to mitigation measures which could be employed to reduce annual mean \(\text{NO}_2\) concentrations adjacent to the Strategic Road Network.

It is also of particular note that a 50 mph speed restriction has been in place on the M60 in the study area since mid-2014 during construction works associated with the aforementioned M60 smart motorway scheme. This speed restriction presents a potential opportunity to determine whether changes in vehicle speed have had an associated impact on annual mean \(\text{NO}_2\) concentrations.

\(^1\) http://roads.highways.gov.uk/projects/m60-junction-8-to-m62-junction-20-2/
\(^2\) Highways Agency (2013), Manchester Managed Motorways Phase 1, Environmental Assessment Report, Volume 1: Main Report.
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Figure 1: Approximate Study Area for Manchester M60 Pilot Study Showing All Monitoring Locations
Study Aims & Objectives

The aims and objectives of this pilot study are to:

• Determine the relative contribution from road traffic, in particular from the M60, and that of other sources to annual mean NO\textsubscript{2} concentrations measured in the study area;
• Determine which factors (e.g. vehicle type and vehicle speed) have the greatest influence on the contribution from the M60 to annual mean NO\textsubscript{2} concentrations;
• Investigate observed trends in monitored NO\textsubscript{2} concentrations and by doing so understand why concentrations have decreased as they have over time;
• Examine the effects of vehicle speed on NO\textsubscript{2} concentrations and therefore the potential efficacy of speed restrictions as an air quality mitigation measure.

Structure of Report

This report is structured as follows:

• Existing air quality and traffic data conditions in the study area are summarised in Section 2;
• The estimated contributions from background sources to measured annual mean NO\textsubscript{2} concentrations in the study area are described in Section 3;
• The estimated contribution from road traffic and specifically the M60, to measured annual mean NO\textsubscript{2} concentrations is described in Section 4;
• Trends in measured NO\textsubscript{x} and NO\textsubscript{2} concentrations are described and investigated in Section 5;
• The effect of the 50 mph speed restriction on measured NO\textsubscript{2} concentrations is evaluated in Section 6;
• The conclusions of the study and implications for Highways England are provided in Section 7; and
• Lessons learned, for instance which investigative techniques have worked well and could be applied elsewhere, are discussed in Section 8.
2. Air Quality & Traffic Conditions

Air Quality
The data sources reviewed in this pilot study include:

- HE NO\textsubscript{2} diffusion tube data, from surveys undertaken to support various HE scheme assessments between 2014 and 2016. There are over 100 monitoring sites in the study area adjacent to the M60 and along transects perpendicular to the main carriageway. These data provide information regarding spatial variations in NO\textsubscript{2} concentrations adjacent to the M60;
- local authority diffusion tube survey data, which include sites at which monitoring has been undertaken for a number of years, which provide information regarding annual mean NO\textsubscript{2} concentrations over the longer term;
- a Continuous Monitoring Station (CMS) adjacent to the M60 near Junction 13 (Salford M60), which given its location and proximity to the M60 presents a unique opportunity to analyse in detail the contribution of the motorway to NO\textsubscript{2} concentrations at this location;
- other CMS in the wider area, including a rural background site at Glazebury, an urban background site at Trafford, an industrial site at Salford Eccles and a roadside site adjacent to the A56 in Trafford.

Diffusion Tube Data
The results of NO\textsubscript{2} diffusion tube monitoring undertaken by Highways England and local authorities within and surrounding the study area are illustrated below in Figure 2, Figure 3 and Figure 4 for the years 2014, 2015 and 2016 respectively\textsuperscript{3}. These results indicate that NO\textsubscript{2} concentrations were exceeded at 22 of 102 locations in the study area in 2014, 19 out of 106 locations in 2015 and 5 out of 18 locations in 2016. The majority of the locations where the AQS objective was exceeded are located within 50 m of the M60 and between Junction 12 and Junction 14. Annual mean NO\textsubscript{2} concentrations adjacent to the M60 therefore appear to vary in magnitude along different sections of the M60. Such differences might for example indicate particular traffic conditions on the M60 (e.g. flow, composition or congestion) which contribute to elevated annual mean NO\textsubscript{2} concentrations.

\textsuperscript{3} Where required, these data have been annualised to represent conditions over a full calendar year in accordance with the methodology described in Box 7.8 of LAQM.TG16.
Figure 2: Measured 2014 Annual Mean NO₂ Concentrations in Study Area

Figure 3: Measured 2015 Annual Mean NO₂ Concentrations in Study Area
Continuous Monitoring Data

The Salford M60 CMS is located within the grounds of St Mark’s Primary School. It is classified as a roadside site and is situated approximately 20 metres to the west of the northbound carriageway of the M60, some 330 metres northeast of M60 Junction 13 (see Figure 5). The elevation of the CMS is approximately equal to that of the motorway.

Monitoring at this site commenced in 1999 and the CMS has been operated and maintained by Ricardo on behalf of Salford Borough Council since at least 2004. The quality of the data obtained at this site is thus considered to be high and equal to that of a DEFRA (Automatic Urban and Rural Network) AURN site.

http://www.airqualityengland.co.uk/local-authority/?la_id=300
Annual mean NO$_2$ concentrations measured at the Salford M60 CMS between the years 2004 and 2016 are shown in Figure 6. These data indicate that the annual mean NO$_2$ AQS objective (40 µg/m$^3$ shown by a red line in the figure) was exceeded at this site in all years. Whilst measured concentrations were relatively consistent between 2004 and 2013, there was a marked reduction in measured concentrations between 2013 and 2016. This downward trend at the Salford M60 CMS in the last three years appears to be unique when compared to trends at other CMS in the Greater Manchester area (see Figure 7 and locations in Figure 1), which suggests that this reduction may be associated with a reduction in the contribution from the M60.
Figure 6: Measured Annual Mean NO₂ Concentrations at Salford M60 CMS (2004 – 2016)

Figure 7: Measured Annual Mean NO₂ Concentrations at CMS in Wider Area* (2004 – 2016)

Meteorological Data
Hourly wind speed and direction data obtained from Manchester Airport, which is located approximately 10 km southeast of the study area, are summarised for 2004 – 2016 in the wind rose and polar plot shown in Figure 8. These indicate that the prevailing winds are from the south, whilst there is also a distinct westerly component.

See Figure 1
Traffic Conditions

Qualitative descriptions of traffic conditions along the M60 within the study area are provided in the following sub-sections, which have been taken from the EAR for the Manchester Managed Motorways scheme:

**M60 Junctions 8 - 12**

This section comprises a three-lane motorway with an approximate length of 6km. Currently experiencing congestion and possessing a poor safety record, the carriageway lies adjacent to neighbouring residential areas and contains closely spaced junctions.

Between Junctions 11 and 12 a two-lane southbound carriageway is supplemented by a two-lane distributor road. An extra lane is also introduced at Junction 11 which carries slow moving heavy goods vehicles (HGVs). A limited ‘weaving length’ between Junctions 11 and 12, the lack of hard shoulder and narrow lanes through Junction 12 cause operational problems.

Traffic generated by the nearby Trafford Centre frequently causes major queues in lane one along this section.

**M60 Junctions 12 - 15**

This section of motorway, approximately 5km long, is one of the most congested sections of the strategic road network in the country, with peak period traffic recorded between 5,000 and 8,000 vehicles per hour along both carriageways. The carriageways vary between three and four lanes in each direction.

During normal operating conditions, average speeds between the junctions can drop to as low as 15 mph; a problem which is exacerbated further during events such as bad weather, road works, and motorway incidents. Delays frequently arise, particularly between Junctions 12 and 13 (A572) and on the approaches to Junction 15 (M60 and M61), where morning peak period congestion on the anti-clockwise carriageway results in long queues of standing traffic on the southbound carriageway of the M61.

Congestion also impacts on the surrounding local road network as traffic is unable to access the motorway, resulting in delays to private vehicles and public transport, as well as causing delays for pedestrians and cyclists. Other issues include high levels of HGVs using the section as an integral part of trans-Pennine journeys between Leeds and Liverpool and a poor safety record between Junctions 12 and 13.

**Traffic Flows**

The measured traffic flows shown in Table 1 indicate that there are significant variations in traffic flow and composition along different sections of the M60 within the study area. For example, these data indicate that total traffic volumes between J12 to J15 of the M60 are up to 34% higher than between J10 and J12. Furthermore, the number of Heavy Goods Vehicles (HGVs) between J12 and J15, in both
absolute and relative terms, is approximately twice that between J9 and J12. These additional vehicle movements, in particular the additional HGV movements, are thought to relate to vehicles using the M62 (for example to travel to and/from Liverpool), which joins the M60 at J12 and has a high proportion of HGV movements.

Table 1: Measured Motorway Traffic Flows in Study Area in 2015

<table>
<thead>
<tr>
<th>Motorway Section</th>
<th>2015 Measured Daily Traffic Flow</th>
<th>HGV%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Cars</td>
</tr>
<tr>
<td>M60 J14 – J15</td>
<td>155,382</td>
<td>113,408</td>
</tr>
<tr>
<td>M60 J13 – J14</td>
<td>152,403</td>
<td>115,058</td>
</tr>
<tr>
<td>M60 J12 – J13</td>
<td>176,853</td>
<td>132,320</td>
</tr>
<tr>
<td>M60 J11 - J12</td>
<td>133,172</td>
<td>106,191</td>
</tr>
<tr>
<td>M60 J10 – J11</td>
<td>131,991</td>
<td>105,706</td>
</tr>
<tr>
<td>M60 J9 – J10</td>
<td>108,500</td>
<td>85,707</td>
</tr>
<tr>
<td>M62 J11 – J12</td>
<td>124,232</td>
<td>89,992</td>
</tr>
</tbody>
</table>

SOURCE: https://www.dft.gov.uk/traffic-counts/

Measured HGV flows broken down by vehicle type and number of axles, as shown in Table 2, suggest that the difference in HGV flows between J12 and J15 compared to between J9 to J12 is primarily as a result of a greater number of larger, articulated HGVs. The movements of these larger vehicles are thought likely to be more ‘strategic’ in nature (i.e. they travel greater distances) and again these vehicles are thought to relate to vehicles using the M62.

Table 2: Measured Motorway HGV Flows in Study Area in 2015

<table>
<thead>
<tr>
<th>Motorway Section</th>
<th>2 Axle</th>
<th>3 Axle</th>
<th>4 or 5 Axle</th>
<th>3 or 4 Axle</th>
<th>5 Axle</th>
<th>6 or More Axle</th>
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<tr>
<td>M60 J14 – J15</td>
<td>4,777</td>
<td>593</td>
<td>916</td>
<td>465</td>
<td>2,590</td>
<td>8,987</td>
</tr>
<tr>
<td>M60 J13 – J14</td>
<td>3,193</td>
<td>1,003</td>
<td>750</td>
<td>698</td>
<td>1,577</td>
<td>9,109</td>
</tr>
<tr>
<td>M60 J12 – J13</td>
<td>3,989</td>
<td>1,098</td>
<td>1,085</td>
<td>641</td>
<td>1,568</td>
<td>8,702</td>
</tr>
<tr>
<td>M60 J11 – J12</td>
<td>2,889</td>
<td>626</td>
<td>847</td>
<td>210</td>
<td>1,174</td>
<td>3,376</td>
</tr>
<tr>
<td>M60 J10 – J11</td>
<td>2,455</td>
<td>556</td>
<td>733</td>
<td>199</td>
<td>1,007</td>
<td>3,329</td>
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<tr>
<td>M60 J9 – J10</td>
<td>2,469</td>
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<td>692</td>
<td>225</td>
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<td>3,154</td>
</tr>
<tr>
<td>M62 J11 – J12</td>
<td>3,087</td>
<td>698</td>
<td>735</td>
<td>602</td>
<td>2,144</td>
<td>7,553</td>
</tr>
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</table>

SOURCE: https://www.dft.gov.uk/traffic-counts/

Detailed traffic data have also been obtained for the M60 between J13 and J14, adjacent to the Salford M60 CMS site. The main source of these data is MIDAS data collection points along the motorway which record minute by minute data for each lane consisting of vehicle number, length and speed. These data have been processed into hourly average traffic flows for Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs) and speed. The average speed dataset has been supplemented, during periods where data is missing, by Trafficmaster data which have been used to estimate vehicle speeds based on journey time data between two points on the motorway. Comparison of average speeds determined using MIDAS data and Trafficmaster data respectively suggest that the values derived are relatively consistent. Trends in total traffic flow, HDV flow and average vehicle speed derived from the data described above are presented in Figure 9, which suggest that:

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6 The number of axles is representative of vehicle size, with larger vehicles likely to have more axles.
8 Motorway Incident Detection and Automatic Signalling (MIDAS) data consist of speed and vehicle length measurements collected per minute for each lane on a motorway as vehicles pass cameras located at suitable locations.
9 Vehicle type was defined based on length with the first two MIDAS categories representing LDVs and the latter two HDVs. LDVs comprise cars and LGVs, whilst HDVs comprise HGVs and buses.
10 Trafficmaster data contains Global Positioning System (GPS) derived journey times of vehicles.
• total traffic flows increased between 2004 and 2011, from approximately 5,900 vehicles per hour to 6,500 (a 10% increase);
• two-way HDV flows decreased slightly between 2004 and 2011, from approximately 710 vehicles per hour to 660 (a 7% decrease);
• Between 2011 and 2014 both traffic flows and HDV flows remained relatively stable;
• average speeds decreased slightly between 2004 to 2007, after which speeds remained relatively consistent from 2007 to 2013 at around 98 kph (approximately 60mph). It is clear that following the implementation of the 50 mph speed restriction in September 2014, there was a large step change in the average speed to 70 kph (i.e. approximately 45 mph).

Figure 9: Trends in Monthly Average Hourly Two-Way Total Flows (top), HDV Flow (middle) and Speed (bottom) (2004 – 2016)  

Figure 10 to Figure 13 show the temporal variations over hours of the day, months and weekdays for total traffic flow, HDV flow, HDV% and speed respectively. Figure 10 indicates that there is a clear diurnal profile for total traffic flow with consistent AM and PM peaks during weekdays. Flows at weekends are more unimodal, peaking between 12:00 and 18:00, with lower flows during each hour of the day than on weekdays. There is also some seasonal variation in traffic flows, with lower hourly flows in winter and spring, potentially associated with public holidays such as Christmas and Easter. Typically, traffic flows increase over the course of the week from Monday to Friday, and decrease considerably at weekends.

Figure 11 indicates that HDV flows are highest between 10:00 and 14:00 on weekdays, however there is also evidence of a smaller, pre-morning rush hour peak at 06:00 on weekdays. Outside of these time periods, HDV flows are significantly reduced, with HDV flows on weekends being less than half those on weekdays.

Figure 12 indicates that HDVs make up a significant proportion of the total traffic volume during the night-time when there are lower flows of LDVs on the network (up to 40% at 02:00 on weekdays). Between 06:00 and 14:00 on weekdays, HDV’s comprise approximately 10-15% of the total vehicle flow.

11 Values are the average hourly measurements of total flow (top), HDV flow (middle) and Speed kph (bottom). Each dataset has had a smooth fit line applied and 95% confidence intervals are represented by shading.
after which time the proportion of HDV’s reduces to approximately 5% by 18:00, before increasing again up to 10% of the total vehicle flow by 23:00. As would be expected the proportion of HDVs is much lower on the weekend (7-10%) than on weekdays (14-17%).

The speed profiles in Figure 13 show that the lowest average speeds occur during the weekday morning and evening rush hours, with speeds reducing to 70 kph (45mph). Average speed increases to approximately 90 kph (55 mph) during the interpeak period, when there is less traffic on the network, and up to 100kph (60 mph) during off peak periods, when there are much lower flows on the network.

Figure 10: Time Variation Plots of Total Traffic Flow (2004 – 2016)

![Total Traffic Flow Graph](image1)

Figure 11: Time Variation Plots of HDV Flow (2004 – 2016)

![HDV Flow Graph](image2)
Figure 12: Time Variation Plots of HDV Percentage (2004 – 2016)

Figure 13: Time Variation Plots of Speed (2004 – 2016)
3. Background Contribution

Introduction

The total concentration of a pollutant comprises the contribution from explicit nearby\(^{12}\) emission sources such as, roads, rail, industry, domestic and commercial boilers, etc., and those that are transported into an area by the wind from further away. Were all the nearby emission sources to be removed, only the distant sources would influence measured concentrations; it is this latter component that is referred to as ‘background’. In many situations, the background contribution may be a dominant proportion of the total pollutant concentration, although this is less likely to be the case close to a busy road.

The background contribution may be further apportioned into a ‘regional’ component and a ‘local’ component. The ‘regional’ background component is the proportion of the background contribution which does not come from ‘local’ sources (i.e. the contribution from emission sources in other parts of the country or even Europe) while the ‘local’ contribution is the contribution from ‘local’ sources (e.g. emissions associated with domestic fuel combustion within Greater Manchester).

Two separate methods have been used to estimate the regional and local background concentrations within the study area, and the relative contribution of both to monitored annual mean NO\(_2\) concentrations at the Salford M60 CMS and diffusion tube sites respectively. These methods are:

- measured annual mean NO\(_2\) concentrations at the Glazebury CMS have been used to estimate the regional background component; and
- an interpolated background NO\(_2\) concentration field has been produced based on the results of diffusion tube monitoring undertaken by local authorities and HE in the wider area (see Appendix A). An estimate of the local background component has subsequently been made by subtracting the regional background determined at Glazebury from this background field.

Having estimated the local background field, maps of modelled background concentrations produced by Defra\(^{13}\) and information on permitted industrial facilities published by the Environment Agency\(^ {14}\) have also been used to assess whether there are any particular sectors or individual emission sources which are likely to make a significant contribution to local background NO\(_2\) concentrations in the vicinity of the M60.

Regional Background Contribution

The Glazebury CMS, which is classified as a ‘rural background’\(^{15}\) site, is located approximately 7km to the south west of the Salford M60 CMS and some distance from the nearest sizeable emission sources, the M62 (2.3 km at its closest point to the south) and the A580 (2.8 km at its closest point to the north). This CMS is therefore considered a representative site from which to estimate the regional background contribution. The annual mean NO\(_2\) concentrations measured at this site between 2004 and 2016, are summarised below in Figure 14.

\(^{12}\) For example, the Design Manual for Roads and Bridges (DMRB) Volume 11 Section 3 Part 1 HA 207/07 suggests that roads more than 200m from a particular receptor are not expected to make a significant contribution.

\(^{13}\) https://uk-air.defra.gov.uk/data/laqm-background-maps?year=2013

\(^{14}\) http://apps.environment-agency.gov.uk/wiyby/default.aspx

\(^{15}\) Sites in a rural area away from roads that are representative of exposure of the general population. Rural background sites should not be influenced by agglomerations or industrial sources and should be representative of a wide area.
Figure 14 indicates that the estimated regional component of annual mean NO$_2$ concentrations in the study area was approximately 16 µg/m$^3$ in 2014 and 2015. There is, however, some year to year variation, which is thought to reflect primarily the influence of meteorology on the dispersion of pollutant emissions.

Although Glazebury is considered to be the CMS most representative of regional background concentrations in the wider study area, due to its classification as a rural background site, its relative proximity to the study area and high data capture, analysis using ‘Openair’$^{16,17}$ does indicate a weak influence of road traffic emissions at this site. For example, Figure 15 shows how concentrations of NO$_2$ monitored at Glazebury vary by wind speed and direction. This shows that the highest concentrations occur at low wind speeds from all wind directions and that concentrations reduce as wind speed increases from all directions. Concentrations under easterly and south westerly winds however do not reduce with increasing wind direction at the same rate or to the same extent as those under southerly and northerly winds. This indicates emissions from sources to the southwest (possibly the M62 and/or the Warrington urban area) and east (possibly the M60 and/or the Manchester urban area) affect monitored concentrations at this site.

Figure 16 replaces the wind speed component in Figure 15 with a temporal element, which indicates there is a clear weekday trend, where concentrations are higher from all wind directions, in particular from the east / southeast and to a lesser extent the north, during Monday to Friday. There is also a diurnal trend with clear AM and PM signals, which are stronger from easterly / south-easterly wind directions. Therefore, regardless of the relatively large distance between road sources and the CMS, these signals suggest that those sources are influencing concentrations at this background site. This also suggests the motorway network has the potential to exert a regional influence on air quality.

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$^{16}$ Openair is an open-source set of statistical and graphical analysis tools for the analysis of air pollution data. It uses ‘R’ and its inbuilt statistical functionality to provide a powerful platform for insightful data analysis.

Figure 15: Polar Plot of NO$_2$ concentrations at Glazebury CMS (2004 – 2016)

Figure 16: Polar Annulus (Weekday and Hour) Plots of NO$_2$ concentrations at Glazebury CMS (2004 – 2016)
Local Background Contribution

The local background contribution has been estimated by two methods:

- taking diffusion tube measurements at background locations to create a local background field map;
- at the Salford M60 CMS, by isolating the measured contribution under high wind speeds from the east (which are less likely to be associated with emissions from the M60) and again subtracting the measured concentration at Glazebury during the same period.

Following an analysis of the locations of all diffusion tubes in the wider area, 49 were considered to provide a true representation of background conditions both in the urban centre of Manchester and further afield beyond the M60. These sites were operational during both the 2014 and 2015 calendar years. In addition, four sites operated by HE in 2014, and one in 2015, were included in the analysis. These measurements have been interpolated to provide an estimated background concentration field, representing conditions well removed from explicit emissions sources.

The interpolated background fields derived from 2014 and 2015 data are shown in Figure 17 and Figure 18 respectively. The differences between the concentration isopleths in the two years should be interpreted with caution, as these patterns are (to an extent) artefacts of the data ranges chosen and the geographical spread of the monitoring locations. Nevertheless, it is clear that concentrations are highest in central Manchester (over 30 µg/m³) and decrease with increasing distance from the centre in a manner that is relatively consistent with the prevailing southerly wind (see windrose in Figure 8). The background concentrations in the study area are in the range 20 to 25 µg/m³ and decrease to 15 to 20 µg/m³ further west of the urban centre.

*Figure 17: Background Monitors and the Interpolated NO₂ Concentration for 2014 (µg/m³)*
Background Emission Sources

A detailed analysis has been undertaken using Defra’s published background maps (generated by Defra using its PCM model), as well as data from the NAEI, the PRTR, and the Environment Agency’s “What’s in my Back Yard?” website, to identify the principal emission sources which shape the local background concentration field. This analysis suggests that there is little influence of industrial activity on background NO₂ concentrations in the vicinity of the M60 within the study area. This is further explored in Section 4 which shows there is no clear industrial signal in monitored concentrations at the Salford M60 CMS. The main active industrial area in Manchester is located to the south of the M602, west of Manchester and outside of the study area. Figure 19 shows the non-road source sectors contributing to more than 5% of the DEFRA mapped background NOx concentrations in each grid square, and the individual emission sources which potentially contribute to these source sector contributions.
Figure 19: Industrial, Domestic and Other Emission Sources in the Study Area Contributing over 5% to Total Mapped Background NOx Concentrations
4. Analysis of Roadside NO$_2$ Concentrations

Introduction
In this section, the contribution of motorway traffic to measured annual mean NO$_2$ concentrations at locations adjacent to the M60 is evaluated. Due to the proximity of the M60 mainline to the monitoring sites in the study area, it is likely that the motorway has a significant influence on these measurements, although it will not be the only contributing source.

The data sources used in the evaluation are:
- hourly measurements of NO$_x$ and NO$_2$ from the Salford M60 CMS and Glazebury CMS;
- annual mean concentrations of NO$_2$ measured using diffusion tubes at numerous roadside sites across the area (from HE and local authority surveys);
- road traffic data including from the MIDAS database, a regional traffic model$^{18}$ and annual average estimates from Department for Transport (DfT); and
- hourly sequential meteorological data for Manchester airport.

The road traffic contribution has been determined using two different approaches:
- using the annual mean NO$_2$ measurements from the diffusion tubes to determine motorway source strength; and
- in-depth statistical analysis of the hourly monitoring data for NO$_x$ and NO$_2$ from the CMS.

Diffusion Tube Analysis
To determine the contribution that motorway emissions make to annual mean NO$_x$ and NO$_2$ concentrations, diffusion tube measurements were used. Monitoring sites which are not near to other, non-motorway, emission sources, or for which the contribution from non-motorway sources can be readily quantified, are required for this exercise.

Diffusion tube monitoring data have been collected by HE at numerous sites including along transects perpendicular to the M60. These data lend themselves well to the analysis of source strength, which relies on understanding the rate at which concentrations reduce on moving away from the motorway, and comparing this with the pattern that would be expected if the motorway were the only local emission source. The fall-off with distance curve used in this analysis is the 2013 iteration of the Design Manual for Roads and Bridges (DMRB) air quality model$^{19}$.

Monitored NO$_2$ concentrations were annualised, where data capture was less than 75% of the calendar year, using published methods. The estimated road-NOx contribution to these annualised annual mean concentrations was then derived using Defra’s NOx to NO$_2$ calculator (version 5.1) and the interpolated background NO$_2$ fields shown in Figure 17 and Figure 18. Estimated Road-NOx, as derived, was then plotted against distance from the M60. The shape of the graph (fall off with distance from motorway) in most cases provides a good fit to the idealised DMRB dispersion curve, with some exceptions at locations close to junctions. Full details of the analysis are given in Appendix A. An example of a transect where the fall-off with distance fits the idealised curve well, the Ryecroft Lane transect, is provided in Figure 20 (the green line indicates the vegetative barrier adjacent to the M60). This transect is located to the east of the M60 between Junctions 12 and 13. For both years, the idealised curve describes the data very well (as shown in Figure 21 and Figure 22), suggesting that the motorway is the primary source of local NOx emissions in this area.

The monitoring sites which do not fit the line as well are either influenced by other roads / junctions which provide an additional source of NO$_x$ emissions, or are in proximity to physical barriers (e.g. noise barriers and vegetation), which may have reduced the measured concentration by inhibiting the dispersion of NOx emissions form the M60 to the monitoring site in question.

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$^{18}$ Developed in order to inform the Tranche 4 Smart Motorway Scheme.
$^{19}$ This curve was, itself, derived directly from measured transects and so there can be reasonable confidence that it accurately describes the average rate of fall-off with distance from a motorway.
Figure 20: Locations of HE and Salford DC diffusion tubes along the Ryecroft Lane Transect.

Figure 21: Fall-off with distance curve in 2014 for the Ryecroft Lane transect.
Figure 22: Fall-off with distance curve in 2015 for the Ryecroft Lane transect.

Figure 23 shows the average calculated road-NO\textsubscript{x} at 10 metres from the edge of the motorway at each site in each year (i.e. the value taken at 10m along each of the fall-off with distance curves derived). The three transects located between Junctions 12 and 13 (Farm Lane, Ryecroft Lane and Grange Road) show very consistent NO\textsubscript{x} concentrations. The higher concentrations measured at Grange Road may reflect its position close to the M62/M60 intersection at Junction 12 to the south. Measured concentrations at Greenleach Lane were also similar to those between Junctions 12 and 13; despite the influence of emissions from Greenleach Lane. To the south of Junction 12, the inferred NO\textsubscript{x} source-strengths appear to be lower than to the north; although monitoring site coverage is lower and the agreement with the idealised fall-off curve is poorer, for these transects.

Figure 23 also shows the equivalent motorway source strengths that were derived in a Geographical Pilot Study carried out for the M1 in Sheffield (“M1 Blackburn” and “M1 Brinsworth”). The M1 values are within the range of the M60 values, suggesting that the M60 north of Junction 12 gives rise to higher concentrations than the M1, while the M60 to the south of Junction 12 gives rise to lower concentrations than the M1.

Figure 24 shows the NO\textsubscript{x} source-strengths expressed per vehicle on each stretch of motorway. The difference between the M60 north and south of Junction 12 per vehicle is less pronounced, nevertheless the difference could intimate that there are factors such as driving patterns or fleet composition that produce higher NO\textsubscript{x} emissions on the M60 north of Junction 12.

Comparing the M60 values in Figure 24 with those for the M1 shows that NO\textsubscript{x} concentrations per vehicle appear to be higher for the M1. It should, though, be noted that the traffic data used were derived from two separate traffic models and there may, therefore, be some systematic bias.
Figure 23: Normalised Road-NOx at 10m

- Greenleach Lane
- Farm Lane
- Ryecroft Lane
- Grange Lane
- Salteye Road
- M60 (Site HE118)
- Lorgetto Road
- (M1 Blacburn)
- (M1 Brinsworth)

Normalised NOx (µg/m³)

2014

2015
Figure 24: Normalised Road-NOx at 10m Expressed per Vehicle per Day

<table>
<thead>
<tr>
<th>Location</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenleach Lane</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Farm Lane</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Ryecroft Lane</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Grange Road</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Salteye Road</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>M60 (Site HE118)</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Loretto Road</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>(M1 Blackburn)</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>(M1 Brinsworth)</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Non-Motorway Contributions

There are a number of other diffusion tube monitoring sites in the study area that were not included in the transect analysis (the locations of which are shown in Figure 25). At all five of these sites north of Junction 13, the measured 2015 road-NOx concentrations, after having removed the calculated motorway contribution to NOx, are negative values (shown in blue). This suggests that the NOx emissions from the motorway along this section are potentially lower than has been assumed (possibly because of the influence of traffic on Greenleach Lane on the results obtained along the Greenleach Lane transect). South of Junction 13, the normalised residual NOx concentrations of between 20 and 40 µg/m³ at sites HE90 and HE202 may be attributed to emissions from the adjacent B5211 and B5214 (Barton Road) respectively. At Site HE199, normalised residual NOx concentrations in the range 60 to 100 µg/m³ have been calculated alongside the A57 (Liverpool Road). At the remaining sites, the normalised residual NOx concentrations are between 0 and 20 µg/m³ and therefore relatively minor.

This simple analysis suggests that at certain monitoring sites in the study area (e.g. sites HE90, HE199 and HE 202) the contribution of the M60 to NOx concentrations alongside the motorway (illustrated in Figure 25) is not significantly greater than the contribution of other local roads in the area.

Figure 25: Normalised Residual NOx at Non-transect Diffusion Tube Sites for 2014

CMS analysis

An in-depth analysis of monitoring data at the Salford M60 and Glazebury CMS has been undertaken to estimate the contribution the M60 makes to measured NO₂ concentrations at the Salford M60 CMS and which factors (e.g. meteorology, vehicle flow and speed, vehicle type) have the greatest influence on measured concentrations.

Analysis of the CMS hourly data has been performed using the statistical programming language ‘R’ and specialist analysis packages ‘Openair’ and ‘Deweather’. The Deweather package further develops Openair’s functionality, providing tools for sophisticated trend analysis of multivariate time series data.

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A summary of the annual mean NO\textsubscript{x} and NO\textsubscript{2} concentrations and data capture rates between 2004 to 2016 at the two CMS of primary interest is provided in Table 3. With the exception of 2008, data capture rates were good (>75%) and in most cases very good (>90%) at both sites.

Table 3: Summary of Automatic Monitoring Data (2004 to 2016)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Year</th>
<th>M60 Salford</th>
<th>Data Capture %</th>
<th>Glazebury</th>
<th>Data Capture %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Mean NO\textsubscript{2} (µg/m\textsuperscript{3})</td>
<td>2004</td>
<td>65.5</td>
<td>96%</td>
<td>17.7</td>
<td>87%</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>67.4</td>
<td>90%</td>
<td>17.8</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>63.7</td>
<td>88%</td>
<td>17.0</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>63.1</td>
<td>96%</td>
<td>18.3</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>68.0</td>
<td>69%</td>
<td>17.3</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>70.5</td>
<td>96%</td>
<td>16.0</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>60.0</td>
<td>98%</td>
<td>19.4</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>64.3</td>
<td>99%</td>
<td>18.3</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>62.2</td>
<td>99%</td>
<td>19.0</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>61.5</td>
<td>88%</td>
<td>14.7</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>59.6</td>
<td>98%</td>
<td>13.5</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>52.1</td>
<td>89%</td>
<td>15.5</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>2016\textsuperscript{a}</td>
<td>45.5</td>
<td>94%</td>
<td>15.9</td>
<td>99%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Annual Mean NO\textsubscript{x} (µg/m\textsuperscript{3})</th>
<th>2004</th>
<th>237.5</th>
<th>96%</th>
<th>30.9</th>
<th>87%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2005</td>
<td>230.3</td>
<td>90%</td>
<td>31.7</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>2006</td>
<td>211.4</td>
<td>88%</td>
<td>30.0</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>2007</td>
<td>208.4</td>
<td>96%</td>
<td>33.0</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>2008</td>
<td>222.1</td>
<td>69%</td>
<td>28.4</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>2009</td>
<td>217.8</td>
<td>96%</td>
<td>25.3</td>
<td>94%</td>
</tr>
<tr>
<td></td>
<td>2010</td>
<td>186.1</td>
<td>98%</td>
<td>34.8</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td>2011</td>
<td>184.9</td>
<td>99%</td>
<td>26.5</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>180.9</td>
<td>99%</td>
<td>32.7</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>172.0</td>
<td>88%</td>
<td>21.9</td>
<td>99%</td>
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<tr>
<td></td>
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<td>98%</td>
<td>21.7</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>139.0</td>
<td>89%</td>
<td>22.1</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>2016\textsuperscript{a}</td>
<td>128.8</td>
<td>94%</td>
<td>25.9</td>
<td>99%</td>
</tr>
</tbody>
</table>

\textsuperscript{a} October to December 2016 data was not yet ratified at the time of analysis

Directional Analysis

The directional analysis of pollutant sources affecting concentrations at the Salford M60 CMS has involved the combined analysis of meteorological data (wind speed and wind direction) and pollutant concentration data (measured NO\textsubscript{2} and NO\textsubscript{x} concentrations). Polar plots of NO\textsubscript{2} and NO\textsubscript{x} concentrations at the Salford M60 CMS (2004 to 2016) are shown in Figure 26 and Figure 27 respectively. Hourly average concentrations are highest during periods of low wind speeds; under such conditions, dispersion is reduced, leading to higher concentrations near to ground-level pollutant sources such as roads.

The plots show that winds from the south and southeast correlate with elevated concentrations of NO\textsubscript{2} and NO\textsubscript{x}. The highest concentrations of NO\textsubscript{2} and NO\textsubscript{x} at Salford CMS occur when wind directions are between 120 and 180 degrees. While these directions yield the highest concentrations, there is a clear emission signal from a wider range of directions i.e. between 40 and 230 degrees. These wind directions carry air from the direction of the motorway (which runs in a north easterly to south westerly orientation) towards the CMS, and therefore strongly indicates the contribution of motorway traffic emissions to NO\textsubscript{2} and NO\textsubscript{x} concentrations at the CMS location. There is also a possible signal from the southwest, which may indicate a contribution from Junction 13 of the M60 and associated slip roads.

Emission sources within the urban area of Manchester are considered to be a potential contributor to concentrations recorded at the CMS when the wind direction is easterly and winds are high speed (i.e. > 8m/s). There is some evidence of such a contribution in Figure 26 with high NO\textsubscript{2} concentrations occurring under strong north easterly winds. The low frequency of high speed winds from this direction...
(see Figure 8), however, mean that the influence on annual mean NO\textsubscript{2} concentrations is likely to be relatively small. This issue is investigated in more detail in the section entitled “source apportionment”. Variations in measured NO\textsubscript{2} and NO\textsubscript{x} concentrations with time and wind direction are illustrated in polar annulus plots in Figure 28 and Figure 29. The patterns that were found for the Salford M60 CMS are consistent with the influence of road traffic on measured concentrations. Peak traffic periods (i.e. 06:00 to 20:00 Monday to Friday) correlate with the highest NO\textsubscript{2} (Figure 28)\textsuperscript{21} and NO\textsubscript{x} (Figure 29)\textsuperscript{22} concentrations from the direction of the motorway.

More detailed analysis of temporal patterns is provided in the next section.

Figure 26: Polar Plot of NO\textsubscript{2} concentrations at Salford M60 CMS (2004 – 2016)

21 Concentrations at the centre of the plot for day of week represent Sunday with subsequent days during the week shown as concentric rings towards Saturday at the outside of the plot.

22 Concentrations at the centre of the plot for hour of day represent midnight with subsequent hours of the day shown as concentric rings towards 11pm at the outside of the plot.
Figure 27: Polar Plot of NO\textsubscript{x} concentrations at Salford M60 CMS (2004 – 2016)

Figure 28: Polar Annulus (Weekday and Hour) of NO\textsubscript{2} concentrations at Salford M60 CMS (2004 – 2016)
Temporal Analysis

Time variation plots of NO\textsubscript{2} and NO\textsubscript{x} recorded at the Salford M60 CMS between 2004 and 2016 are shown in Figure 30 and Figure 31 respectively\textsuperscript{23}.

During the weekday AM peak traffic period (06:00 – 08:00), the traces for both pollutants replicate what is typically expected from a site heavily influenced by road traffic sources, with both elevated NO\textsubscript{2} and NO\textsubscript{x} concentrations occurring during this period (top row of graphics in each figure). This is thought to represent the effect of greater traffic volumes and increased congestion (illustrated by lower vehicles speeds in Figure 13) on road traffic emissions during the morning rush-hours.

NO\textsubscript{2} and NO\textsubscript{x} concentrations are, however, both substantially lower during the weekday PM peak than during the AM peak, which is unexpected given that total traffic flows on the M60 during the PM peak are equal to, if not higher than, those during the AM peak (see Figure 10). This difference could however potentially be explained by the fact that HDV flows are significantly lower during the PM peak period than the AM peak period (see Figure 11), that possibly there is greater congestion and therefore increased emissions during the AM peak and/or that the regional background contribution is greater during the AM peak than during the PM peak.

The average diurnal profiles in NO\textsubscript{2} and NO\textsubscript{x} concentrations differ slightly (bottom left graphic of Figure 30 and Figure 31) although both show sharp increases in the morning, associated with AM peak traffic. Concentrations of NO\textsubscript{x} decline continuously once the AM peak has been reached, the rate of decay slowing down after midday. The diurnal profile of NO\textsubscript{2} differs to that of NO\textsubscript{x}, showing a decline after the AM peak then stabilising for several hours before increasing very slightly during the PM peak. This difference in patterns indicates a change in the diurnal NO\textsubscript{x}/NO\textsubscript{2} ratio, which is investigated in more detail later in the following section.

NO\textsubscript{2} and NO\textsubscript{x} concentrations peak around 10:00 on Saturday and 17:00 on Sunday, but are substantially lower than on weekdays, reflecting lower total traffic volumes, lower HDV flows and higher average speeds on the M60.

\textsuperscript{23} Clockwise from top the figures show: average weekday diurnal profiles, weekday mean, monthly mean and hourly mean profiles.
The seasonal variation in both pollutants is as expected with the highest concentrations in the winter and a reduction in the summer. This difference relates to seasonal cycles such as the availability of sunlight and ozone, temperature and dispersion conditions (atmospheric stability). Elevated concentrations in winter are to some extent the result of increased fuel combustion for domestic heating and seasonal weather conditions which inhibit the dispersion of pollutants, but may also be contributed to by higher traffic emissions per vehicle kilometre in winter due to poorer performance of emissions reduction technology in lower temperatures\(^\text{24}\).

**Figure 30: Time Variation Plots of NO\(_2\) concentrations at Salford M60 CMS (2004 – 2016)**

**Figure 31: Time Variation Plots of NO\(_x\) concentrations at Salford M60 CMS (2004 – 2016)**

**NO₂ to NOₓ ratio**

Figure 32 shows a polar plot for the ratio of NO₂ to NOₓ concentrations recorded at the Salford M60 CMS (2004 to 2016). The ratio is low (<0.5) when the wind is between 40 and 230 degrees and during low wind speeds (<10 m/s). A low ratio indicates only a relatively small portion of ambient NO has converted to NO₂ following its emission. With a conversion rate in the order of hours, a low NO₂ to NOₓ ratio is indicative that little time, and thus distance, has passed between the point of emission and that of measurement. The low ratios indicate a very proximate source to the CMS, with little opportunity for the conversion of NO to NO₂ (in this case the M60). North westerly winds and higher wind speeds are associated with the highest ratios (>0.7), suggesting that longer range transport is most important for this direction.

![Polar Plot of the NO₂ to NOₓ ratio at Salford M60 CMS (2004 – 2016)](image)

The polar annulus plot in Figure 33 shows that the NO₂ to NOₓ ratios are lowest on weekdays during the daytime period. There is a clear diurnal cycle for all wind directions as indicated by the concentric ring pattern in the left-hand figure. The right-hand figure shows that the lowest ratios occur during the AM peak which increase during the day (this is also evident in Figure 33). This peak is clearest from between 40 and 220 degrees. The lowest ratio occurs for longer between 140 and 170 degrees and does not pass a ratio of 0.5 in any hour when winds are from these directions. This sector corresponds to the shortest distance between the CMS and the M60.

---

25 Sunlight enables the reaction of NO (which makes up the majority of NOx) with ozone to form NO₂ in a reversible reaction.
Figure 33: Polar Annulus Plot (Weekday and Hour) of NO$_2$ : NO$_x$ ratio at Salford M60 CMS (2004 – 2016).

Figure 34: Time Variation Plots of NO$_2$:NO$_x$ Ratio at Salford M60 CMS (2004 – 2016)
Removal of Regional Background

The understanding of the M60 contribution to measured concentrations at the Salford M60 CMS can be improved by attempting to remove the contribution from other sources, thus “strengthening” the signal from the M60. This was achieved by subtracting from the measured roadside concentration the measured regional background concentration at the Glazebury CMS (on an hour by hour basis). This process effectively removes pollutant contributions from regional background sources not associated with the M60 and other more local sources.

Having removed the regional background, the residual concentrations are the combined contribution from the M60 and other nearby roads and local background sources (including the Manchester urban area component). Where the Glazebury concentration was greater than the Salford M60 concentration (resulting in a negative value after the subtraction), these concentrations were removed from the dataset. Bivariate (polar and polar annulus) plots of the M60 minus Glazebury concentrations of NO\textsubscript{2} and NO\textsubscript{x} are provided in Figure 35 to Figure 37. The time variation of Salford M60 minus Glazebury NO\textsubscript{2} is presented in Figure 38.

The patterns in the plots are similar to those presented earlier for the M60 concentrations without the subtraction of Glazebury. This suggests that the M60 is one of the dominant contributors to NO\textsubscript{2} and NO\textsubscript{x} concentrations monitored at the Salford M60 CMS site. One key difference upon removing Glazebury NO\textsubscript{2} concentrations is shown between Figure 28 and Figure 36. This relates to the higher concentrations of NO\textsubscript{2} measured during the AM peak hours relative to the PM peak hours, which is more consistent with the traffic data profiles presented in Figure 10 once the regional contribution is removed. This suggests that the difference in measured NO\textsubscript{2} concentration at the Salford M60 CMS between the AM and PM peak periods is primarily driven by the contribution from emission sources across the wider region, rather than from the M60.

Figure 35: Polar Plot of Salford M60 CMS minus Glazebury CMS NO\textsubscript{2} and NO\textsubscript{x} (2004 – 2016).
Figure 36: Polar Annulus (Weekday and Hour) of Salford M60 CMS minus Glazebury CMS NO₂ (2004 – 2016).

Figure 37: Polar Annulus (Weekday and Hour) of Salford M60 CMS minus Glazebury CMS NOₓ (2004 – 2016).
Source Apportionment

Polar plots can be interpreted to infer the direction (in degrees) of possible contributing sources relative to the Salford M60 CMS. It is thus possible to attempt apportionment of the annual mean concentration of NO$_2$ at the M60 CMS into different component sources, based on the direction of these emission sources relative to the CMS.

A regional component can readily be assigned to the total annual mean NO$_2$ concentration using the measured concentrations at the Glazebury CMS. This component was calculated by averaging the hourly concentrations recorded at Glazebury where there was a corresponding hourly concentration recorded at the M60 Salford site, to give an annual mean contribution$^{26}$.

Having removed the regional component, the residual annual mean concentration can be apportioned according to different sources based on wind direction and speed. Measured concentrations at lower wind speeds (i.e. <8 m/s) are typically indicative of local, low level emission sources such as nearby roads, whereas measured concentrations at higher wind speeds (i.e. >8 m/s) are generally considered to be more heavily influenced by high level emission sources (e.g. stack emissions) and/or more distant emissions sources (e.g. regional / urban components).

The polar plots presented in Figure 26 to Figure 29 indicate that the M60 is the key contributor to the measured NO$_2$ concentrations at the Salford M60 CMS site. The M60 is located between 40 and 220 degrees relative to the CMS (this segment is shown on a polar plot in Figure 39). The highest concentrations occur when wind is from these directions at various wind speeds. The concentrations also show an inverse relationship with speed which is indicative of a nearby, low-level source (i.e. the M60). There is an exception at approximately 50 and 120 degrees whereby concentrations increase with wind speed, which is indicative of a contribution from a high-level source (e.g. stack emissions) and/or regional / urban sources further afield. There are no high level industrial sources located between 50 and 120 degrees relative to the CMS at a distance close enough to have a measurable impact on annual mean concentrations (Figure 19) and therefore this component is likely to be attributable to the urban background contribution from Greater Manchester.

It is therefore considered reasonable to assign measured concentrations under wind speeds of between 0.1 and 8 m/s and wind directions between 40 and 220 degrees to the M60 and above 8 m/s and between 50 and 120 degrees to the Greater Manchester urban component.

$^{26}$ Where a value was recorded at the M60 CMS but not at Glazebury, the missing data for Glazebury was infilled with the average concentration at Glazebury for the corresponding hour for that year.
It is difficult to assign measured concentrations during calm conditions to a single source, as by definition there is no associated wind direction during these periods, therefore concentrations resulting from these conditions have been apportioned separately.

In addition to these sources, the bivariate plots indicate a measurable signal from between 230 and 270 degrees. The nearest and most logical source of this signal is the A-road network associated with Junction 13 of the M60. This signal decreases with increasing wind speed indicating a contribution from a local emission source within this wind segment. Concentrations occurring from within this wind segment and with any speed above 0 m/s have therefore been attributed to the A-road network at Junction 13.

The remaining concentrations are classified as “local NO$_2$” arising from sources that are not explicitly identifiable using the above analysis. A summary of the source apportionment breakdown and the assumed conditions considered relevant to each source is presented in Table 4.

**Table 4: Indicative NO$_2$ Sources and Assumed Wind Conditions at the Salford M60 CMS**

<table>
<thead>
<tr>
<th>Indicative Source</th>
<th>NO$_2$ concentrations</th>
<th>Wind Direction</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional background</td>
<td>Glazebury</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>M60 Mainline</td>
<td>Glazebury</td>
<td>&gt;=40 and &lt;=220</td>
<td>&gt;0 and &lt;=8</td>
</tr>
<tr>
<td>A-Road Network at Junction 13</td>
<td>Salford M60 – Glazebury</td>
<td>&gt;=230 and &lt;=270</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Urban Component</td>
<td>Salford M60 – Glazebury</td>
<td>&gt;=50 and &lt;=120</td>
<td>&gt;8</td>
</tr>
<tr>
<td>Calm Conditions</td>
<td>All</td>
<td>=0</td>
<td></td>
</tr>
<tr>
<td>Local Component</td>
<td>Remainder of the annual mean NO$_2$ at the M60 CMS minus the above components</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 39: Polar Plot of NO$_2$ at Salford M60 CMS (2004 – 2016) showing 40 to 220º Sector**
The results of the Salford M60 CMS source apportionment are presented in Figure 40 and Table 5, which indicate that the M60 is estimated to make the largest contribution in all years to measured NO\textsubscript{2} concentrations (51 - 63%), followed by regional background sources (22 - 35%). The source apportionment analysis also indicates that the magnitude of the contribution from vehicles on the M60 to concentrations at the Salford M60 CMS ranged between 34.9 µg/m\textsuperscript{3} and 38.6 µg/m\textsuperscript{3} between 2011 and 2014. This contribution decreased noticeably to 26.6 µg/m\textsuperscript{3} in 2015 and 24.2 µg/m\textsuperscript{3} in 2016, suggesting that the large reduction in concentrations measured at the Salford M60 CMS in recent years (see Figure 6) is primarily a result of a reduction in the contribution from the M60.

The A-road network at Junction 13 to the west of the Salford M60 CMS is estimated to make a measurable contribution (3 to 5 µg/m\textsuperscript{3}) to annual mean concentrations of NO\textsubscript{2}. This contribution is relatively consistent across the time series. The local component is of similar magnitude and again, is reasonably consistent across the time series. The Manchester urban component is negligible in all years, suggesting emissions from Greater Manchester do not make a sizeable contribution to NO\textsubscript{2} concentrations at the Salford M60 CMS, beyond the contribution they make at Glazebury.

**Figure 40: Source Apportioned Annual Mean NO\textsubscript{2} at the Salford M60 CMS (2004 to 2016)**

**Table 5: Apportionment of NO\textsubscript{2} at the Salford M60 CMS (2004 to 2016)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual Mean NO\textsubscript{2} (µg/m\textsuperscript{3})</th>
<th>Source Contribution to Annual Mean NO\textsubscript{2} (µg/m\textsuperscript{3})</th>
</tr>
</thead>
</table>
**Deweather Model**

**Model Construction and Evaluation**

Analysis of trends in air quality data is frequently hampered by the competing influences of different emission and dispersion processes. For example, it can be difficult to determine if a particular change in concentration is driven by changes in emissions or meteorology. This leads to large uncertainty when determining the causes of recorded concentration changes or the effectiveness of mitigation strategies.

The ‘Deweather’ package developed in ‘R’ is designed to remove the influence of meteorology from measured concentrations. Deweather uses hourly meteorology or other predictor variables paired with hourly measured concentrations. These data are used to construct a statistical model capable of predicting concentrations for a defined set of conditions using a boosted regression tree. This approach makes it possible to account for the effects of a variable or variables on concentration data. The influence of individual variables can be identified by holding all other variables constant. For example, the effects of meteorology may be removed from a time series of NO\textsubscript{2} concentrations leaving only the trend caused by changes in other factors, such as local emissions.

A Deweather model for the Salford M60 CMS has been constructed using concentrations of NO\textsubscript{2} and NO\textsubscript{x} (with the corresponding regional component from Glazebury removed), meteorological data from Manchester airport and traffic data from MIDAS. The meteorological variables included are: air temperature, wind speed, wind direction, precipitation, a cloud cover index and relative humidity. In addition, the in-built variables “trend”, "hour", "weekday" and "week" are included. Where traffic data have been included, the following variables are considered: speed, LDV flow and HDV flow (limitations in the dataset of which are given in the Table).

Further details of the variables used are provided in Table 6.

**Table 6: Summary of Variables included in Deweather Model for Salford M60**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0c</td>
<td>Hourly ambient air temperature measured at Manchester Airport</td>
</tr>
<tr>
<td>ws</td>
<td>Hourly wind speed measured at Manchester Airport</td>
</tr>
<tr>
<td>wd</td>
<td>Hourly wind direction measured at Manchester Airport</td>
</tr>
<tr>
<td>p</td>
<td>Hourly precipitation measured at Manchester Airport</td>
</tr>
<tr>
<td>CL</td>
<td>Hourly cloud cover index measured at Manchester Airport</td>
</tr>
<tr>
<td>RH</td>
<td>Hourly relative humidity measured at Manchester Airport</td>
</tr>
<tr>
<td>Trend</td>
<td>The variable representing the time-series trend</td>
</tr>
<tr>
<td>Hour</td>
<td>The hour of the day, representing diurnal variation not accounted for in other variables</td>
</tr>
<tr>
<td>Weekday</td>
<td>The day of the week, representing weekday variation not accounted for in other variables</td>
</tr>
<tr>
<td>Week</td>
<td>The week of the year, representing seasonal variation not accounted for in other variables</td>
</tr>
<tr>
<td>LDV_flow_2way_infill</td>
<td>Combined hourly LDV northbound and southbound traffic flow on M60. Data infilled post October 2014 when MIDAS data collection stopped for the construction of the smart motorway infrastructure, using previous 12 months of traffic data for missing periods.</td>
</tr>
<tr>
<td>HDV_flow_2way_infill</td>
<td>Combined hourly HDV northbound and southbound traffic flow on the M60. Data infilled post October 2014 when MIDAS data collection stopped for the construction of the smart motorway infrastructure, using the previous 12 months of traffic data for missing periods.</td>
</tr>
<tr>
<td>Speed_2way_infill</td>
<td>Combined northbound and southbound flow-weighted hourly average traffic speed on the M60. MIDAS speed data ceased in 2014, therefore an aggregate dataset has been used consisting of MIDAS speed from 2004 to 2014, supplemented by hourly speeds derived from Trafficmaster data from the start of 2014.</td>
</tr>
</tbody>
</table>

The Deweather model was constructed using a randomly selected sample of 80% of the available measured time series data. The remaining 20% of values were used to test model performance; a good
fit was achieved in each case. A series of model evaluation statistics, including FAC2 (fraction of predictions within a factor of two), Mean Bias, Mean Gross Error, Normalised Mean Bias, Normalised Mean Gross Error, Root Mean Square Error, r, Coefficient of Efficiency (predictive power of the model relative to the population mean) and Index of Agreement are presented alongside the individual data points in (Figure 41 and Figure 42). The value of ‘r’ is 0.85 for the NO\textsubscript{2} model and 0.86 for the NO\textsubscript{x} model which indicates a reasonably good fit in both cases (the ideal value being 1.0). The FAC2 is greater for NO\textsubscript{2} when compared to NO\textsubscript{x} with a value of 0.75 compared with 0.65.

*Figure 41: Model Validation Statistics for Salford M60 CMS minus Glazebury CMS NO\textsubscript{2}*

![Figure 41: Model Validation Statistics](image)

*Figure 42: Model Validation Statistics for Salford M60 CMS minus Glazebury CMS NO\textsubscript{x}*

![Figure 42: Model Validation Statistics](image)
Partial Dependencies

Partial dependency analysis considers how each variable changes when all others are held at their mean values. The analysis can further be used to identify the most important variables for predicting pollutant concentrations. Partial dependency plots for the NO$_2$ and NO$_x$ concentrations at the Salford M60 CMS (Glazebury regional background removed) are presented in Figure 43 and Figure 44 respectively. Plots are ordered such that variables with the greatest influence on concentrations are shown first.

Figure 43: Partial Dependencies for NO$_2$ concentrations at the Salford M60 CMS (regional background removed). Shading indicates 95% confidence intervals.

Figure 44: Partial Dependencies for NO$_x$ concentrations at the Salford M60 CMS (regional background removed). Shading indicates 95% confidence intervals.

There is consistency in the influence of some variables on both NO$_2$ and NO$_x$ concentrations with the regional background removed. For example, wind direction proves the most influential variable in both models, which is as expected owing to the orientation of the M60 and its proximity relative to the CMS. The graphs within the partial dependencies indicate a step change from around 200 degrees, as winds from directions more westerly than this are not cross-motorway. Other important predictor variables include hour of day, day of the week and wind speed.

The influence of temporal variables is as expected during the day and over the course of the week. For example, there is an increase in NO$_2$ concentrations in the morning and stable concentrations thought the day before a decline in the late evening, which indicates the typical diurnal relationship of NO$_2$ and O$_3$ in relation to sunlight. The diurnal relationship in NO$_x$ can also be explained in the same way. The weekday plots show there are lower concentrations at weekends relative to weekdays which is
representative of the influence on emissions of increased road traffic movements and business and institutional operating hours on weekdays.

The influence of relative humidity, temperature, cloud cover and precipitation is minimal, with the influence of each variable explaining less than 4.5% of the observed variability. Cloud cover and precipitation are consistently the least important predictor variables for both NO\textsubscript{2} and NO\textsubscript{x} concentrations, with neither having an influence greater than 1.9% and 0.5% respectively.

The relationship between NO\textsubscript{2} and NO\textsubscript{x} concentrations and traffic flow variables highlights some interesting differences between the influence traffic on the M60 has on the two pollutants. Figure 43 shows that the LDV and HDV flow variables have differing levels of influence on concentrations of NO\textsubscript{2}, with LDV flow being the more important of the two, and the second most important variable overall, with an influence of 12.3%. NO\textsubscript{2} concentrations increase with LDV flow up to an hourly LDV flow of approximately 12,000 after which NO\textsubscript{2} concentrations decrease. This decrease may relate to the evening period when there is a lower number of HDVs on the network, resulting in freer flowing traffic and therefore lower LDVs emissions. The 95% confidence intervals do widen beyond this point however, which may indicate limited data availability, therefore suggesting this region should be interpreted with caution.

HDVs are also an important influencing factor for NO\textsubscript{2} concentrations, although only approximately half as important (6.6%) as LDVs. The relationship between HDV flow and NO\textsubscript{2} concentration is more complex with relatively stable concentrations at low vehicle flows followed by an increase from between approximately 500 to 800 vehicles per hour, before another period of relative stability, followed by a further increase between 1,200 and 1,800 vehicles per hour, after which concentrations appear to remain stable once again.

In contrast, LDV flow has a relatively less important (7.7%) influence on NO\textsubscript{x} concentrations (as shown in Figure 44), while HDV flow is a very important (19.4%) predictor variable. The relationship for LDV flow is straightforward with NO\textsubscript{x} concentrations increasing with LDV flow. The relationship for HDV flow and NO\textsubscript{x} concentrations is similar to that for NO\textsubscript{2} in Figure 43 with concentrations stabilising at approximately 1,800 vehicles per hour. The different influences that LDV and HDV flows have on NO\textsubscript{2} and NO\textsubscript{x} concentrations is an interesting finding and is thought to be indicative of the higher proportion of NO\textsubscript{x} emitted as NO\textsubscript{2} from LDVs than from HDVs.

Speed appears to be a relatively unimportant predictor variable for both NO\textsubscript{2} and NO\textsubscript{x} with an influence of 2.4% and 2.5% respectively (less than relative humidity and temperature). The relative unimportance of speed in these partial dependency models could indicate that the absolute measure of speed in kilometres per hour is not a good representation of traffic conditions and therefore emissions for a particular hour (e.g. average speed may not accurately capture the effect of stop-start conditions on emissions). In addition, the two-way speed does not differentiate between conditions on opposite carriageways, e.g. one direction could be free-flowing, but the other could be heavily congested resulting in higher emissions closer to the CMS.

Traffic Origin and Destination Data

Analysis has been undertaken using a regional traffic model\textsuperscript{18} to understand the origin and destination of different vehicle types travelling on the section of the M60 between Junction 13 and Junction 14. Figure 45 to Figure 56 show the origin and destination during the AM peak for northbound and southbound Car, LGV and HGV movements respectively. A summary of the origins and destinations of each vehicle type is provided below:

**Cars**

Northbound and southbound car journeys on this section of the M60 appear to comprise both local and strategic journeys. Northbound movements typically originate in the local area and the south and are destined for areas to the northeast and northwest of Manchester. These destination areas contain large urban areas including Harrogate, Huddersfield, Leeds and York to the northeast and Blackburn, Blackpool, Preston and Southport to the northwest. The opposite is true for southbound car movements, with vehicles originating in these urban areas and travelling to the Manchester area and the south.

**LGVs**

Northbound LGV movements also appear to consist of a mixture of local and strategic journeys. The strategic journeys originate from a wide area south of Stoke-on-Trent extending into Wales. Many LGVs also appear to originate from a small area to the east of Warrington. The destination of many of these
northbound LGVs is to an area around Blackpool, Fleetwood and Preston. Large amounts of LGVs also travel further to the north and east of England.

The origin of southbound LGVs is spread over a large area to the north and east of Manchester. The highest numbers originate from a small area around Halifax and Huddersfield. The destination of these journeys is typically an area to the east of Warrington and Northwich. There are also a considerable number of longer journeys to the south of Stoke-on-Trent.

**HGVs**

Journeys of HGVs differ slightly to cars and LGVs as there appears to be a more sizeable number of east–west journeys. The origin of northbound HGVs is mainly from the Warrington area and also Liverpool, with the greatest number destined for an area around Blackpool and Fleetwood. A number of HGV movements are also destined further north, as well as for the area around Barnsley, Bradford, Halifax, Huddersfield, Leeds and Wakefield.

The majority of HGVs travelling southbound typically originate from an area to the north of Leeds, as well as areas around Bury and Bolton. The main destination of southbound HGVs is to an area around Northwich, with the remainder relatively evenly distributed over a large area to the south.
Figure 45: M60 J13 to J14 Northbound Origin - Car

Figure 46: M60 J13 to J14 Northbound Destination - Car

Figure 47: M60 J13 to J14 Southbound Origin - Car

Figure 48: M60 J13 to J14 Southbound Destination - Car
Geographical Pilot Study – Manchester M60
Lot 1 SPaTS Framework

Figure 49: M60 J13 to J14 Northbound Origin - LGV

Figure 50: M60 J13 to J14 Northbound Destination - LGV

Figure 51: M60 J13 to J14 Southbound Origin - LGV

Figure 52: M60 J13 to J14 Southbound Destination - LGV
Figure 53: M60 J13 to J14 Northbound Origin - HGV

Figure 54: M60 J13 to J14 Northbound Destination - HGV

Figure 55: M60 J13 to J14 Southbound Origin - HGV

Figure 56: M60 J13 to J14 Southbound Destination - HGV
5. Trends in Measured NO\textsubscript{2} Concentrations

Introduction

As reported in Section 2, a substantial reduction in annual mean NO\textsubscript{2} concentrations has been observed at the Salford M60 CMS between 2013 and 2016, which did not occur at other CMSs in the Greater Manchester area (see Figure 7). To understand what influence different factors have had on concentrations measured at the Salford M60 CMS, temporal trends are examined in detail in this section. It is evident from Figure 6 for the Salford M60 CMS that there are two time periods of interest, over which different trends are observed. The first is 2004 to 2012, over which period there is relatively little variation in annual mean NO\textsubscript{2} concentrations. The second period is 2013 to 2016, over which a 16 µg/m\textsuperscript{3} (26.5\%) reduction in annual mean NO\textsubscript{2} is seen.

The analysis of trends in NO\textsubscript{x} and NO\textsubscript{2} has therefore looked at the overall period for which CMS data were available (2004 to March 2017) and subsequently at these two distinct periods, 2004 to 2012 and 2013 to 2017. The observed reduction in NO\textsubscript{2} concentrations in recent years is of particular interest, as this period coincides with a number of key events which may have influenced NO\textsubscript{2} concentrations at this site:

- the introduction of a 50 mph speed restriction on the section of the M60 adjacent to the CMS in September 2014;
- the entry into the UK vehicle fleet of HGVs meeting the Euro VI emission standard\textsuperscript{27} in January 2014;
- the entry into the UK vehicle fleet of cars meeting the Euro 6 emission standard in September 2015; and
- the entry into the UK vehicle fleet of cars and LGVs meeting the Euro 6 emission standard in September 2016.

The observed trend is therefore of interest with regard to potential mitigation measures, i.e. if the trend can be demonstrated to be associated with one or another of these factors, this will potentially provide key information on what measures could be employed here or elsewhere to improve air quality.

Finally, to investigate whether observed trends were unique to the M60 motorway or were indicative of national trends, data from the CMS adjacent to the M4 at Hillingdon, Greater London, were evaluated over the same period for comparative purposes.

Long Term Trend (2004 to 2017)

The trends over time in CMS data can be calculated and investigated using Openair functions (smoothTrend\textsuperscript{28} and TheilSen\textsuperscript{29}). These functions have the option to ‘deseason’\textsuperscript{30} the data before calculating the trend. Since NO\textsubscript{x} and NO\textsubscript{2} experience seasonal trends due to temperature and higher concentrations of ozone in the spring and summer months, the ‘deseason’ option has been applied in the following analysis.

The smoothTrend plots of NO\textsubscript{x} and NO\textsubscript{2} concentrations at the Salford M60 CMS (2004 to 2017) are shown in Figure 57 and Figure 58. For NO\textsubscript{x}, there is a continual downward trend from 2004 to 2017, the gradient of which marginally steepens from 2010 onwards. The trend in measured NO\textsubscript{2} concentration is noticeably different, with no clear trend between 2004 to 2012 followed by a considerable reduction of almost 20 µg/m\textsuperscript{3} thereafter to 2017. The trends in the two figures indirectly indicate that the NO\textsubscript{2} to NO\textsubscript{x} ratio has been increasing over time, which is confirmed in Figure 59, which shows a gradual increase in

\textsuperscript{27} European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU and EEA member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards. European emission standards for HDVs are defined using roman numerals (e.g. Euro V) and for LDVs using Arabic numerals (e.g. Euro 5).

\textsuperscript{28} Calculates the smooth trend in monthly mean concentrations, showing a smooth line through the data and 95\% confidence intervals of the fit.

\textsuperscript{29} Calculates the straight-line regression slope in monthly mean concentrations with 95\% confidence intervals. A measure of statistical significance of the trend is also calculated.

\textsuperscript{30} A seasonal component is calculated for each month (mean value of each month). This seasonal component is then “loess-smoothed” to determine the trend.
this ratio over the time series, with the rate of this increase steepening between 2009 and 2015. These figures therefore indicate that whilst NOx concentrations have been consistently decreasing between 2004 and 2017, the resulting effect on NO2 concentrations has been limited until more recently by a corresponding increase in the NO2:NOx ratio.

Figure 57. Trend in Measured NOx at the Salford M60 CMS (2004 to 2017)

Figure 58. Trend in Measured NO2 at the Salford M60 CMS (2004 to 2017)
Figure 59. Trend in Measured NO$_2$ to NO$_x$ ratio at the Salford M60 CMS (2004 to 2017)

TheilSen regression analysis provides the rate of change in concentrations per year over a time period of interest. This is accompanied by lower and upper confidence intervals (95%) and a measure of statistical significance.$^{31}$ A straight-line regression of the NO$_x$ and NO$_2$ concentrations presented in Figure 57 to Figure 59 respectively shows that there is a highly statistically significant (indicated by *** ) downward trend in both NOx and NO$_2$ over this period, with a much greater year on year reduction in NO$_x$ compared with NO$_2$. Furthermore, there was also a statistically significant increasing trend in the NO$_2$ to NOx ratio over the same time period:

- Trend Significance NO$_x$: -9.1 [-10.6, -7.3] µg/m$^3$/year ***;
- Trend Significance NO$_2$: -1.4 [-1.9, -0.9] µg/m$^3$/year ***; and
- Trend Significance NO$_2$ to NOx ratio: 0.009 [0.007, 0.011] ***

Historical Trend (2004 to 2012)

The trend in NO$_x$ concentrations at the Salford M60 CMS for the period 2004 to 2012 is shown in Figure 60, which indicates that there was a consistent downward trend in concentrations over this period. The trend in NO$_2$ concentrations presented in Figure 61 however shows that concentrations of this pollutant remained stable over the same time period. As NO$_x$ concentrations have consistently decreased over this time period, and NO$_2$ concentrations have remained stable, the NO$_2$ to NO$_x$ ratio has increased over this time period (see Figure 62).

---

$^{31}$Note p-value symbols relate to the level of statistical significance of each trend estimate:

- $p < 0.001 = ***$
- $p < 0.01 = **$
- $p < 0.05 = *
- $p < 0.1 = +$
Figure 60. Trend in Measured NO$_x$ at the Salford M60 CMS (2004 to 2012)

Figure 61. Trend in Measured NO$_2$ at the Salford M60 CMS (2004 to 2012)
Figure 62. Trend in Measured NO₂ to NOₓ ratio at the Salford M60 CMS (2004 to 2012)

Straight-line regressions of the concentrations presented in Figure 60 to Figure 62 show that between 2004 and 2012 there was a large and highly statistically significant downward trend in NOₓ, whereas concentrations of NO₂ exhibited only a weak downward trend, although this was not statistically significant, and there was a statistically significant increasing trend in the NO₂:NOₓ ratio:

- Trend Significance NOₓ: -6.9 [-9.9, -4.1] µg/m³/year ***
- Trend Significance NO₂: -0.5 [-1.1, 0.2] µg/m³/year
- Trend Significance NO₂ to NOₓ ratio: 0.006 [0.003, 0.009] ***

More Recent Trend (2013 to 2017)

The more recent trend (2013 to 2017) in NOₓ concentrations measured at the Salford M60 CMS is shown in Figure 63. The smoothTrend function is not as consistent as in the figures above for 2004 to 2012. Instead there is a slight initial increase followed by a steep decrease during 2014 and then a steady decline thereafter to 2017. The trend for measured NO₂ in Figure 64 largely follows the trend in NOₓ.

Figure 63. Trend in Monitored NOₓ at the Salford M60 CMS (2013 to 2017)
Straight-line regressions of the data presented in Figure 63 to Figure 65 show that more recently, and in contrast to the historic trend, there is a large, highly statistically significant downward trend in both NO\textsubscript{x} and NO\textsubscript{2}. Furthermore, the year on year reduction in NO\textsubscript{x} between 2013 and 2017 was an almost 2.5 times larger than between 2004 and 2012. There was also an increasing trend in the NO\textsubscript{2}:NO\textsubscript{x} ratio over this time period. This was not statistically significant, however:

- Trend Significance NO\textsubscript{x}: -16.8 [-21.2, -12] µg/m\textsuperscript{3}/year ***
- Trend Significance NO\textsubscript{2}: -5.5 [-6.7, -4.3] µg/m\textsuperscript{3}/year ***
- Trend Significance NO\textsubscript{2} to NO\textsubscript{x} ratio: 0.009 [-0.001, 0.019]

It is thought that the differences in trends in NO\textsubscript{x} and NO\textsubscript{2} concentrations observed over different time periods and the associated NO\textsubscript{2} to NO\textsubscript{x} ratio may be attributable to changes in vehicle fleet composition as vehicles are gradually replaced over time and replaced with newer models and as result of an increasing proportion of diesel cars and LGVs. For example, a key component of near-road concentrations of NO\textsubscript{2} derives from directly emitted (primary) NO\textsubscript{2} from vehicles, notably those with a
The NO₂ to NOₓ ratio in vehicle exhausts has increased over the past ten years due to the introduction of retrofitted diesel oxidation catalysts (DOC) to reduce CO and hydrocarbons, diesel particulate filters (DPF) to trap particulates, and three way catalysts (TWC) to reduce emissions of CO and NOₓ from petrol vehicles. A summary of these exhaust emission reduction systems is provided in Table 7 and Table 8 for LDVs and HDVs respectively (the date provided is for new type approval; the implementation date for all new vehicle registrations is normally one year later).

By way of their action, DOCs and DPFs also increased exhaust emissions of NO₂ whereas this was not the case for TWC which were found to be effective at reducing NOₓ and NO₂. This increase in NO₂ emissions associated with DOCs and DPFs, combined with a lower than expected reduction in total NOₓ emissions from vehicles, has meant that the anticipated reduction in ambient NO₂ concentrations has not been observed. However, Carslaw et al. (2016)³² have observed signs in recent air quality monitoring data for London, that suggest the situation is changing.

To investigate how vehicle technologies have changed over time and how they have affected the emission of NO₂, Carslaw et al. (2016) looked at trends in NO₂ and NOₓ using ambient measurements and remote sensing data for vehicle emissions in London. They found evidence for a decrease in NO₂ concentrations, driven by relatively large reductions in the amount of primary NO₂ emitted since around 2010 and less evidence for a reduction in total NOₓ. The reduction in NO₂ to NOₓ ratio was also found to be driven by HGVs and buses rather than LDVs, although there is also evidence that, as Euro 4 and 5 cars age, the NO₂ to NOₓ ratio reduces (possibly due to a reduction in catalyst efficiency).

### Table 7 – Summary of Light Duty Diesel Engine Technologies

<table>
<thead>
<tr>
<th>Reduction system</th>
<th>Introduced*</th>
<th>Applied to</th>
<th>Intended result</th>
<th>Impact on NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Oxidation Catalyst</td>
<td>Jan 2000</td>
<td>Euro 3 diesel</td>
<td>Reduce CO, HC by using Pt/Pd to oxidise</td>
<td>Increased primary NO₂ emissions</td>
</tr>
<tr>
<td>Diesel Particulate Filter</td>
<td>Jan 2005</td>
<td>Some Euro 4 diesel</td>
<td>Increase residence time to oxidise soot</td>
<td>Increased primary NO₂ emissions</td>
</tr>
<tr>
<td></td>
<td>Sept 2009</td>
<td>Euro 5 diesel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lean NOx trap</td>
<td>Sept 2014</td>
<td>Euro 6 diesel</td>
<td>Reductants (CO, HC) to reduce NOx</td>
<td>Reduce NOx emissions without affecting NO₂:NOx ratio</td>
</tr>
<tr>
<td>SCR catalyst</td>
<td>Sept 2014</td>
<td>Euro 6 diesel</td>
<td>Urea to convert NOx to N and water</td>
<td></td>
</tr>
</tbody>
</table>

*date for new type approval, implementation date for all new vehicle registrations is normally one year later

### Table 8 – Summary of Heavy Duty Diesel Engine Technologies

<table>
<thead>
<tr>
<th>Reduction system</th>
<th>Introduced*</th>
<th>Applied to</th>
<th>Intended result</th>
<th>Impact on NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust gas recirculation</td>
<td>Oct 2008</td>
<td>Euro V diesel</td>
<td>Increase residence time to oxidise soot</td>
<td>Increased primary NO₂ emissions</td>
</tr>
<tr>
<td>SCR catalyst</td>
<td>Oct 2008</td>
<td>Euro V diesel</td>
<td>Urea to convert NOx to N and water</td>
<td>Reduce NOx emissions without affecting NO₂:NOx ratio</td>
</tr>
<tr>
<td>Lean NOx trap</td>
<td>Jan 2013</td>
<td>Euro VI diesel</td>
<td>Reductants (CO, HC) to reduce NOx</td>
<td>Reduce NOx emissions without affecting NO₂:NOx ratio</td>
</tr>
</tbody>
</table>

*date for new type approval, implementation date for all new vehicle registrations is normally one year later

Comparison with other CMS Sites

To investigate whether long-term trends in NO\textsubscript{x} and NO\textsubscript{2} concentrations at the Salford M60 CMS reflect national factors such as the introduction of Euro VI HDVs, or local factors such as the 50 mph speed restriction, monitoring data for the Hillingdon M4 CMS were examined over the same time period. The Hillingdon M4 CMS is located within the M25, north of Heathrow airport and 400m west of M4 Junction 3. It is approximately 35m to the north of the M4 eastbound carriageway on Simpson Road a few metres below the height of the motorway. The trends in measured NO\textsubscript{x} and NO\textsubscript{2} concentrations and NO\textsubscript{2} to NO\textsubscript{x} ratio at the Hillingdon M4 CMS are shown in Figure 66 to Figure 68 respectively.

![Figure 66. Trend in Monitored NO\textsubscript{x} at the Hillingdon M4 CMS (2004 to 2017)](image1)

![Figure 67. Trend in Monitored NO\textsubscript{2} at the Hillingdon M4 CMS (2004 to 2017)](image2)
Straight-line regressions of the data presented in Figure 66 to Figure 68 show there is slight upward trend in NO\textsubscript{x} at this site, although this is not statistically significant. Concentrations of NO\textsubscript{2} however show a statistically significant slight increasing trend. There was also a statistically significant increasing trend in the NO\textsubscript{2}:NO\textsubscript{x} ratio at this site over this time period:

- Trend Significance NO\textsubscript{x}: 0.4 [-0.3, 1.2] \(\mu g/m^3/\text{year}\)
- Trend Significance NO\textsubscript{2}: 0.7 [0.4, 1.0] \(\mu g/m^3/\text{year}\)***
- Trend Significance NO\textsubscript{2} to NO\textsubscript{x} ratio: 0.004 [0.002, 0.006]***

Neither the long-term trend in NO\textsubscript{x} nor NO\textsubscript{2} at the Salford M60 CMS (shown in Figure 57 and Figure 58) is replicated at the Hillingdon M4 CMS. The NO\textsubscript{x} concentration at the Hillingdon M4 CMS has remained stable around 100 \(\mu g/m^3\) and does not decrease over the time series, while at the Salford M60 CMS concentrations have decreased significantly. In addition, there is a notable difference in the NO\textsubscript{x} concentrations at the two sites in 2004, despite similarly high vehicle flows on the two motorways. At the beginning of the time series the NO\textsubscript{x} concentration at the Salford M60 CMS is approximately 170 \(\mu g/m^3\) or 50\% higher than that at the Hillingdon M4 CMS. Whilst some of this difference is likely to be explained by the influence of the height, distance and alignment of the respective monitors relative to the motorway, a significant proportion is thought to relate to differences in fleet composition on the M4 compared to the M60. For example, as shown in Table 9 the proportion of HGVs on the M4 (4.0\%) is less than half that of the M60 (10.7\%). Furthermore, as shown in Table 10, there appears to be a much smaller proportion of articulated HGVs on the M4 (42\%) than the M60 (70\%), and a much greater proportion of larger articulated HGVs (i.e. with 6 or more axles) on the M60 (56\%) than the M4 (17\%).

**Table 9: Measured Motorway Traffic Flows on M60 and M4 in 2015**

<table>
<thead>
<tr>
<th>Motorway Section</th>
<th>2015 Measured Daily Traffic Flow</th>
<th>HGV%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Cars</td>
</tr>
<tr>
<td>M60 J13 – J14</td>
<td>152,403</td>
<td>115,058</td>
</tr>
<tr>
<td>M4 J4 – J4b</td>
<td>144,394</td>
<td>116,075</td>
</tr>
</tbody>
</table>

SOURCE: https://www.dft.gov.uk/traffic-counts/

**Table 10: Measured Motorway HGV Flows on M60 and M4 in 2015**

<table>
<thead>
<tr>
<th>Motorway Section</th>
<th>Rigid HGV</th>
<th>Articulated HGV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Axle</td>
<td>3 Axle</td>
</tr>
<tr>
<td>M60 J13 – J14</td>
<td>3,193</td>
<td>1,003</td>
</tr>
<tr>
<td>M4 J4 – J4b</td>
<td>2,235</td>
<td>372</td>
</tr>
</tbody>
</table>

SOURCE: https://www.dft.gov.uk/traffic-counts/
The trend of monthly mean NO\(_2\) concentrations at the Hillingdon M4 CMS shows two clear periods of contrasting trends compared to the Salford M60 CMS. The first part of the time series (2004 to 2012) shows an increase, followed by a slight, gradual decrease from 2013 to 2017. This has some similarities to the pattern observed at the Salford M60 CMS site, which indicated a stable trend from 2004 to 2012 and then a decreasing trend post 2013. Although the decreasing trends at both sites occur during the same time periods, and the trend pivots around the same time, the rate of decrease is significantly greater at the M60 compared to the M4. This suggests that a similar factor may have influenced NO\(_2\) concentrations at both sites from 2013 onwards, but that at the M60 the effect is more pronounced.

Further work was undertaken to compare the observed trend at the Salford M60 CMS with a variety of other CMS sites around Manchester to establish if the considerable reduction in NO\(_2\) concentrations at the Salford M60 CMS in recent years was observed regionally. The results for NO\(_2\), summarised in Table 11 and illustrated graphically in Figure 69, suggest that the recent (2013 to 2017) significant downward trend in NO\(_2\) is a characteristic of the Salford M60 CMS alone. There have been declining trends in NO\(_2\) across Manchester, however none of the sites show a trend that is as significant in terms of the magnitude of change.

Table 11: Rates of change in NO\(_2\) concentration at each CMS between 2013 to 2017

<table>
<thead>
<tr>
<th>Statistic</th>
<th>M60</th>
<th>M4</th>
<th>Eccles</th>
<th>Glazebury</th>
<th>A56</th>
<th>Trafford</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Type</td>
<td>Motorway</td>
<td>Motorway</td>
<td>Industrial</td>
<td>Rural Background</td>
<td>Roadside</td>
<td>Urban Background</td>
</tr>
<tr>
<td>Slope (µg/m(^3)/yr)</td>
<td>-5.5</td>
<td>0.0</td>
<td>-1.1</td>
<td>0.3</td>
<td>-1.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>Lower Limit (95%)</td>
<td>-6.7</td>
<td>-1.3</td>
<td>-2.0</td>
<td>-0.4</td>
<td>-2.9</td>
<td>-1.3</td>
</tr>
<tr>
<td>Upper Limit (95%)</td>
<td>-4.3</td>
<td>1.6</td>
<td>0.0</td>
<td>0.9</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Significance†</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

† Note p-value symbols relate to the level of statistical significance of each trend estimate:
p < 0.001 = ***
p < 0.01 = **
p < 0.05 = *
p < 0.1 = +

Figure 69. Changes in NO\(_2\) concentration per year between 2013 and 2017 for multiple CMS Sites

It is also interesting to note, that whilst no significant long-term trend in NO\(_2\) concentration was observed within the M1 Tinsley Pilot Study\(^{33}\) at the Tinsley Infant School CMS site between 2010 and 2016, a

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A slight decreasing trend does appear to have occurred at this site from 2014 onwards as shown in Figure 70. This point of inflexion suggests the factor(s) which influenced NO$_2$ concentrations at the Salford M60 CMS, and to a lesser extent the Hillingdon M4 CMS, may also have affected NO$_2$ concentrations adjacent to the M1 in Tinsley.

*Figure 70. Long term trend of NO$_2$ at Tinsley Infant School (2010 – 2016).*

### Conditional Extraction of Motorway Source Signal

**Method**

Analysis has been undertaken that follows the methodology of Malby et al., 2013$^{34}$, to ‘conditionally’ select and analyse monitoring data from the Salford M60 CMS. This method effectively attempts to isolate measured hourly concentrations attributable solely to the motorway, thereby increasing the signal to noise ratio. (Note that the magnitude of the resulting NO$_2$ concentrations is not directly comparable with that of the concentrations shown in Figure 58, for example, which illustrate the long term average values, as measured.) This gives more confidence that the measured concentrations being analysed are a result of emissions from the target source, in this case, the M60. The Salford M60 CMS data have been conditioned using the following data windows in order to obtain the ‘purest’ motorway signal:

- **days of the Week** – Monday to Friday (i.e. when traffic flows on the M60 are highest);
- **wind Direction** – 40 to 220 degrees (i.e. from the direction of the M60);
- **wind Speed** – 3 to 6 m/s (i.e. during wind speeds which are less likely to transport emissions from sources further afield); and
- **time of day** – 06:00 to 10:00 (i.e. during the period of the day when it is thought that there is the greatest difference between road traffic emissions and emissions from more diffuse sources (e.g. commercial and industrial combustion)).

A background component can be removed to further isolate the signal of the target source. Hourly concentrations at the Glazebury CMS were therefore removed for each corresponding hour of the day. The resulting concentrations are referred to as ‘motorway NO$_2$’ i.e. those that are conditioned to be solely attributable to the motorway source.

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Trend Analysis

The trend in motorway NO\textsubscript{2} concentration shown in Figure 71 is broadly similar to the trend seen in the raw (unconditioned) data in Figure 58, which further supports the hypothesis that the M60 is the primary source influencing concentrations measured at the Salford M60 CMS.

Figure 71: M60 minus Glazebury smoothTrend NO\textsubscript{2} for the fully conditioned dataset (2004 to 2017)

The trends with upper and lower confidence intervals for the motorway NO\textsubscript{2} signal at the Salford M60 CMS are presented in Table 12. The year on year trends in the conditioned motorway signal exhibit a greater downward gradient than for the ‘raw’ NO\textsubscript{2} presented in the previous section, with at least twice the µg/m\textsuperscript{3}/per year reduction in each time period examined. The downward trend in motorway NO\textsubscript{2} between 2004 and 2012 is also statistically significant, whereas the trend in the raw NO\textsubscript{2} over the same period is insignificant. These differences suggest the reductions in NO\textsubscript{2} observed at the Salford M60 CMS are strongly influenced by a reduction in the contribution from the M60.

Table 12: Trends in Motorway NO\textsubscript{2} at the Salford M60 CMS (2004 to 2017)

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Mean Frequency°</th>
<th>Gradient (µg/m\textsuperscript{3}/year)</th>
<th>Upper Limit (95%)</th>
<th>Lower Limit (95%)</th>
<th>Significance†</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 – 2017</td>
<td>22</td>
<td>-3.4</td>
<td>-4.2</td>
<td>-2.6</td>
<td>***</td>
</tr>
<tr>
<td>2004 – 2012</td>
<td>22</td>
<td>-2.0</td>
<td>-3.2</td>
<td>-0.6</td>
<td>**</td>
</tr>
<tr>
<td>2013 – 2017</td>
<td>22</td>
<td>-11.7</td>
<td>-14.9</td>
<td>-8.3</td>
<td>***</td>
</tr>
</tbody>
</table>

° Based on the number of hours in which there is a monitored value over the time series (2013 – 2017) averaged over 52 months

† Note p-value symbols relate to the level of statistical significance of each trend estimate:

- p < 0.001 = ***
- p < 0.01 = **
- p < 0.05 = *
- p < 0.1 = +

A corresponding analysis for motorway NO\textsubscript{x} is presented in Figure 72 and Table 13.
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Figure 72: Salford M60 minus Glazebury smoothTrend NOx for the fully conditioned dataset (2004 to 2017)

![Graph showing smooth trend of NOx concentrations from 2005 to 2017.

Table 13: Trends in Motorway NOx at the Salford M60 CMS (2004 to 2017)

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Mean Frequency</th>
<th>Gradient (µg/m³/year)</th>
<th>Upper Limit (95%)</th>
<th>Lower Limit (95%)</th>
<th>Significance†</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 – 2017</td>
<td>22</td>
<td>-29.6</td>
<td>-33.6</td>
<td>-25.5</td>
<td>***</td>
</tr>
<tr>
<td>2004 – 2012</td>
<td>22</td>
<td>-33.2</td>
<td>-39.9</td>
<td>-26.5</td>
<td>***</td>
</tr>
<tr>
<td>2013 – 2017</td>
<td>22</td>
<td>-39.3</td>
<td>-56.7</td>
<td>-21.9</td>
<td>***</td>
</tr>
</tbody>
</table>

Notes:
- Based on the number of hours in which there is a monitored value over the time series (2013 – 2017) averaged over 52 months.
- Note p-value symbols relate to the level of statistical significance of each trend estimate:
  - p < 0.001 = ***
  - p < 0.01 = **
  - p < 0.05 = *
  - p < 0.1 = +

When comparing the trends in motorway NO₂ and motorway NOx, there are clear differences in the relative rates of decrease over different time periods. For example, the rate of decline in NOx is relatively similar between 2004 and 2012 as between 2013 and 2017. The rate of reduction, however, in NO₂ is almost six times greater between 2013 and 2017 as between 2004 and 2012. This suggests the ratio of motorway NO₂ to NOx has decreased between 2013 and 2017, which may indicate that the proportion of primary NO₂ emitted by vehicles has been decreasing. The relationship between motorway NO₂ and motorway NOx is shown as a NO₂ to NOx ratio in Figure 73 between 2004 and 2017. This figure shows a general increase in the NO₂:NOx ratio up to 2012, followed by a consistent decrease which accelerated from 2016 onwards.

Comparison of the NO₂:NOx ratios shown in Figure 73 (for the conditioned motorway dataset) with that shown in Figure 65 (for the unconditioned dataset) indicates some key differences. Firstly, the magnitude of the NO₂:NOx ratio for the unconditioned dataset is approximately twice that of the conditioned motorway dataset. The lower NO₂:NOx ratio for the conditioned motorway dataset reflects the fact that only a relatively small portion of ambient NO has converted to NO₂ following its emission and therefore that little time, and thus distance, has passed between the point of emission and that of measurement. In contrast, the higher NO₂:NOx ratios in the unconditioned dataset reflect the influence of more distant NOx emission sources. Having travelled a greater distance, over a longer time period, a greater proportion of these emissions have been converted to NO₂ by the time they have reached the Salford M60 CMS. These differences in the NO₂:NOx ratio from different directions are illustrated in Figure 32, which indicates that the NO₂:NOx ratio from the northwest (i.e. not from the motorway) is
approximately twice that from the southeast (i.e. from the motorway). Secondly, the NO$_2$:NOx ratio in the unconditioned dataset increases from 2016 onwards, whereas the NO$_2$:NOx ratio for the conditioned motorway dataset decreases over this period. This discrepancy is also thought to be explained by the difference in the NO$_2$:NOx ratio between motorway and non-motorway emission sources, and the increasing relative influence non-motorway sources have on the unconditioned dataset from 2016 onwards as the motorway contribution decreases.

**Figure 73: M60 smoothTrend motorway NO$_2$:NOx ratio for the fully conditioned dataset (2004 to 2017)**

**Contribution per Vehicle**

In order to more fully understand trends in vehicle emissions over time, it is important to account for the potential confounding influence of changes in traffic flows over the same time period. Trends in hourly traffic flows between J13 and J14 of the M60 have therefore been calculated as follows:

- 55 [35,77]*** vehicles per hour per year between 2004 to 2016;
- 130 [93,170]*** vehicles per hour per year between 2004 to 2012; and
- 0 [-80, 76] vehicles per hour per year between 2013 and 2016.

These calculated trends suggest that traffic flows increased between 2004 and 2012, before stabilising in more recent years. It should be remembered however that no traffic data are available between J13 and J14 of the M60 from October 2014 onwards and that traffic data from this point onwards have been infilled based on measured flows in previous years. To an extent therefore the stabilisation in traffic flows between 2013 and 2016 shown in the trends above is reflective of this assumption; however, the available traffic data for this period do suggest minimal traffic growth in recent years (see Figure 9).

The motorway NO$_2$ contribution per vehicle has been calculated by dividing the hourly Motorway NO$_2$ concentration derived in the preceding section by the corresponding total two-way traffic flow. The resulting trend in motorway NO$_2$ per vehicle is shown in Figure 74.
The trend in conditioned motorway NO$_2$ per vehicle shows a similar pattern to the trend in motorway NO$_2$ (shown in Figure 71), with no clear trend between 2004 and 2012, followed by a decreasing trend from 2013 onwards. A distinct increase in the motorway NO$_2$ contribution per vehicle is however noticeable between 2007 and 2009, which correlates with the period over which there was a significant increase in the motorway NO$_2$:NOx ratio (see Figure 73). This indicates that the observed increase in motorway NO$_2$ per vehicle between 2007 and 2009 was driven by an increase in primary NO$_2$ emissions from motorway traffic. The observed trends in motorway NO$_2$ per vehicle are as follows:

- $-0.29 [-0.41, -0.19]^{***}$ ng/m$^3$ per year between 2004 and 2017;
- $0.04 [-0.12, 0.20]$ ng/m$^3$ per year between 2004 and 2012; and
- $-1.34 [-1.66, -0.90]^{***}$ ng/m$^3$ per year between 2013 and 2017.

These trends indicate that there was a small, but statistically significant, decreasing trend in motorway NO$_2$ per vehicle between 2004 and 2017, a negligible, but not statistically significant, increasing trend between 2004 and 2012 and a sizeable, statistically significant, decreasing trend between 2013 and 2017.

Motorway NOx per vehicle between 2004 and 2017 is presented in Figure 75 with trends over the different time periods of interest summarised below:

- $-2.96 [-3.42, -2.51]^{***}$ ng/m$^3$ per year between 2004 and 2017;
- $-2.79 [-3.54, -2.05]^{***}$ ng/m$^3$ per year between 2004 and 2012; and
- $-3.80 [-5.56, -1.46]^{***}$ ng/m$^3$ per year between 2013 and 2017.

These trends indicate that there has been a relatively large, statistically significant, decreasing trend in motorway NOx between 2004 and 2017, but that there was a larger, statistically significant, decreasing trend between 2013 and 2017 than between 2004 and 2012.
Diurnal Variations in the Impact per Vehicle

Malby et al.\textsuperscript{34} investigated changes in motorway NO\textsubscript{2} per vehicle over time at different hours of the day, compared these changes to measured variations in traffic flow and composition and by doing so inferred that an observed increase in NO\textsubscript{2} concentration was most likely to be associated with non-HGVs under heavily-congested conditions. A similar analysis has therefore been undertaken as part of this study to see if any similar conclusions can be drawn for the periods of interest.

Changes in motorway NO\textsubscript{2} concentration per vehicle between 2004 and 2012 by hour of day are presented in Figure 76. It should be noted that there are no values at 01:00 in 2004 due to the lack of CMS monitoring data for that hour. Figure 76 indicates that there was general reduction in motorway NO\textsubscript{2} per vehicle between 2004 and 2012, but that the greatest absolute and relative reductions in motorway NO\textsubscript{2} per vehicle between 2004 and 2012 (up to -25.0 ng m\textsuperscript{-3} per vehicle or -35\%) occurred between 00:00 and 05:00 when the proportion of HGVs on the M60 is greatest (see Figure 79). Furthermore, during peak traffic periods (see Figure 78) when the proportion of HDVs is relatively low (see Figure 79), there was relatively little reduction in motorway NO\textsubscript{2} per vehicle between 2004 and 2012, if not an increase (e.g. at 07:00 and 19:00).

The same analysis comparing motorway NO\textsubscript{2} per vehicle between 2013 and 2016 is presented in Figure 77. This shows that there has been a large decrease of between -28\% and -47\% in motorway NO\textsubscript{2} per vehicle during each hour of the day. Again however, the greatest absolute decreases occur during the night-time when HGV proportions are highest (see Figure 81). The smallest reductions in both absolute and relative terms are also observed during the morning peak hours (07:00 and 08:00) when traffic flows are relatively high (see Figure 80) HDV proportions are relatively low (see Figure 81).
Figure 76: Diurnal variation in Motorway NO$_2$ per Vehicle (expressed in absolute and percentage terms) for 2004 to 2012

Figure 77: Diurnal variation in Motorway NO$_2$ per Vehicle (expressed in absolute and percentage terms) for 2013 to 2016
Figure 79 and Figure 81 indicate that there appears to be two broad traffic regimes, one where HDVs are more prevalent 01:00 – 05:00 and one where LDVs are more prevalent 07:00 – 19:00. The HDV regime represents a period with a high proportion of HDVs and lower total vehicle flows typically resulting in more free flow conditions. During the LDV regime there is a reduced, albeit still sizeable, proportion of HDVs and higher total traffic flows on the network. By comparing the impact per vehicle over these two regimes, it is possible to assess which vehicle type may have resulted in the greatest reduction in per vehicle contribution to roadside NO$_2$ concentrations. Figure 82 and Figure 83 show the differences in per vehicle contribution for each regime over the two time periods of interest.

Figure 82: Motorway NO$_2$ per Vehicle for two daily intervals in 2004 and 2012
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Figure 83: Motorway NO₂ per Vehicle for two daily intervals in 2013 and 2016

Figure 82 and Figure 83 indicate that the HDV regime results in the greatest average contribution per vehicle to motorway NO₂ concentrations in each year, being over three times that of the LDV regime. Between 2004 and 2012 the relative decrease in the per vehicle contribution to motorway NO₂ concentrations during the HDV regime (20%) is over twice the reduction in the per vehicle contribution during the LDV regime (9%). Between 2013 and 2017 there was a much larger decrease in the contribution per vehicle across both regimes, with a decrease of 54% and 70% across the LDV and HDV regimes respectively.

This analysis suggests that there has been a sizeable reduction in contribution per vehicle to motorway NO₂ concentrations between 2013 and 2017 during periods with high proportions of both LDVs and HDVs, but that there has been a larger reduction in this contribution per vehicle during periods of the day with higher proportions of HDVs. This suggests that there has been a larger reduction in NOx emissions from HDVs than from LDVs over this time period.

Theoretical Emissions using EFT and CURED

In order to test the hypothesis that there has been a greater reduction in emissions from HDVs than LDVs between 2013 and 2016, theoretical estimates of NOₓ and primary NO₂ emissions for LDVs and HDVs have been calculated. The following emission tools were used to calculate a number of different alternative emission estimates:

- DEFRA Emission Factor Toolkit (EFT) (Version 6.0.2) released November 2014;
- DEFRA Emission Factor Toolkit (EFT) (Version 7.0) released July 2016;
- CURED35 (Version 1A) released March 2016; and
- CURED (Version 2A) released July 2016.

CURED is based on Defra’s EFT, but uses emissions factors from COPERT 4V11 for the latest Euro standards. This is to provide a reasonable worst-case set of emission factors for modelling. The CURED emission factors also take account of recent real-world emissions test data.\(^{36}\)

NOx emission rates were calculated at 5kph intervals between 5 – 120 kph for LDVs and HDVs respectively for each available year in the various emission tools\(^{37}\) up to 2017. These emission rates were linearly interpolated for each hour of the year to replicate gradual fleet composition changes i.e. so there was no assumed step change in emissions between years. Emission factors were also calculated on the same basis for the fraction of primary NO₂ that makes up the total NOₓ emission. Primary NO₂ fractions for LDVs and HDVs were derived using the fraction of NOx emitted as NO₂ by vehicle type and

\(^{35}\) Air Quality Consultants Ltd. Calculator Using Realistic Emissions for Diesels (CURED)


\(^{37}\) For example, Defra’s EFT v7.0 only allows the user to calculate emissions from 2013 onwards.
Euro standard and fleet composition projection data from the National Atmospheric Emissions Inventory (NAEI)\textsuperscript{38,39}.

Hourly LDV and HDV flows were then multiplied by the corresponding emission factor for the speed recorded in that hour for either side of the carriageway. This calculated the hourly emission of NO\textsubscript{x} (g/km/s) for each vehicle type in either direction. These values were then added together to obtain the total M60 NO\textsubscript{x} emissions between Junctions 13 and 14 for both vehicle types. The hourly NO\textsubscript{x} emissions were also multiplied by the corresponding primary NO\textsubscript{2} fraction. This provided an hourly primary NO\textsubscript{2} emission for each vehicle type.

Two-way NO\textsubscript{x} emissions for LDVs, HDVs and total vehicles are presented in Figure 84 to Figure 86 respectively.

\textbf{Figure 84. Trend in Two-Way LDV NO\textsubscript{x} Emissions using EFT and CURED (2008 to 2017)}

\textbf{Figure 85: Trend in Two-Way HDV NO\textsubscript{x} Emissions using EFT and CURED (2008 to 2017)}

Figure 84 suggests that LDV NOx emissions remained relatively stable between 2010 and 2014, after which there has been a slight decrease. Conversely, Figure 85 suggests that there has been a substantial reduction in HDV NOx emissions over this time period, particularly from 2013 onwards. The theoretical trend in total NOx emissions shown in Figure 86 therefore, which is relatively consistent with the trend in motorway NOx concentrations shown in Figure 72, is therefore primarily driven by the reduction in estimated HDV NOx emissions.

Two-way estimates of primary NO2 emissions for LDVs, HDVs and total vehicles are presented in Figure 87 to Figure 89 respectively.

Figure 87: Trend in Two-Way LDV Primary NO2 Emissions using EFT and CURED (2008 to 2017)
Estimated primary NO$_2$ emissions from LDVs shown in Figure 87 suggest that emissions increased between 2010 and 2014. As a similar increase in NOx emissions does not occur over the same time period (see Figure 84), this increase solely reflects an increase in the fraction of NOx emitted as NO$_2$ from LDVs.

Primary NO$_2$ emissions from HDVs shown in Figure 88 are estimated have decreased substantially since 2008, with the rate of this decrease steepening after 2013. This pattern corresponds to the estimated reduction in NOx emissions from HDVs shown in Figure 85. It should be noted that whilst total estimated primary NO$_2$ emissions from HDVs were approximately equal to that from LDVs in 2008, by 2016 estimated primary NO$_2$ emissions from HDVs are approximately one third of those from LDVs.

Estimated trends in total primary NO$_2$ emissions shown in Figure 89 closely match the patterns in measured NO$_2$ concentrations at the Salford M60 CMS shown in Figure 58 and the conditioned motorway NO$_2$ signal shown in Figure 71, with a period of relative stability between 2004 and 2012, followed by a substantial decrease from 2013 onwards. This correlation
indicates strongly therefore that the effect of reductions in M60 NOx emissions on annual mean NO$_2$ concentrations at the Salford M60 CMS has been limited until relatively recently by increased primary NO$_2$ emissions from LDVs and that the more recent reduction in annual mean NO$_2$ concentrations observed at the Salford M60 CMS was primarily driven by a reduction in emissions of NOx and NO$_2$ from HDVs.
6. Effect of Speed Restriction

Introduction
As part of the smart motorway construction works, a speed restriction of 50 mph was introduced along the M60, including between Junction 13 and Junction 14 adjacent to the Salford M60 CMS. The implementation of the speed restriction was phased with camera columns erected and associated signage installed before the speed cameras were installed and the covers removed. The installation process ran from August 2014 to the end of September 2014. The speed limit has been in place and enforced since October 2014. Therefore, speeds reduced gradually over this period rather than decreasing sharply (see Figure 9). In addition, lane narrowing took place from early February 2015.

Impact of Speed Restriction on Measured NO\textsubscript{2} Concentrations
A comparison of the measured concentrations attributable to the M60 motorway at the Salford M60 CMS has been undertaken to establish the impact of the speed restriction. A period immediately before and immediately after the implementation of the speed restriction have been compared using Openair software. The conditionally selected data attributable to the M60 have been deseasoned to account for variations in seasonal influences on measured concentrations (e.g. more stable meteorological conditions during winter). Measured concentrations attributable to the M60 were selected by filtering monitored NO\textsubscript{2} concentrations minus Glazebury NO\textsubscript{2} concentrations to wind conditions where winds were from the direction of the motorway (i.e. between 40 and 220 degrees) and greater than 0 m/s but less than 8 m/s as per Section 4.

In an attempt to limit the potential effect of changes in vehicle fleet composition over time, a comparison of measured pre- and post-speed restriction concentrations has been made over the short term (i.e. months as opposed to years). This also has the added benefit of evaluating the impact of the speed restriction prior to lane narrowing to limit any confounding effects. The monthly average M60 NO\textsubscript{2} concentration for the three months prior to and three months after the implementation of the speed restriction has therefore been compared, as well as the month long transition phase between the two (September 2014), as shown in Figure 90.

Figure 90: Average Motorway NO\textsubscript{2} at the Salford M60 CMS Pre- and Post-Speed Restriction

![Graph showing NO\textsubscript{2} concentrations]

Figure 90 indicates that there is relatively little difference between motorway NO\textsubscript{2} concentrations measured immediately before and immediately after the speed restriction was introduced, with mean NO\textsubscript{2} concentrations after the speed restriction being approximately 4% higher. Although this period is thought to have similar traffic flows to the pre-restriction period, the lower speed of vehicles appears to have caused a slight increase in concentrations. This finding is consistent with separate research undertaken on behalf of Highway England, which is discussed in more detail in the following section. The transition phase representing the period when speeds began to decline towards 50 mph is the
period with the highest concentrations perhaps reflecting increased congestion during this period as road users adapt to the speed restriction.

**Highways England Research into Dynamic Management of Motorway Traffic Conditions**

Highways England has separately commissioned research to investigate the potential impact of dynamic management of motorway traffic conditions on air quality e.g. through the introduction of variable speed limits at different times of the day. The work by Carslaw and Bellamy (2017) has analysed pollutant concentrations, meteorological data and traffic data for two areas to determine the key factors affecting concentrations. Statistical models were developed to understand what effect dynamic traffic management measures would have under different conditions. The study used data from M60 J13-14 (as well as M25 J13-14) and therefore the findings are particularly relevant to this pilot study. The period examined in this research was 2014 and 2015.

Contrary to previous understanding of the shape of the vehicle speed-emission curve (i.e. the highest speeds are associated with higher emissions), the NO\textsubscript{x} concentrations measured adjacent to the M60 were found to decrease when traffic speeds were above 60 mph and when the hourly traffic flow was between 6,000 and 8,000 vehicles. The highest NO\textsubscript{x} concentrations were instead found when vehicle flows were over 6,000/hour with speeds below 60 mph. The authors suggest this indicates “flow breakdown” and traffic instability i.e. vehicles accelerating and decelerating. Higher speeds were found to be associated with lower concentrations, as free flowing conditions are likely to arise when traffic flows are lower and vehicles can travel faster.

Comparison of the data with and without speed control in place on the M60 revealed that the highest NO\textsubscript{x} concentrations occurred under the same conditions in both scenarios, i.e. when hourly flows were over 8,000 and speeds were around 50 mph which is indicative of when flow breakdown occurs. Peak NO\textsubscript{x} concentrations did, however, decrease from 350 µg/m\textsuperscript{3} to 300 µg/m\textsuperscript{3} between the two scenarios. This suggests that while the speed restriction has not prevented flow breakdown from occurring it has reduced speed variability, particularly above 50mph. Notably, however, the without speed control period did not reveal evidence of increasing concentrations above 60 mph. Furthermore, the research confirms that flows have not been affected by the reduction in speed limit. This is consistent with use of the M60 as a strategic route.

The research also found that “long vehicles” are more influential on NO\textsubscript{x} concentrations than “short vehicles”, and that the speed of short vehicles is more important than the flow with NO\textsubscript{x} concentrations decreasing as short vehicle speed increases (opposite effect for long vehicle speed).
7. Conclusions

Principal Findings

The conclusions of this study are summarised below, followed by the implications of the study’s findings to Highways England with regard to the development of air quality mitigation measures. The principal findings relate to:

- the relationship between the observed NO\textsubscript{2} concentrations at the roadside and the volume of traffic flows on the M60, with an emphasis on the relative volumes of HDV and LDV flows;
- the effect of HGVs meeting the Euro VI emission standard entering the fleet in 2014;
- the effect of a changing ratio of NO\textsubscript{2}/NOx emissions from LDVs and HGVs on the M60 over time; and
- the effect of speed restriction on emissions and the observed concentrations.

These findings are described below. This study has shown that motorway traffic emissions contribute strongly to observed NO\textsubscript{2} concentrations alongside the M60. Estimates of this M60 contribution, together with the estimated contribution from regional background sources, satisfactorily explains the majority of measured annual mean NO\textsubscript{2} concentrations adjacent to the M60. A small number of monitoring locations adjacent to the M60 are also influenced by emissions from other roads, for example at locations close to junctions, and in some cases the magnitude of this contribution is similar to that of the M60.

The magnitude of the contribution from the M60, and the resulting annual mean NO\textsubscript{2} concentration at roadside locations, appears to be substantially greater north of J12 than south of J12. This difference in M60 “source strength” (which is approximately double) is thought to relate to not just a difference in total traffic flow (up to 34% higher), but also fleet composition (approximately twice the number of HGVs). These additional vehicle movements, and the additional HGV movements in particular, are thought to relate to vehicles using the M62 (to/from Liverpool), which joins the M60 at J12.

Statistical analysis at the Salford M60 CMS indicates that, after wind direction, LDV flow on the M60 has the greatest influence on NO\textsubscript{2} concentrations and that this influence is approximately twice that of HDV flow on the M60. Conversely, for NOx, HDV flow has the second greatest influence (19.4%), which is more than twice that of LDV flow (7.7%). This suggests a greater proportion of NOx emissions from LDVs are emitted as NO\textsubscript{2} than for HDVs.

Annual mean NO\textsubscript{2} concentrations have reduced significantly in recent years at the Salford M60 CMS (from 61.5 µg/m\textsuperscript{3} in 2013 to 45.5 µg/m\textsuperscript{3} in 2016 – a 26% reduction). Source apportionment analysis, and comparison with monitoring results at other CMS sites in the wider area, suggests that this decrease is primarily a result of a reduction in the contribution from vehicles using the M60.

Analysis of the trends in measured NOx and NO\textsubscript{2} concentrations at the Salford M60 CMS indicates that, between 2004 and 2012, there was a large, statistically significant decrease in NOx (-6.9 µg/m\textsuperscript{3} per year), whilst there was only a slight and not statistically significant decrease in NO\textsubscript{2} concentrations (-0.5 µg/m\textsuperscript{3} per year). In contrast, between 2013 and 2017, there was a much larger, statistically significant decrease in NOx concentrations (-16.8 µg/m\textsuperscript{3} per year) coupled with a large, statistically significant decrease in NO\textsubscript{2} concentrations (-5.5 µg/m\textsuperscript{3}). These differences in trends between the two time periods suggest that, whilst NOx concentrations decreased between 2004 and 2012, the effect of this reduction on NO\textsubscript{2} concentrations was limited by an increase in the NO\textsubscript{2}:NOx ratio (i.e. a greater proportion of NOx was emitted as NO\textsubscript{2}). Since 2013, however, there has been a much greater reduction in NOx concentrations and little or no change in the NO\textsubscript{2}:NOx ratio, which has resulted in a significant reduction in NO\textsubscript{2} concentrations.

The increase in the NO\textsubscript{2}:NOx ratio at the Salford M60 CMS between 2004 and 2012 is thought to be primarily due to an increase in primary NO\textsubscript{2} emissions from diesel LDVs over this period. Several studies have shown that the use of Diesel Oxidation Catalysts (DOC) and particle filters in both light and heavy duty vehicles have led to increased NO\textsubscript{2}:NOx ratios in vehicle exhaust. More recent research, however, using measurements in London suggests that the proportion of NOx emitted as NO\textsubscript{2} appears to have decreased in recent years and that this reduction was found to be primarily driven by HGVs and buses rather than LDVs.

A large reduction in M60 LDV and/or HDV movements between 2013 and 2016 would have resulted in a large decrease in NOx emissions and therefore potentially explain the reduction in NO\textsubscript{2} concentrations.
over this period. In fact, traffic flows on this section of the M60 increased slightly between January 2012 and October 2014, although after this date no data are available as the traffic monitoring equipment along this stretch of the M60 were deactivated as a result of construction works. The construction works and associated 50 mph speed restriction may have caused a reduction in traffic flow as drivers used alternative routes. The short-period of data available after the introduction of the speed restriction suggests this was not the case, however.

A 50 mph speed restriction was introduced on the M60 in September 2014. The reduction in average vehicle speed, and potential increase in laminar traffic flows, may have resulted in lower engine loads and consequently lower NOx emissions from vehicles. Estimates of the contribution of vehicles on the M60 to measured NOx concentrations at the M60 Salford CMS immediately before and after the implementation of the 50 mph speed restriction suggest, however, that the speed restriction did not result in a reduced contribution from the M60 and that it may have slightly (4%) increased. This conclusion is supported by research recently undertaken by Highways England, which concluded that a 50 mph speed restriction was unlikely to result in a significant reduction in NOx concentrations and may even result in a slight increase.

The entry into the UK vehicle fleet in January 2014 of HGVs meeting the Euro VI emission standard and, in September 2015, of cars, and, in September 2016, of LGVs, meeting the Euro 6 emission standard, may have influenced NOx emissions from the M60 over the period of interest. The use of conditional analysis to give a ‘pure’ motorway signal at the M60 Salford CMS, evaluation of trends in this signal and comparison with trends in traffic flows over the same period, all indicate a significant (33%) decrease in the contribution per vehicle to NOx concentrations between 2013 and 2016. The greatest absolute reductions in this contribution per vehicle occur during periods with the highest proportion of HDVs (i.e. during the night), suggesting that emissions per vehicle have significantly reduced between 2013 and 2016 and that these reductions in the contribution per vehicle are more likely to have been driven by reductions in emissions from HDVs than from LDVs.

Theoretical trends in NOx and NO2 emissions between 2004 and 2016, estimated using four different sets of emission factors, suggest that there has been a substantially greater reduction in NOx emissions from HDVs than LDVs over this period. Furthermore, estimated primary NOx emissions from LDVs are estimated to have remained relatively stable, even increasing between 2010 and 2014, whilst estimated primary NO2 emissions from HDVs appear to have reduced significantly, primarily as a function of the reduction in NOx emissions from these vehicles. Whilst these emission estimates are indicative, these patterns strongly suggest that the recent reduction in ambient NO2 concentrations at the Salford M60 CMS has primarily been driven by a reduction in NOx emissions from HDVs and that, before this, the effect of any reduction in NOx emissions from HDVs was offset by increased primary NO2 emissions from LDVs.

**Implications for Highways England**

Annual mean NO2 concentrations adjacent to the M60 are primarily influenced by emissions from the M60, rather than other emission sources, and therefore reducing emissions from the M60 is likely to be the most effective way of reducing annual mean NO2 concentrations at these locations.

Annual mean NO2 concentrations are higher between J12 and J15 of the M60 than between J10 and J12, most likely as a result of higher total traffic and HGV flows on these sections of the M60. These additional vehicle movements, and the additional HGV movements in particular, are thought to relate to vehicles using the M62 (to/from Liverpool), which joins the M60 at J12. Measures aimed at reducing emissions from these vehicles would therefore have the potential to reduce the elevated annual mean NO2 concentrations which occur between J12 and J15.

As LDVs appear to have a greater influence on NO2 concentrations adjacent to the M60 than HDVs, reducing NOx (and NO2) emissions from LDVs on the M60 is likely to be the most effective way of reducing annual mean NO2 concentrations at these locations.

Speed control, in itself, appears unlikely to have a significant effect on roadside NO2 concentrations. The effectiveness of speed control as an air quality mitigation measure is therefore likely to be limited to any associated effects on traffic flows, which, for strategic routes where suitable alternative routes are not available, could potentially be minimal (as appears to be the case in this study area).

The recent reduction in NO2 concentrations at the Salford M60 CMS appears to have primarily been driven by a reduction in emissions from HDVs. This suggests that schemes aimed at encouraging HDV
fleet renewal should be encouraged, whilst noting that much of the benefit of a switch to Euro VI engines may have already been realised.

Whilst emissions from the HDV fleet in the study area appear to have reduced considerably in recent years, it is unclear whether this is reflective of the relatively large number of larger, articulated HGVs on this section of the M60, which may not be replicated elsewhere. These larger, long-distance HGVs are likely to be replaced more frequently in national fleets than smaller HGVs used by local and smaller operators. An ANPR survey on this section of the M60 would therefore be useful to ascertain if certain sections of the HGV fleet in this area are more modern than others, perhaps indicating that it is these vehicles which are most heavily influencing the observed reductions in NO₂ concentration. Ideally these data would be compared to the results of a similar ANPR survey elsewhere (perhaps adjacent to the M4 in Hillingdon) to assess whether there are any significant differences in the composition of the HGV fleet in these areas.
8. Lessons Learned

This study has undertaken several detailed analyses to extract insights from available data. The lessons learned during this study and the potential application of these analyses are summarised in the following sections.

Openair Analysis

The analysis of air quality monitoring and traffic data using Openair within this study has been particularly informative. It should be recognised, however, that the value of this analysis was heavily influenced by the location of the Salford M60 CMS. The Salford M60 CMS affords a rare opportunity to investigate the motorway contribution in detail, due to its proximity to the M60 and its relative distance from other emission sources. This has allowed the M60 signal to be isolated relatively easily and investigated in detail, facilitating the extraction of useful information from this monitoring site, and maximising its value. The lack of similar such sites (highlighted by the fact that observed trends in Manchester have had to be compared to a site adjacent to the M4 in Hillingdon) is a limiting factor, as it is unclear whether similar trends are observed elsewhere.

The Openair Deweather tool was useful to an extent, particularly in determining the relative influence of HDV and LDV flows on NOx and NO\textsubscript{2} concentrations respectively, although it is noted that ‘influence’ does directly relate to the absolute magnitude of the contribution from different vehicle types.

The analysis undertaken using the methodology proposed by Malby et al. was useful and gave additional confidence that observed trends were primarily influenced by a reduction in the contribution from the M60. Such analysis is likely to be even more useful at other monitoring sites where the motorway signal is less clear and conditional analysis is essential in order to isolate such a signal. Assessing the change in NO\textsubscript{2} per vehicle was useful, as this allowed changes in traffic flows over time to be taken into account. Assessing changes in the contribution per vehicle to NO\textsubscript{2} concentrations by hour of day was also useful in terms of assessing changes in contributions during periods with high proportions of HDVs and LDVs respectively.

Trends in Primary NO\textsubscript{2}

A key finding of this study was the limiting influence of primary NO\textsubscript{2} emissions from LDVs on annual mean NO\textsubscript{2} concentrations in previous years, but in particular the fact that peak primary NO\textsubscript{2} may have been reached and that NO\textsubscript{2}:NOx ratios appear to be reducing. Further investigation of this issue is recommended.

Select Link Analysis

The select link analysis undertaken as part of this study was not considered particularly useful given the relatively large scale at which origin and destination data is provided. This analysis did, however, highlight the combined local and strategic nature of the vehicles using the M60.

Monitoring Data

A significant amount of time was spent annualising the results of Highways England diffusion tube monitoring in order to inform this study. For future studies, it is recommended that HE diffusion tube data are annualised in advance using an appropriate and consistent methodology.

Traffic Data Availability

An unfortunate consequence of the current managed motorway construction works is that MIDAS survey points have been removed within the study area, thereby limiting the availability of traffic data in the study area. MIDAS data availability was also limited for the M4. It is therefore recommended that prior to the commencement of further such studies, a review of MIDAS data availability is undertaken as this data source is particularly useful.
Appendix A – Spatial Patterns in Diffusion Tube Measurements
Appendix A - Spatial Patterns in Diffusion Tube Measurements

This appendix investigates the spatial patterns in measured background nitrogen dioxide concentrations within the study area and explains how data from background monitoring sites have been interpolated to determine a continuous measured background field. It then goes on to describe the detailed data analysis that has been performed on diffusion tube monitoring results, commissioned by both Highways England (HE) and the Greater Manchester Combined Authority (GMCA), along and around the M60 motorway.

Measured Background Concentration Field

Methodology

The Greater Manchester Combined Authority monitors concentrations of nitrogen dioxide at more than 200 sites throughout the ten boroughs, 49 of which were considered to represent background conditions. These sites were operational during both the 2014 and 2015 calendar years.

The GMCA sites were augmented with an additional four sites operated by HE for 2014, and only one for 2015.

In both cases, each site in the network was examined to ensure that it provided a good representation of background conditions. The data from those sites which were considered to be too close to roads were discarded from the background field analysis.

The annual mean NO$_2$ concentration from the Glazebury rural background AURN site (13.5 µg/m$^3$ in 2014 and 15.5 µg/m$^3$ in 2015) was then subtracted from the measured concentrations to generate the local background concentrations.

The combined dataset was then interpolated using kriging with the following linear variogram:

$$Y(h) = C_0 + Sh$$

(eq. 1)

Where $Y$ is the variogram value, $h$ is the separation distance, $C_0$ is the nugget effect (eq. 2), $S$ is the slope (eq. 3), $D_{nn}$ is the mean distance to the nearest neighbour, $D_{avg}$ is the inter-sample separation distance, $G_{nn}$ is $½$ the mean squared difference between nearest neighbours and $\text{Var}$ is the sample variance.

$$C_0 = \max \left\{ \frac{G_{nn}D_{avg} - \text{Var}D_{nn}}{D_{avg} - D_{nn}}, 0 \right\}$$

(eq. 2)

$$S = \max \left\{ \frac{\text{Var} - G_{nn}}{D_{avg} - D_{nn}}, 0 \right\}$$

(eq. 3)

Results

The interpolated fields are given in Figure 1 (for 2014) and Figure 2 (for 2015). It is considered that each interpolated field is likely to give a reasonable estimate of concentrations in those locations close to a monitoring site, or between monitors that recorded similar values. Where there are no nearby monitors, or where a strong concentration gradient is predicted, the interpolated concentrations should be treated as indicative only.

It should be recognised that the isopleths in Figure 1 and Figure 2 do not represent step-changes and the choice of colour band can give the impression of different patterns. In particular, the shape of the 10-15 µg/m$^3$ colour band is quite different comparing Figure 1 with Figure 2, but had a different banding been used, the patterns would appear very similar.
Figure 1 and Figure 2 indicate that background NO$_2$ concentrations are highest in central Manchester, with concentrations decreasing with distance from the centre. Concentrations reduce more slowly with distance from the city centre in some directions than others. Some of the areas where background NO$_2$ concentrations are relatively elevated are the urban centres of Oldham, Stockport, Bolton and Bury. Other areas with relatively elevated concentrations appear to follow motorways (for example the M60 and M56), but it is impossible to know whether these patterns would persist if the diffusion tubes were located further from the motorways.

![Interpolated Nitrogen Dioxide Concentration for 2014 (μg/m$^3$)](image-url)

*Figure 1: Interpolated Nitrogen Dioxide Concentration for 2014 (μg/m$^3$)*
Figure 2: Interpolated Nitrogen Dioxide Concentration for 2015 (µg/m³)
Determining Signal from M60 Motorway Methodology

Several locations along the M60 where diffusion tubes were positioned linearly and at varying distances from the motorway were identified as appropriate transects. In most cases, data were available for both 2014 and 2015. These sites were predominately located to the west of Manchester City centre.

In some transects the diffusion tubes were managed by both HE and the relevant Local Authority. Initial analyses suggested that there may be systematic differences between the concentrations measured in different surveys and so, in order to avoid any confounding effects from these differences, the analysis has focused on the HE tubes. Concentrations measured at appropriate diffusion tubes within each transect were processed through Defra’s NOx from NO\textsubscript{2} calculator (V5.1), taking background NO\textsubscript{2} from the rural component plus the interpolated fields given in Figure 1 and Figure 2, to obtain the equivalent ‘road-NOx’ concentration.

For each DT within each transect location, the distance to outside lane of the M60 was measured, and used to interpolate the equivalent ‘road NOx’ concentration at a distance of 10 metres from the motorway using the fall-off with distance curve produced by AQC for the DMRB Air Quality Model (2013 iteration)\textsuperscript{1}. This curve can be expressed as:

\[
C_b = C/(\text{IF}(A<1.4765,3.92454283234404,\text{IF}(A<4.704,\text{EXP}((0.0289*(\ln(A)^3)-0.2988*(\ln(A)^2)+0.2197*(\ln(A))+1.3253)),\text{IF}(A<73.47,\text{EXP}((0.0064*(\ln(A)^3)-0.0656*(\ln(A)^2)-0.5226*(\ln(A))+1.9991),\text{EXP}((-0.0752*(\ln(A)^2)-0.2556*(\ln(A))+1.5368)))))))*\text{IF}(B<1.4765,3.92454283234404,\text{IF}(B<4.704,\text{EXP}((0.0289*(\ln(B)^3)-0.2988*(\ln(B)^2)+0.2197*(\ln(B))+1.3253)),\text{IF}(B<73.47,\text{EXP}((0.0064*(\ln(B)^3)-0.0656*(\ln(B)^2)-0.5226*(\ln(B))+1.9991),\text{EXP}((-0.0752*(\ln(B)^2)-0.2556*(\ln(B))+1.5368)))))))
\]

where

- \(C_b\) = road-NOx at distance B;
- A = input/monitor location distance to the edge of the road (m);
- B = output/normalised location distance to the edge of the road (m); and
- C = road-NOx at distance A from the edge of the road.

These values were then averaged, with the resultant average concentration used to extrapolate concentrations along the DMRB fall-off curve from the kerb to generate an idealised fall-off with distance from the M60.

Figure 3 and Figure 4 show the locations of each of the transects with available data in 2014 and 2015 respectively, while Figure 5 and Figure 6 show the NO\textsubscript{2} concentrations measured at each site. Each transect is then described in turn. In some cases, the values do not fit with the idealised curve at all well, indicating there are confounding factors affecting the measured concentrations. In other cases, there are so few monitoring points on the transect that it is difficult to determine any meaningful trends. Despite these points, it is considered that something useful can be drawn from the all of data presented; particularly when viewed as a whole. The principal reason for including all of the data in this way is to allow a comparison of the relative contributions that the motorway makes to concentrations in different locations. This comparison is given in the next section.

\textsuperscript{1} HE internal document.
Figure 3: Transects with data for 2014
Figure 4: Transects with data for 2015
Figure 5: Annual Mean NO\textsubscript{2} in 2014 at Transect Monitoring Sites
Figure 6: Annual Mean NO$_2$ in 2015 at Transect Monitoring Sites
The section of the M60 adjacent to the diffusion tubes located along the Greenleach Lane transect is elevated. In this instance, site HE157, to the west of the motorway, is located near to the base of the bridge, and below the source of emissions. Sites HE 157 and HE 183 are both much closer to Greenleach Lane than they are to the M60. Traffic using Greenleach Lane is likely to affect the measured concentrations, but the idealised line assumes that the motorway is the only local emission source. It is also noted that the planar distance between the outside lane of the motorway and the diffusion tube has been measured, leading to a likely underestimation of the distance.

Figure 8 and Figure 9 show the fall-off with distance curve generated from the data from two sites to the west of the M60, with the two data points laying either side of the idealised curve. This is the pattern that would be expected if the motorway was not the only source of local emissions and suggests that emissions from Greenleach Lane are having an appreciable influence on measured concentrations.
Figure 8: Fall-off with distance curve using tubes HE183 and HE157 for 2014, west of the M60

Figure 9: Fall-off with distance curve using tubes HE183 and HE157 for 2015, west of the M60
**Farm Lane**

![Map of Farm Lane Transect](image)

Figure 10: Locations of HE diffusion tubes along the Farm Lane Transect, east of the M60. The green line indicates the vegetative barrier adjacent to Farm Lane.

Two separate idealised fall-off curves have been plotted for Farm Lane in Figure 11 and Figure 12. The first (red line and points) is based on only the four sites which form an obvious transect from the M60 (sites HE 168, HE95, HE93, and HE106). The second fall-off with distance curve (blue line) is generated using an additional four sites, scattered between the M60 and Barton Road (blue points), as well as the original four sites. In each year, the two curves are almost identical, with all data fitting the idealised curve well, suggesting that emissions from the motorway are dominating concentrations at these sites.
Figure 11: Fall-off with distance curve generated using 8 suitable HE tubes (blue line) and only four tubes - HE168, HE95, HE93 and HE106 (red line) located on Farm Lane for 2014.

Figure 12: Fall-off with distance curve generated using 8 suitable HE tubes (blue line) and only four tubes - HE168, HE95, HE93 and HE106 (red line) located on Farm Lane for 2015.
Figure 13: Locations of HE and Salford DC diffusion tubes along the Ryecroft Lane Transect, east of the M60. The green line indicates the vegetative barrier adjacent to the M60.

The Ryecroft Lane transect is located to the east of the M60 between Junctions 12 and 13. Three of the sites shown in Figure 13 (Slf24, Slf29 and Slf30) are managed by the GMRC and are not, therefore, included in the analysis. For both years, the idealised curve describes the data very well, suggesting that the motorway is the primary source of local emissions.
Figure 14: Fall-off with distance curve in 2014 for the Ryecroft Lane transect.

Figure 15: Fall-off with distance curve in 2015 for the Ryecroft Lane transect.
Grange Road is located to the east of the M60, south of Ryecroft Lane. As shown in Figure 16, there are six diffusion tubes managed by HE along this transect. For generating the fall-off with distance curves, HE 116 has been discarded owing to its proximity to Barton Road resulting in elevated concentrations. Measured concentrations from the remaining five tubes fit the fall-off curve well in both years.
Figure 17: Fall-off with distance curve for 2014 for Grange Road transect.

Figure 18: Fall-off with distance curve for 2015 for Grange Road transect.
Salteye Road

Figure 19: Locations of HE diffusion tubes along the Salteye Road Transect, west of the M60.

Figure 20: Fall-off with distance curve for 2014 for Salteye Road transect.

Salteye Road is located to the west of the M60, just south of Junction 12. The grid references available for sites HE 47 and HE 191 indicate them to be very close to one another, however it has not been possible to verify this. Despite their proximity, in 2014 they measured quite different concentrations.
In 2015 only two tubes measured concentrations of NO$_2$. One of these measured a concentration vastly different to what was measured in 2014, and therefore a fall-off with distance curve has not been generated.

Figure 21: Locations of HE and Trafford DC diffusion tubes adjacent to the M60 Transect, west of the M60. The green line indicates the vegetative barrier adjacent to the M60.

There are four Highways England diffusion tubes parallel to the M60 between Junctions 9 and 10. The westbound off-slip road for Junction 10 passes diffusion tubes HE120 (28.4 m from the M60), and HE121 (37.6 m from the M60). These sites clearly do not form a transect, but they are interesting nonetheless.

Figure 22 and Figure 23 use blue lines to show the inferred idealised fall-off curve if all of the sites are treated equally. The points do not fit at all well to the line. In order to test whether this poor fit relates to proximity to Junction 10, the line was re-plotted (red line) to intersect site HE118, which is the furthest site from the junction. Figure 24 and Figure 25 show the offset between the red lines in Figure 22 and Figure 23 and the measurements as a function of distance from Junction 10 (distances measured perpendicular to the motorway and to the edge of Redclyffe Circle – which is the roundabout that forms part of Junction 10). There appears to be an approximate linear relationship between distance from the junction and the degree to which a prediction based solely on the measurement at HE118 and distance from the road under-predicts the measurements. The junction thus appears to be exerting an effect on concentrations which extends out at least 400 m from the roundabout and which adds more than 50% to motorway-related NOx concentrations.
Figure 22: Fall-off with distance curves for 2014 for M60 Transect.

Figure 23: Fall-off with distance curves for 2015 for M60 Transect.
Figure 24: Under-prediction of Normalised Road-NOx (at 10m from motorway) by Distance from Junction 10 (2014) – Under-prediction is the difference between the prediction based on Site HE118 only, expressed as percentage of measured value at each site.

\[ y = -0.0008x + 0.6412 \]

Figure 25: Under-prediction of Normalised Road-NOx (at 10m from motorway) by Distance from Junction 10 (2015) – Under-prediction is the difference between the prediction based on Site HE118 only, expressed as percentage of measured value at each site.

\[ y = -0.001x + 0.8281 \]
Figure 26: Locations of HE diffusion tubes adjacent to the Loretto Road Transect, on either side of the M60. The green line indicates the vegetative barriers adjacent to the M60.

There are four tubes close to Loretto Road, with two on each side of the M60. Sites HE186 and HE89, located to the west of the motorway, are bounded by the M60 and open parkland/fields, adjacent to a minor road with a 5 mph speed limit. In both 2014 and 2015 measured concentrations of NO$_2$ from HE186 appear to be lower than background concentrations, and it has not, therefore, been possible to interpret the source-strength from the motorway.

Site HE184 is significantly lower than the height of the motorway and is also shielded from the motorway by a bank of tall trees. In order to avoid placing undue weight on the concentration measured at Site HE184, the fall-off with distance curve has been set to pass through HE205, which is considered to be the best representation of local concentrations. Clearly this means that the source-strength for the motorway has been derived from one monitoring site only, but the good fit of the DMRB fall-off curve to the other transects shown previously adds confidence to this approach.
Figure 27: Fall-off with distance curve fitted to HE205, located east of the M60 for 2014.

Figure 28: Fall-off with distance curve fitted to HE205, located east of the M60 for 2015.
Comparison of Motorway Source-strengths

Figure 29 shows the average calculated road-NOx at 10 metres from the edge of the motorway at each site in each year (i.e. the value taken at 10m along each of the fall-off with distance curves presented above). The three transects located between Junctions 12 and 13 (Farm Lane, Ryecroft Lane and Grange Road) show very consistent NOx concentrations. The higher concentrations measured at Grange Road may reflect its position close to the M62/M60 intersection at Junction 12. Measured concentrations at Greenleach Lane were also similar to those between Junctions 12 and 13; despite the clear confounding influence of emissions from Greenleach Lane itself. This might suggest that NOx emissions from the motorway to the north of Junction 13 are lower than those to the south of Junction 13.

To the south of Junction 12, the inferred NOx source-strengths are much lower than those to the north; although it should be recognised that the number of monitors is lower, and the agreement with the idealised fall-off curve is poorer, for these transects. Despite this, there does appear to be a pattern of lower motorway-related NOx concentrations to the south of Junction 12 than to the north. The lowest concentrations were recorded at the M60 transect. These values were derived from just one monitoring site, but the other concentrations measured nearby, but closer to Junction 10, support the values used.

Figure 29 also shows the equivalent motorway source strengths that were derived in another Geographical Pilot Study carried out for Highways England beside the M1 in Sheffield. These are shown as “M1 Blackburn” and “M1 Brinsworth”. The M1 values are within the range of the M60 values, suggesting that the M60 north of Junction 12 gives rise to higher concentrations than the M1, while the M60 to the south of Junction 12 gives rise to lower concentrations than the M1.

Figure 30 shows the same data as Figure 29, but this time with the NOx source-strengths expressed per vehicle using the particular stretch of motorway. In this figure, there is less differentiation between the sections of the M60 to the north and south of Junction 12, but there is still a significant difference, which might suggest that some factors relating to driving patterns or fleet compositions result in higher NOx emissions for the motorway section to the north of Junction 12. Interestingly, in this analysis, the values for Loretto Road are comparable with those for Ryecroft, but it is noted that the values for Loretto Road are particularly uncertain since they are based on a single monitoring site.

Comparing the M60 data in Figure 30 with those for the M1 shows that NOx concentrations per vehicle appear to be higher beside the M1 than beside the M60. It should, though, be noted that the traffic data used were derived from two separate traffic models and there may, therefore, be some systematic bias.

\[\text{Traffic data taken from the regional traffic model developed to inform the Tranche 4 Smart Motorway Scheme.}\]
Figure 29: Normalised Road-NOx at 10m
Figure 30: Normalised Road-NOx at 10m Expressed per Vehicle per Day
Non-motorway NOx Source-strengths

Figure 31 and Figure 32 show that there are a number of other diffusion tube monitoring sites in the area that were not included in the transect analysis that was presented above. Figure 33 and Figure 34 show the measured road-NOx concentrations at each of these sites after having the calculated motorway contribution to NOx (calculated by taking the values for the distance specific to each monitoring site from the fall-off with distance curve for each section of motorway). The result, as shown in Figure 33 and Figure 34, is the NOx concentration that cannot be attributed to emissions from the mainline of the motorway.

All of the sites to the north of Junction 13 are shown as negative values. This suggests that the NOx emissions from the motorway along this section are lower than has been assumed. The value for the motorway here was taken from the Greenleach Lane normalised NOx value, which is thought to be influenced by traffic on Greenleach Lane itself. It is not, therefore, surprising that distance-weighted concentrations which are not beside Greenleach Lane are lower than those that are beside Greenleach Lane.

South of Junction 13, the values for Site HE90 suggest that a normalised residual NOx concentration of between 20 and 40 \(\mu g/m^3\) may be attributed to emissions from the B5211 (Barton Road) (i.e. the road alongside Site HE90). This range is comparable with the concentrations attributed to the M60 at Site HE118 and at Salteye Road in Figure 29. At Site HE199, normalised residual NOx concentrations in the range 60 to 100 \(\mu g/m^3\) have been calculated alongside the A57 (Liverpool Road), which is comparable with the highest sections of the M60 as shown in Figure 29. At Site HE202, the normalised residual NOx concentrations are in the 20 to 40 \(\mu g/m^3\) in 2014 and 0 to 20 \(\mu g/m^3\) in 2015. This site is beside the B5214 (Barton Road) and suggest that this road may also be a significant source of NOx emissions. Elsewhere, the normalised residual NOx concentrations are lower.

This analysis is quite tentative, since it relies on subtracting one extrapolated value from another, but it suggests that the contribution of the M60 to concentrations alongside the motorway is not significantly greater than the contribution of some other roads in the area.

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3 M60 NOx for the area to the north of Junction 13 was taken from the Greenleach Lane transect. M60 NOx for the area between Junctions 12 and 13 was taken as the average of the values at Farm Lane, Ryecroft, and Grange Road. M60 NOx for the remaining areas was taken as the average of the values at Salteye Road, Site HE118, and Loretto Road.
Figure 31: Measured Annual Mean NO₂ Concentrations at Other Tubes Near to Transects (2014)
Figure 32: Measured Annual Mean NO₂ Concentrations at Other Tubes Near to Transects (2015)
Figure 33: Normalised Residual NOx for 2014
Figure 34: Normalised Residual NOx for 2015