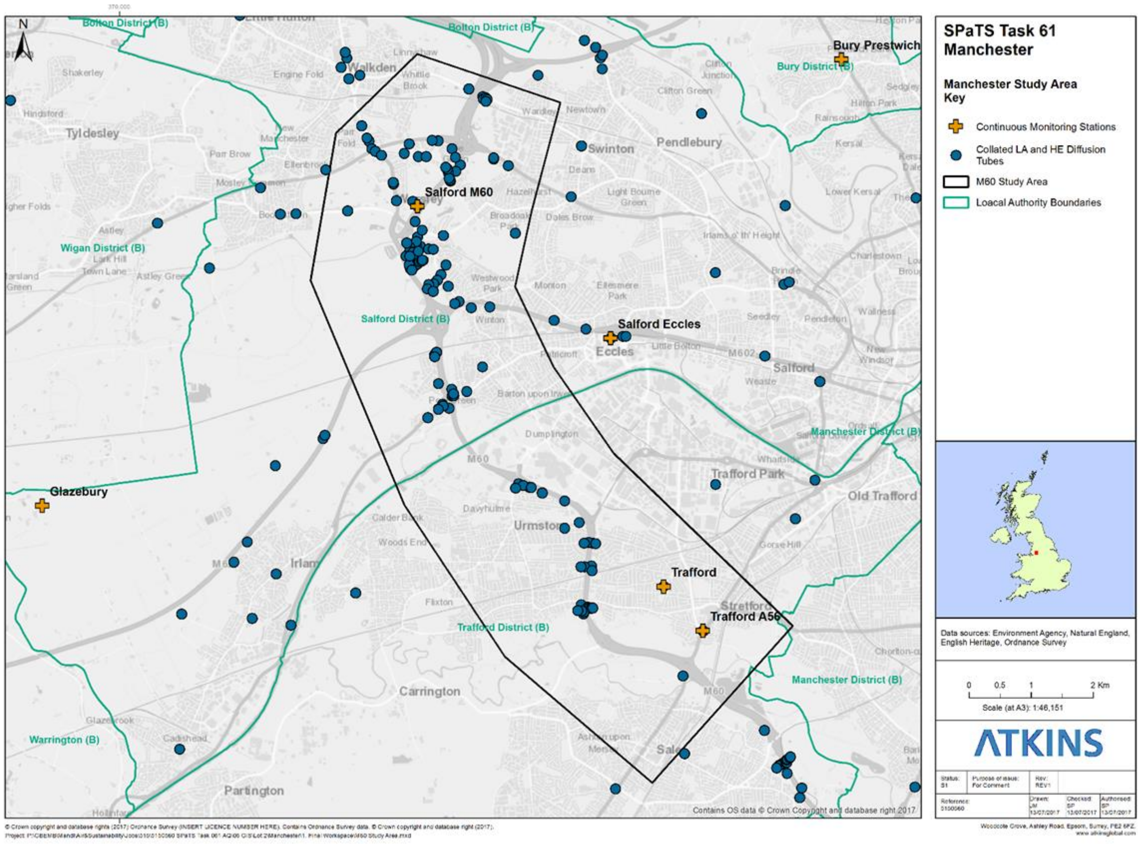
1. Introduction and Context

Annual mean nitrogen dioxide (NO_2) concentrations above the Air Quality Strategy (AQS) objective of 40 µg/m^3 have been measured at many locations representative of residential properties near to the M60 motorway in Manchester in recent years. Almost all of the motorway is situated within Air Quality Management Areas. The purpose of this pilot study is to investigate in detail the factors which influence NO_2 concentrations adjacent to the M60, so that Highways England (HE) might develop mitigation strategies to improve air quality.

Study Area

This pilot study focusses on the north-western section of the M60, between Junctions 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 in areas where elevated NO_2 concentrations have been recorded.

Figure 1: M60 Study Area



This section of the M60 suffers from congestion, which is thought to be a result of high volumes of both long distance and local traffic and conflict between traffic joining and exiting the motorway, exacerbated by the close spacing of junctions. These characteristics can result in increased exhaust emissions from road traffic and can therefore influence pollutant concentrations measured at the roadside.

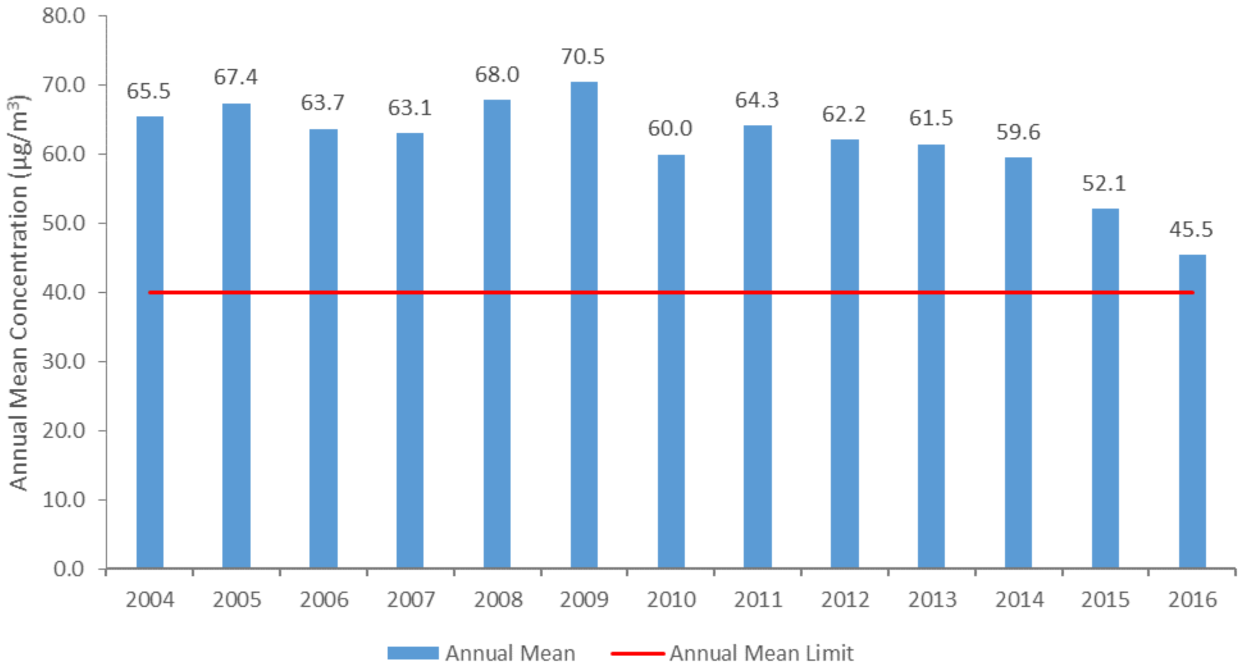
Air Quality Conditions

The results of diffusion tube monitoring undertaken by Highways England (HE) and Salford City Council (SCC) indicate that annual average NO_2 concentrations exceeded 40 µg/m^3 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 within 50 m of the M60 and between Junction 12 and Junction 14. Annual mean NO_2 concentrations adjacent to the M60 therefore appear to vary in magnitude along different sections of the M60. Such differences might, for example, indicate that characteristics of traffic conditions between Junction 12 and Junction 14 (e.g. flow, composition or congestion) contribute to elevated annual mean NO_2 concentrations.

Monitoring is also undertaken by SCC at a Continuous Monitoring Site (CMS) adjacent to the M60 between J13 and J14 (the "Salford M60 CMS"). Monitoring data obtained at this site are of particular interest, as the relatively "pure" motorway signal provides an opportunity to investigate in detail the contribution of the M60 to measured NO_2 concentrations.

The annual mean AQS objective was exceeded at this location in all years between 2004 and 2016 (see Figure 2). More recently, however, annual mean NO_2 concentrations have reduced significantly (by 26% in the period 2013 - 2016). Reductions of this magnitude have not been observed at other CMS sites in the wider area, which suggests that this reduction may be associated with a reduction in the contribution from vehicles using the M60. Determining if this is indeed the case and what factors may have caused this reduction will be informative when developing mitigation measures to reduce annual mean NO_2 concentrations adjacent to the Strategic Road Network. This potentially significant feature of the observed NO_2 (and NOx) concentrations was a major focus for the investigations undertaken as part of this study.

Figure 2: Measured Annual Mean NO_2 Concentrations at Salford M60 CMS (2004 – 2016)



Traffic Conditions

Traffic flow data indicate that there are significant variations in traffic flow and composition along different sections of the M60 within the study area. For example, total traffic volumes between J12 to J14 of the M60 are up to 34% higher than those between J10 and J12. Furthermore, the number of Heavy Goods Vehicles (HGVs) between J12 to J14 are approximately twice that between J10 and J12, in both absolute and percentage terms. These additional vehicle movements between J12 and J14, 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.

Measured HGV flows broken down by vehicle type and number of axles suggest that the difference in HGV flows between J12 and J14 compared to between J10 to J12 is primarily a result of a greater number of larger, articulated HGVs[1]. The movements of these larger vehicles are thought likely to be more 'strategic' in nature (i.e. they travel greater distances[2]) and again these vehicles are thought to relate to vehicles using the M62.

Analysis of hourly traffic data between J13 and J14 of the M60 indicates that total traffic flows increased between 2004 and 2011, from approximately 5,900 vehicles per hour to 6,500 (a 10% increase), whereas

[1] The number of axles is representative of vehicle size, with larger vehicles likely to have more axles

[2] https://www.gov.uk/government/statistical-data-sets/rfs01-goods-lifted-and-distance-hauled

Heavy Duty Vehicle[3] (HDV) flows decreased slightly from approximately 710 vehicles per hour to 660 (a 7% decrease). Between 2011 and 2014 however both traffic flows and HDV flows remained relatively stable.

Average vehicle speeds were relatively constant between 2008 and September 2014, after which point there was a significant step change in speed from approximately 96kph (60 mph) to 70kph (45 mph). This reduction in vehicle speed corresponds with the introduction of a 50 mph speed restriction on the M60 during construction works associated with the M60 Junction 8 to M62 Junction 20 smart motorway scheme. As this speed restriction coincides with the period over which a significant reduction in NO_2 concentrations is observed at the Salford M60 site, the effect (if any) this speed restriction may have had on annual mean NO_2 concentrations at the Salford M60 CMS site is of interest, particularly as speed restrictions have been proposed as a way of improving air quality.

2. Background Contribution

In order to understand the contribution that traffic using the M60 makes to measured annual mean NO_2 concentrations in the study area, the contribution made by other sources, i.e. the "background" component, must be quantified[4]. As the M60 is the closest, major emission source to the majority of monitoring sites in the study area, subtracting the background contribution from the observed concentration means that the residual concentration can reasonably be attributed to the M60.

The background contribution may itself be 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).

Monitoring data collected by HE and SCC in 2014 and 2015 were used to interpolate measured background NO_2 concentrations across the study area. This gave a concentration in the range of 20 to 25 $\mu g/m^3$, decreasing to 15 to 20 $\mu g/m^3$ further west of the urban centre.

The 'regional background' for the study area was derived from a CMS site in Glazebury, which is a rural background monitoring site to the south of Warrington, well away from major emission sources. The estimated regional component to annual mean NO_2 concentrations in the study area using measurements made at this site is approximately 16 $\mu g/m^3$.

Subtraction of this 'regional' background from the interpolated background concentration suggests that the contribution from local background sources to measured NO_2 concentrations in the study area ranges from 0 to 9 $\mu g/m^3$ and is therefore relatively small compared to total measured concentrations adjacent to the M60.

3. M60 Contribution

Diffusion Tube Analysis

To determine the contribution that emissions from vehicles using the M60 make to annual mean NOx (and thereby NO_2) concentrations, diffusion tube monitoring data collected by HE, including along transects perpendicular to the M60, were analysed.

In most cases, the decrease in NOx concentrations with increasing distance from the M60 conforms to the relationship typically observed in these circumstances, suggesting that the motorway is the primary source of local NOx emissions at these sites. There are some exceptions, where concentrations are thought to

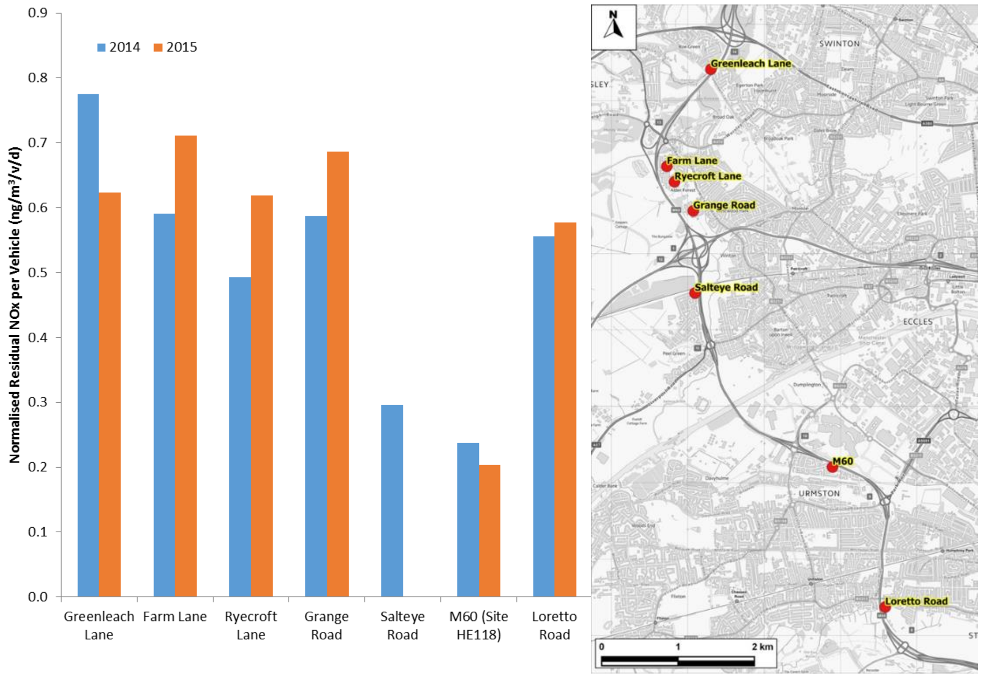
[3] Automated traffic counts distinguish between Light Duty Vehicles (i.e. cars and vans) and Heavy Duty Vehicles (i.e. HGVs, buses and coaches) based on the recorded length of each vehicle. It should be noted however that the proportion of buses and coaches on the M60 is less than 1% of the total flow, and therefore measured HDV flows relate primarily to HGVs.

[4] The total concentration of a pollutant comprises the contribution from explicit local emission sources such as roads, and those that are transported into an area by the wind from further away. Were all the local emission sources to be removed, only distant sources would influence measured concentrations. This latter component is referred to as the 'background' contribution.

be influenced either by emissions from other roads / junctions (which provide an additional source of NOx), or owing to their close proximity to physical barriers (e.g. noise barriers and vegetation), which may impede the dispersion of vehicle emissions.

A comparison of the average calculated road-NOx at 10 metres from the motorway edge at transects adjacent to different sections of the M60 suggests that the implied source-strength of the M60 is lower between J10 and J12 than between J12 and J14. This difference north and south of Junction 12 is less pronounced (see Figure 3) once vehicle flow is accounted for. Nevertheless, the difference implies there are factors such as driving patterns or fleet composition that produce higher NOx emissions between M60 J12 and J14. This may, in part, be due to the greater proportion of HGVs on the M60 north of J12.

Figure 3: Normalised Road-NOx Concentrations at 10m, Expressed per Vehicle per Day



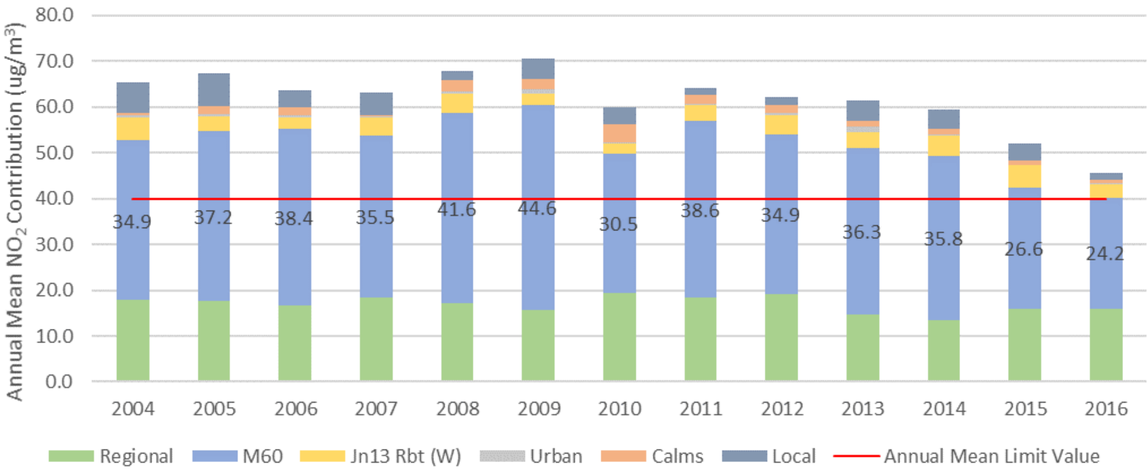
CMS Analysis

Analysis of wind speed and direction data with NO_2 and NOx concentrations at the Salford M60 CMS site indicates that directional and spatial variations in measured concentrations are consistent with those expected at a site which is heavily influenced by emissions from the M60.

To understand more fully the influence of the M60 has on measured NO_2 concentrations at the Salford M60 CMS, the monitoring data were ‘conditioned’ to isolate the contribution from the motorway and from other nearby emission sources. This conditioning involved removing the contribution from regional background sources by subtracting concentrations measured at the Glazebury CMS site from those at the M60 and using wind direction (and in some cases wind speed) to apportion measured concentrations under those conditions to a particular source.

The resulting source apportionment (illustrated in Figure 4) indicates that whilst the absolute contribution from different sources varies year on year (not least due to the influence of meteorology), the M60 makes the largest contribution to measured NO_2 concentrations in all years (51 - 63%) followed by the assumed contribution from regional background sources (22 - 35%). The results of this analysis also suggest minor contributions from traffic on J13 of the M60 (4 - 10%) and local background sources (3 - 11%), while the contribution of emission sources within Greater Manchester is negligible (1 - 2%).

Figure 4: Source Apportioned Annual Mean NO_2 Concentrations at the Salford M60 CMS (2004 to 2016)



Statistical analysis was undertaken to understand the influence of different factors on measured NO_2 and NOx concentrations at the Salford M60 CMS (the regional background contribution having been removed). This analysis indicates that, after wind direction, LDV flow on the M60 has the greatest influence on NO_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_2 than for HDVs.

The source apportionment analysis (see Figure 4) indicated that the magnitude of the contribution from all vehicles on the M60 to concentrations at the Salford M60 CMS ranged between 34.9 $\mu g/m^3$ and 38.6 $\mu g/m^3$ between 2011 and 2014. This contribution decreased noticeably to 26.6 $\mu g/m^3$ in 2015 and 24.2 $\mu g/m^3$ in 2016, suggesting that the large reduction in concentrations measured at the Salford M60 CMS in recent years (see Figure 2) is primarily a result of a reduction in the contribution from vehicles using the M60.

In order to confirm this hypothesis, additional statistical analysis was undertaken of the monitoring data obtained at the Salford M60 CMS in order to investigate trends in more detail.

4. Observed Trend in Concentrations

Analysis of the trends in measured NOx and NO_2 concentrations at the Salford M60 CMS between 2004 and 2016 shows a large (-9.1 $\mu g/m^3$ per year), statistically significant reduction in NOx concentrations (see Figure 5), coupled with a smaller (-1.4 $\mu g/m^3$ per year), statistically significant reduction in NO_2 concentrations (see Figure 6). There are, however, different patterns over different time periods. For example, between 2004 and 2012, there was a large, statistically significant decrease in NOx (-6.9 $\mu g/m^3$ per year), whilst there was only a slight and not statistically significant decrease in NO_2 concentrations (-0.5 $\mu g/m^3$ per year). In contrast, between 2013 and 2017, there was a much larger, statistically significant decrease in NOx concentrations (-16.8 $\mu g/m^3$ per year) coupled with a large, statistically significant decrease in NO2 concentrations (-5.5 $\mu g/m^3$). 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_2 concentrations was limited by an increase in the NO_2:NOx ratio (i.e. a greater proportion of NOx was emitted as NO_2). Since 2013, however, there has been a much greater reduction in NOx and little or no change in the NO_2:NOx ratio, which has resulted in a significant reduction in NO_2.

Figure 5: Trend in Measured NOx Concentrations at the Salford M60 CMS (2004 to 2017)

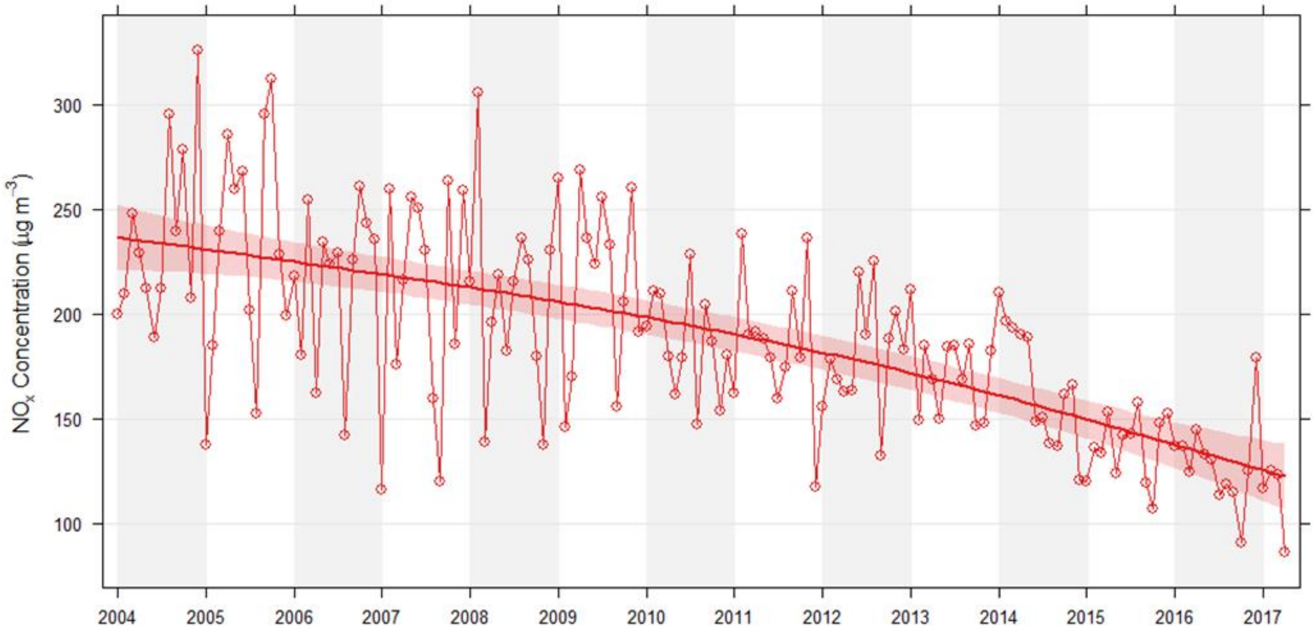
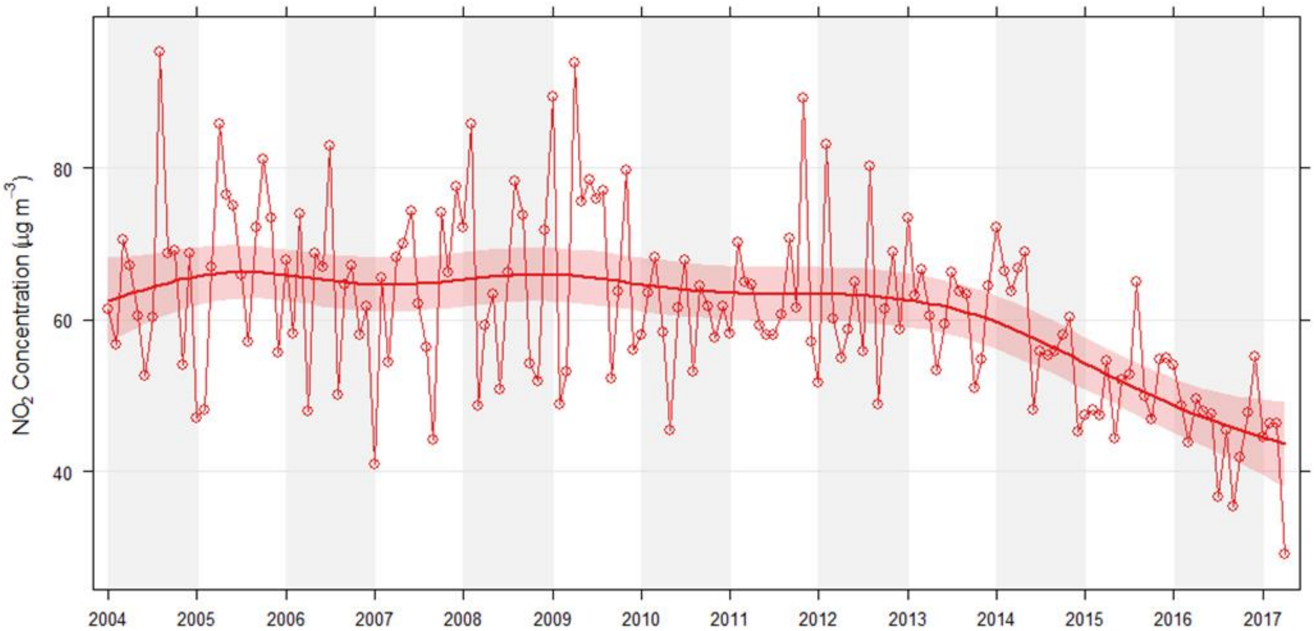


Figure 6: Trend in Measured NO2 Concentrations at the Salford M60 CMS (2004 to 2017)



The increase in the NO_2:NOx ratio at the Salford M60 CMS between 2004 and 2012 is thought to be primarily due to an increase in primary NO_2 emissions from diesel vehicles 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_2:NOx ratios in vehicle exhaust. More recent research, however, using measurements in London suggests that the proportion of NOx emitted as NO_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.

The key factors that may have caused the reduction in the contribution from the M60 to measured NO_2 concentrations at the Salford M60 CMS between 2013 and 2016 - changes in traffic flows, the speed restriction and individual vehicle emissions - were investigated in turn.

Changes in Traffic Flows

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 could explain the reduction in NO_2 concentrations over this period. 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.

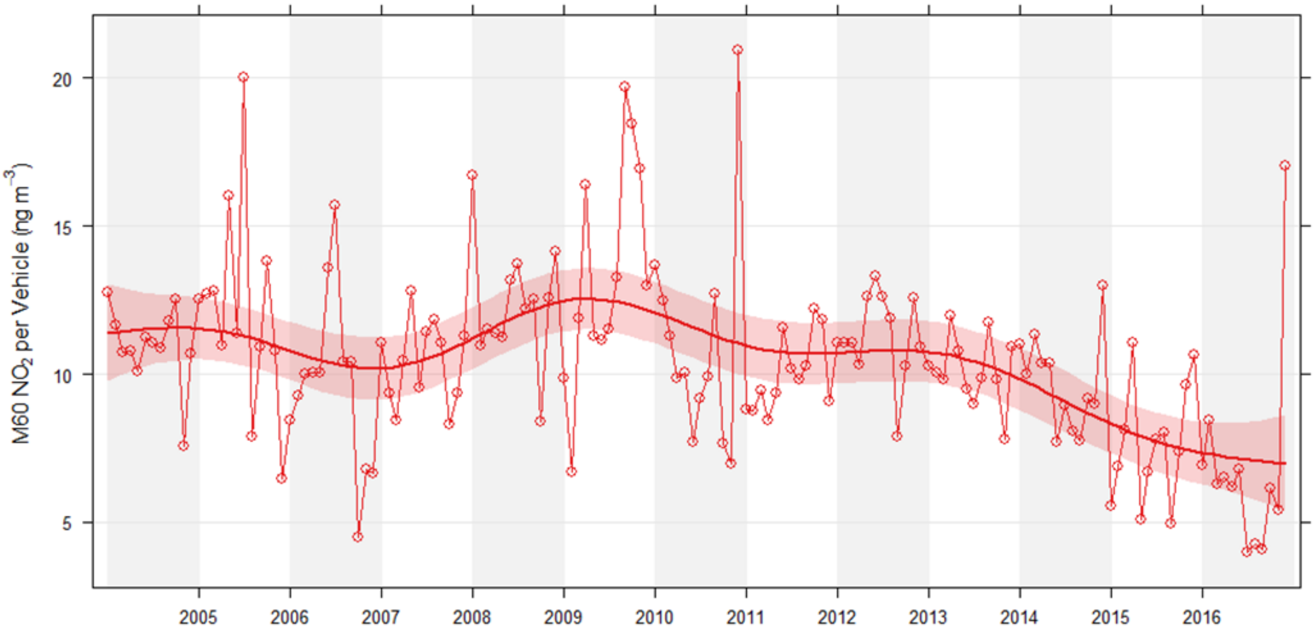
Speed Restriction

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 NO_2 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[5], which concluded that a 50 mph speed restriction was unlikely to result in a significant reduction in NO_2 concentrations and may even result in a slight increase.

Reductions in Emissions per Vehicle

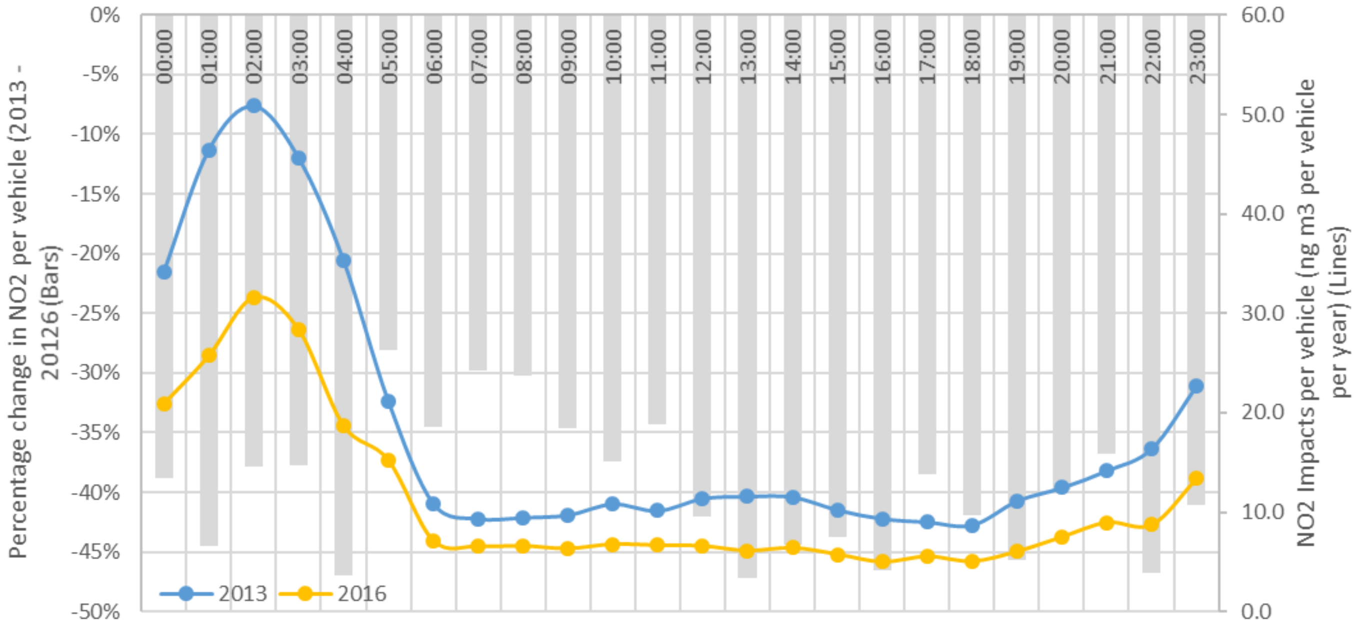
The entry into the UK vehicle fleet in January 2014 of HGVs meeting the Euro VI emission standard and, in September 2015 of cars and September 2016 of LGVs meeting the Euro 6 emission standard, may have influenced NOx emissions from the M60 over the period of interest. The use of conditional analysis 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 NO_2 contribution per vehicle between 2013 and 2016 (see Figure 7). The greatest absolute reductions in NO_2 per vehicle (see Figure 8) 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 are more likely to have been driven by reductions in emissions from HDVs than from LDVs.

Figure 7: Trend in M60 NO_2 Contribution per Vehicle (2004 to 2017)



[5] Carslaw D. and Bellamy N. (2017), HE Dynamic Speed Limits: Summary of Air Quality Analysis.

Figure 8: Diurnal variation in NO_2 Impact per Vehicle (expressed in absolute and percentage terms) for 2013 to 2016



Theoretical trends in NOx and NO_2 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 (see Figure 10) than LDVs (see Figure 9) over this period. Furthermore, estimated primary NO_2 emissions from LDVs (see Figure 11) are estimated to have remained relatively stable, even increasing between 2010 and 2014, whilst estimated primary NO_2 emissions from HDVs (see Figure 12) appear to have reduced significantly, primarily as a function of the reduction in NOx emissions from these vehicles. Whilst these emission estimates are entirely indicative, the patterns strongly suggest that the recent reduction in NO_2 concentrations at the Salford M60 CMS has primarily been driven by a reduction in emissions from HDVs and that, before this, the effect of any reduction in NOx emissions from HDVs was curbed by increased primary NO_2 emissions from LDVs.

Figure 9: Trend in Estimated M60 LDV NOx Emissions

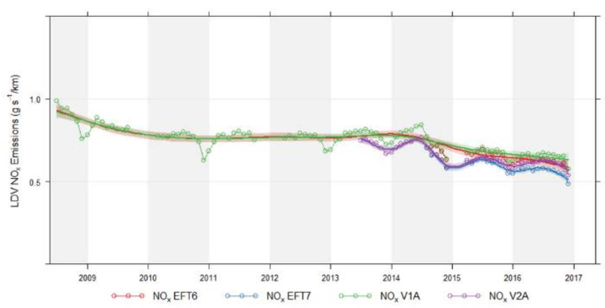


Figure 11: Trend in Estimated M60 LDV Primary NO_2 Emissions

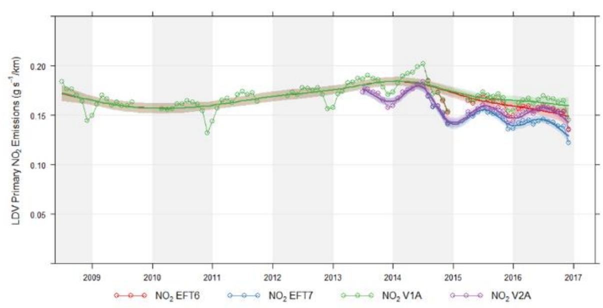


Figure 10: Trend in Estimated M60 HDV NOx Emissions

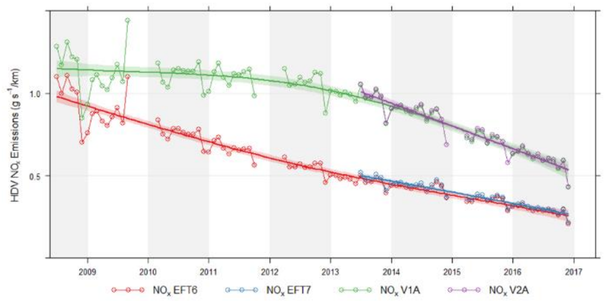
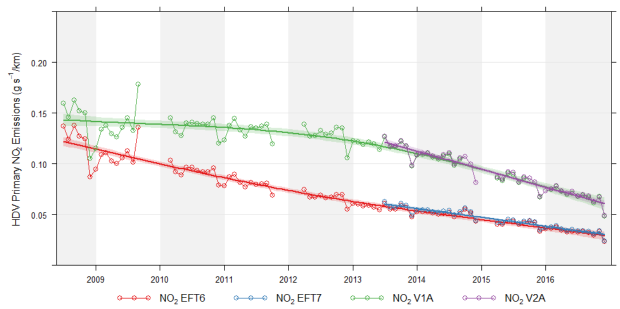


Figure 12: Trend in Estimated M60 HDV Primary NO_2 Emissions

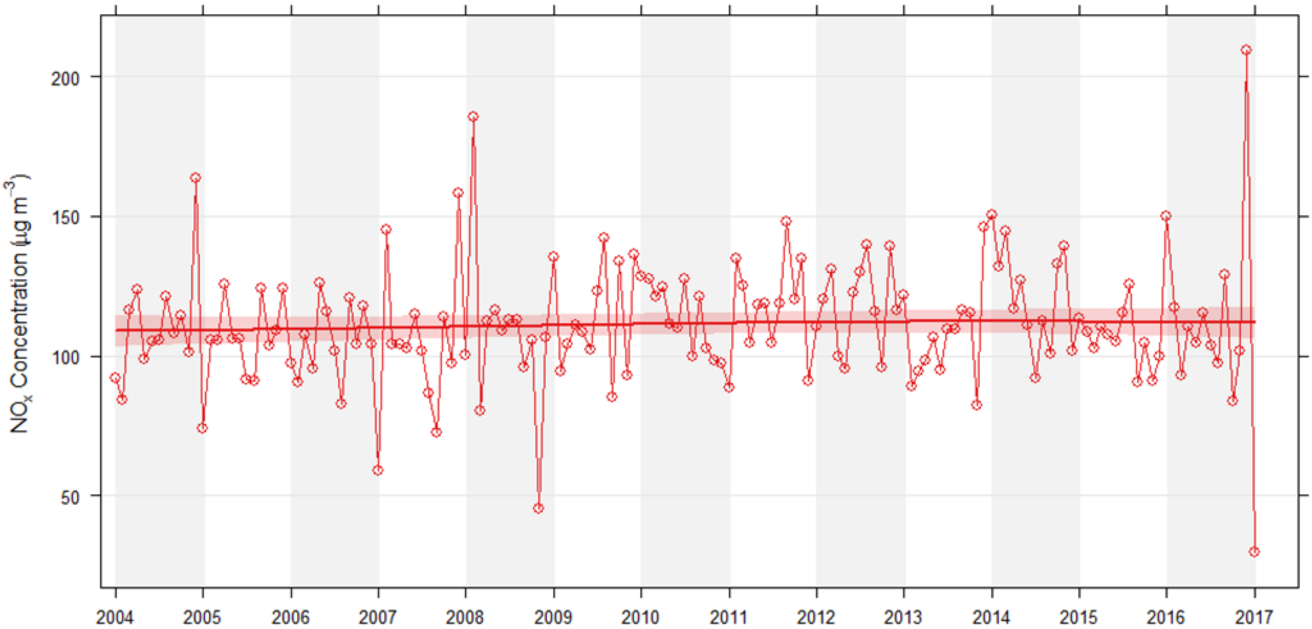


The Salford M60 CMS is relatively unique in respect of its location adjacent to a major motorway and the influence that the emissions from motorway traffic have on the observed concentrations. No other site on the national network is able to provide the same insights into motorway traffic emissions over a prolonged period of time. The only site that is similar is the one near the M4 in Hillingdon, although this site is more complex in terms of other influences (e.g. Heathrow Airport).

To examine whether the trends observed at the Salford site have been replicated elsewhere, and are therefore a function of NOx emission reductions in vehicle emissions in the national fleet, measurements made over the same time period at the M4 Hillingdon CMS site were analysed. The observed trends at the M4 Hillingdon CMS are notably different to those at the Salford M60 CMS. No significant change in NOx concentrations is observed between 2004 and 2016 (see Figure 13) while NO_2 concentrations increased between 2004 and 2012 (see Figure 14), then slightly decreased from 2013. Whilst initially these trends seem contrary to what would be expected, based on the measurements and analysis for the Salford M60 CMS, these differences in observed trends may be explained by the fact that (a) there was a significant increase in traffic volume on the M4 between 2007 and 2014, which is likely to have limited the effect of any reduction in emissions per vehicle and (b) the proportion of HDVs on the M4 (4.0%) is less than half that of the M60 (10.7%), thereby diminishing the effect of the assumed reduction in NOx and primary NO_2 emissions from HDVs (and amplifying the effect of increasing primary NO_2 from LDVs).

Furthermore, 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%). UK fleet composition projections[6] suggest that articulated HGVs are likely to be replaced with new vehicles meeting the Euro VI emission standard much more rapidly than rigid HGVs, and it is thought likely that larger, articulated HGVs have higher annual mileage[7] and are owned by larger haulage companies, and therefore may be replaced more quickly.

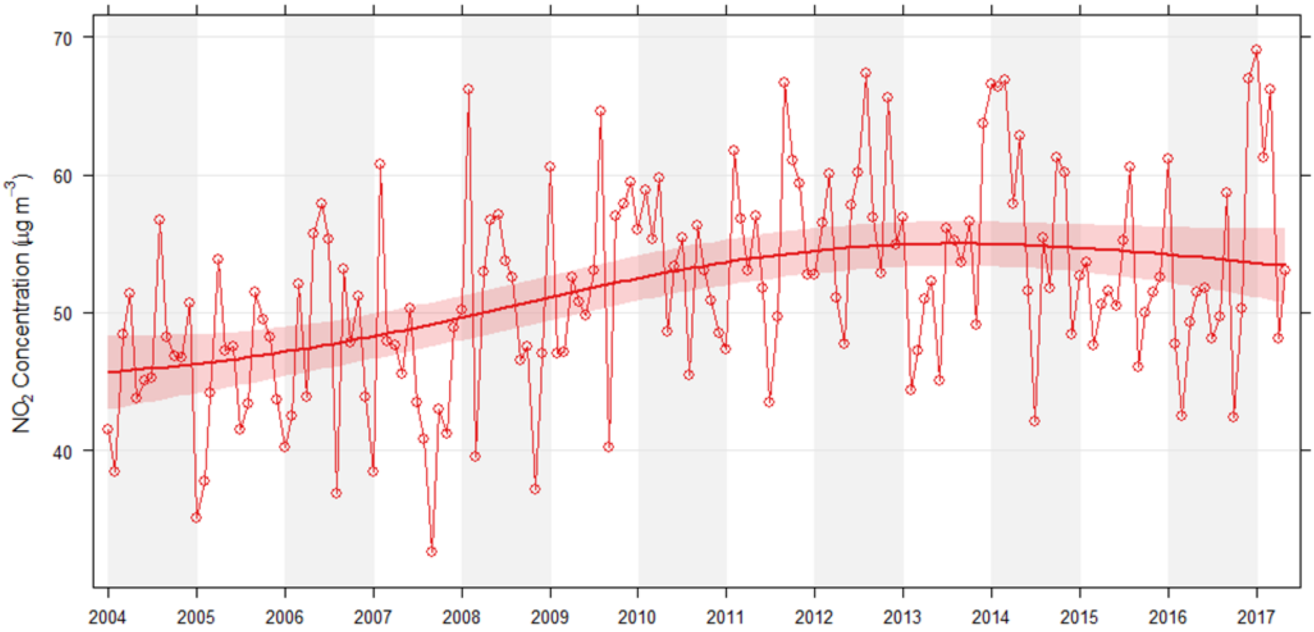
Figure 13: Trend in NOx Concentrations at the M4 Hillingdon CMS (2004 to 2017)



[6] NAEI (2014), rtp_fleet_projection_Base2013_v3.0_final. Available at: http://naei.beis.gov.uk/data/ef-transport

[7] http://www.fta.co.uk/policy_and_compliance/fuel_prices_and_economy/fuel_prices/fuel_fractions.html

Figure 14: Trend in NO_2 Concentrations at the M4 Hillingdon CMS (2004 to 2017)



5. Conclusions

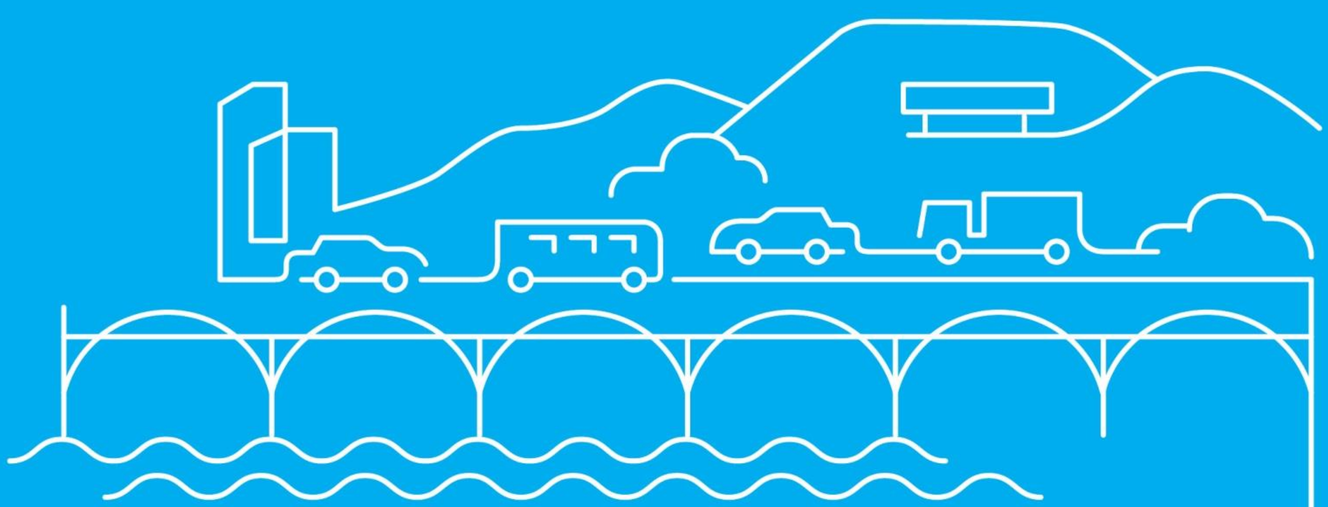
This study has shown that motorway traffic emissions contribute strongly to observed NO_2 concentrations alongside the M60, therefore reducing emissions from the M60 is likely to be the most effective way of reducing annual mean NO_2 concentrations at these locations.

The magnitude of the contribution from the M60 appears to be greater between J12 and J15 of the M60 than between J10 and J12. This difference is thought to be associated with a greater number of vehicles (and HGVs in particular) associated with the M62, which joins the M60 at J12. Measures aimed at reducing emissions from such vehicles would therefore have the potential to reduce the elevated annual mean NO_2 concentrations which occur between J12 and J15.

Statistical analysis indicates that LDV flow on the M60 has approximately twice as much influence on NO_2 concentrations as HDV flow, whilst the opposite is true for NOx. This suggests a greater proportion of NOx emissions from LDVs are emitted as NO_2 than for HDVs. Reducing NOx emissions from LDVs on the M60 is therefore likely to be the more effective in reducing annual mean NO_2 concentrations adjacent to the M60, than reducing NOx emissions from HDVs.

Annual mean NO_2 concentrations have reduced significantly in recent years at the Salford M60 CMS (a 26% reduction), primarily as a result of a reduction in the contribution from vehicles using the M60. Analyses indicate that there has been a significant (33%) decrease in the contribution per vehicle to NO_2 concentrations over the same period, that this reduction is more likely to have been driven by reductions in emissions from HDVs than from LDVs and that, before this, the effect of any reduction in NOx emissions from HDVs was offset by increased primary NO_2 emissions from LDVs. This suggests that schemes aimed at stimulating HDV fleet renewal should be encouraged, whilst noting that much of the benefit of a switch to Euro VI engines may have already been or will soon be realised.

A 50 mph speed restriction was introduced on the M60 in September 2014. Estimates of the contribution of vehicles on the M60 to measured NO_2 concentrations immediately before and after the implementation of the speed restriction suggest that this did not result in a reduced contribution from the M60 and that it may have slightly (4%) increased. Speed control, of itself, therefore appears unlikely to have a significant effect on roadside NO_2 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.



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