Introduction

This report discusses interactions of traffic flow and congestion, prevailing wind direction/speed and roadside concentration of Nitrogen dioxide (NO_2) on a busy junction in Headingley in Leeds for the year 2008. Pollutant NO_2 is chosen as it has significant health impacts (COMEAP, 2015). Ratified data used for the report was provided by University of Leeds and Leeds City Council (LCC) for the study junction sites and DEFRA, (2019a) for Headingley kerbside AURN (Automatic Urban and Rural Network).

Kerbside sites/ Study Junction

Fig-1 and fig-2 shows the study junction between roads A660 and B6157 located 3.5 km distance from city center. There are four environment monitoring stations (ENV1-4) as shown in fig-1 representing pollutants measured at 15-minute average concentration. Within 100m radius of the junction there are four bus stops (two towards north on A660 and two towards west on B6157 with junction as reference). The traffic count for vehicles on A660 lane-1, lane-2 and lane-3 are 3319507, 3074841 and 4580666 respectively for the entire year recorded at 15-minute interval.

The topography around the junction includes three street canyons (SC) in total. SC-1 with ENV-1 and ENV-2 north of junction has unbroken buildings towards east side of A660 and west side of A660 are buildings with different roof shapes and broken spaces in between (Tate et al., 2009). SC-2 ($H/w \approx 1.3$) with ENV-3 along B6157 has unbroken buildings on one side and closely packed buildings on other side with different roof shapes (Tate et al., 2009). SC-3 ($H/w \approx 0.8$) south of junction has uneven buildings with different roof shapes on the west side of A660 while east side of A660 is continuous with different unbroken buildings (Tate et al., 2009). The monitoring stations around the junction are subjected to traffic flows, congestion and idling or start/stop features of vehicles passing by. Above mentioned information makes the chosen sites for ENV1-3 are desirable to study interaction between traffic flow and atmospheric parameters like wind speed/direction in street canyons.

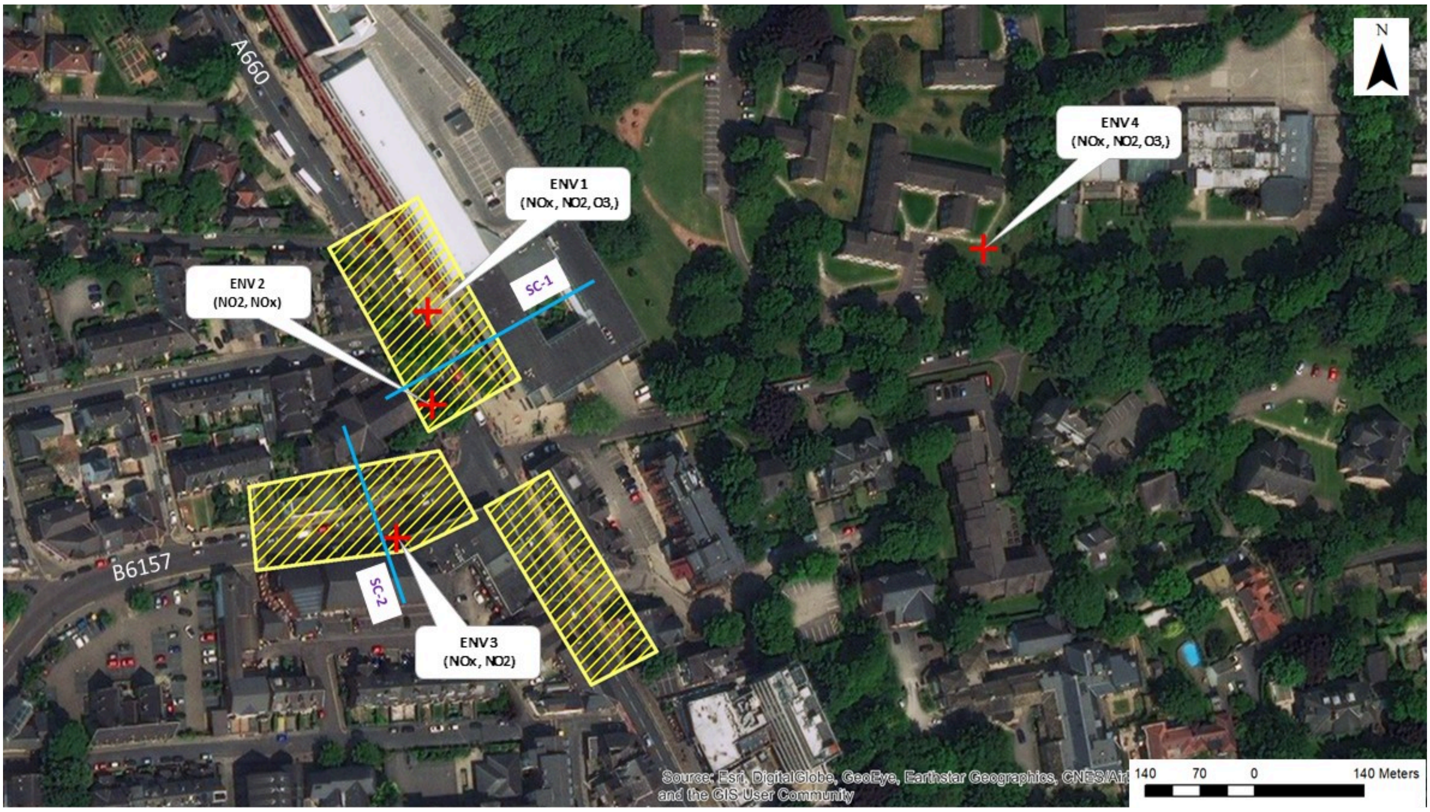

Fig-1 Site schematic of study junction (hashed area represents part of the street canyons, plus sign represents site location and cyan line indicate cross section used for study) (Tate et al., 2009)

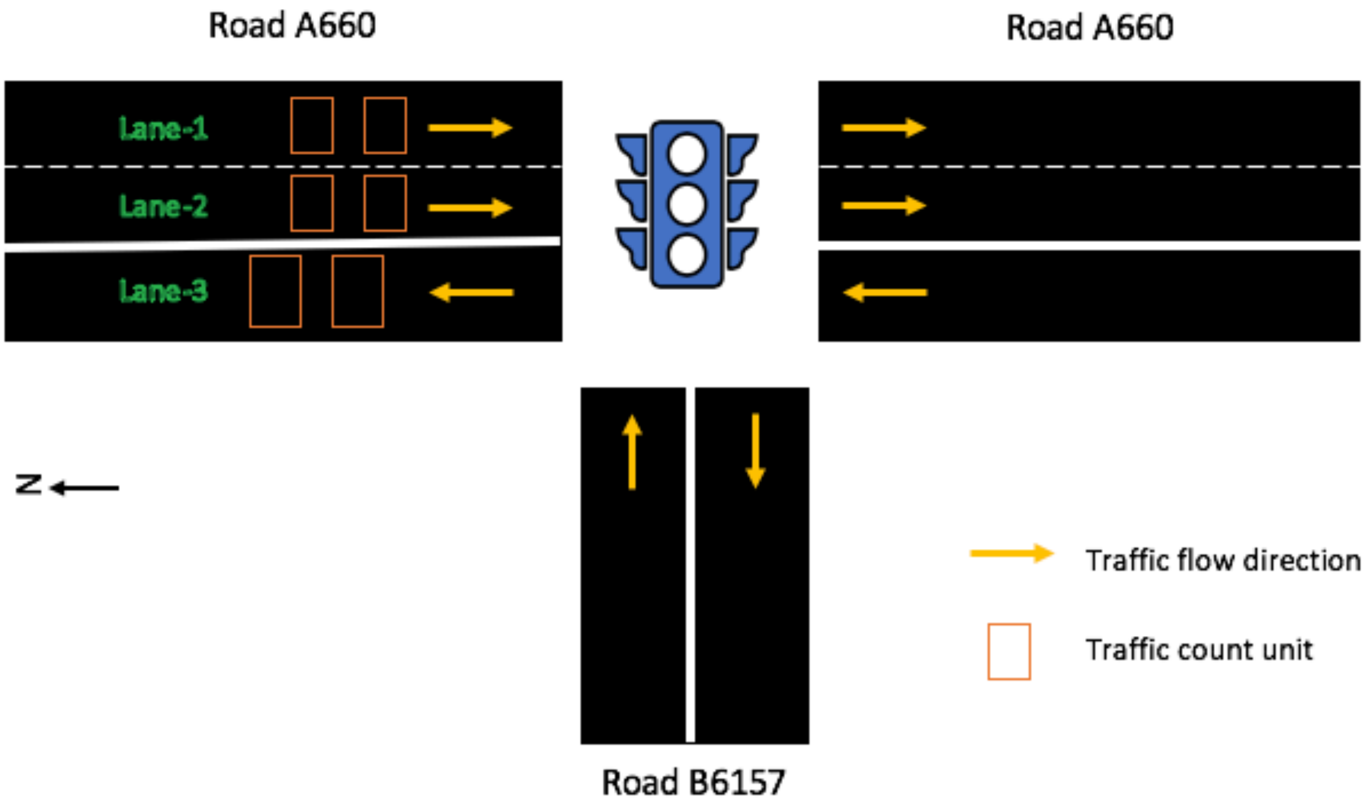

Fig-2 Traffic flow schematic at study junction (Tate et al., 2009)

Windrose plot in fig-3 represents wind speed and direction frequencies split into scale shown and prevailing wind direction for the site is from the west. Wind dispersion along the section SC-1 in fig-2 is shown in fig-4. Fresh winds from west hits building-K and ENV-1 coming down picking up pollution from vehicle emissions and recirculating it again in downward direction resulting in primary vortex; this results in polluted air being pushed towards leeward side (Yazid et al., 2014). Similar is the dispersion of wind at site ENV-2 as shown fig-4, however fig-2 indicates presence of trees at site ENV-2 which can influence the reading due to absorption or resuspension of pollutants (DEFRA, 2010) and location closer to junction under influence of corner eddies (Wood et al., 2009).

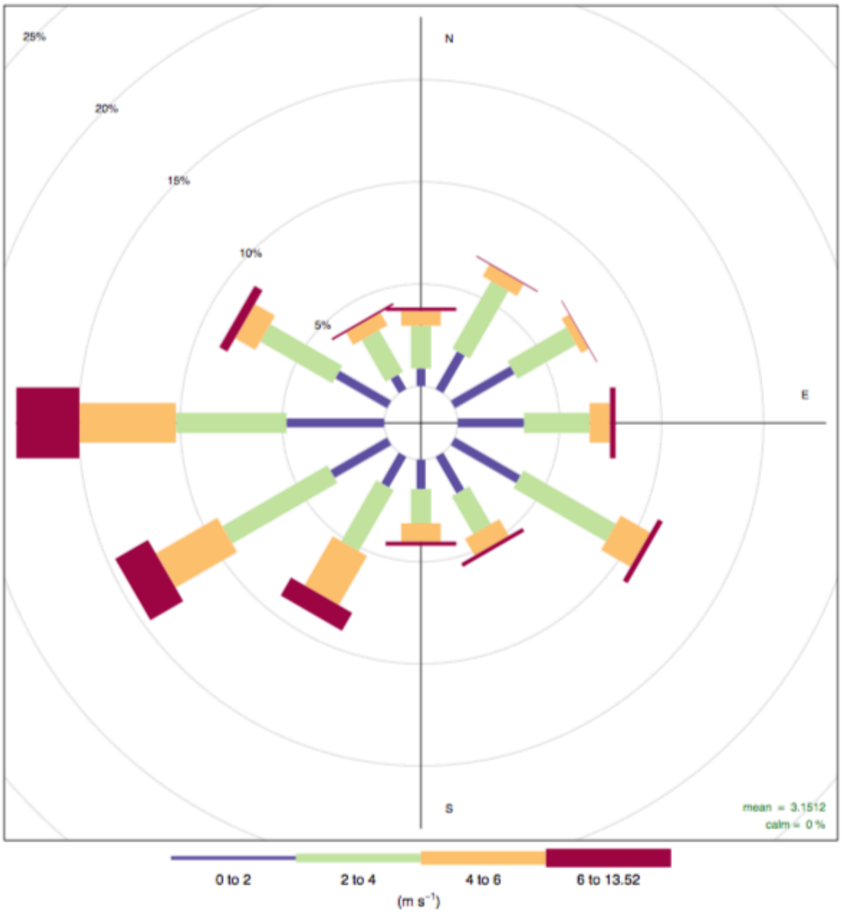

Fig-3 Wind flow at the study junction

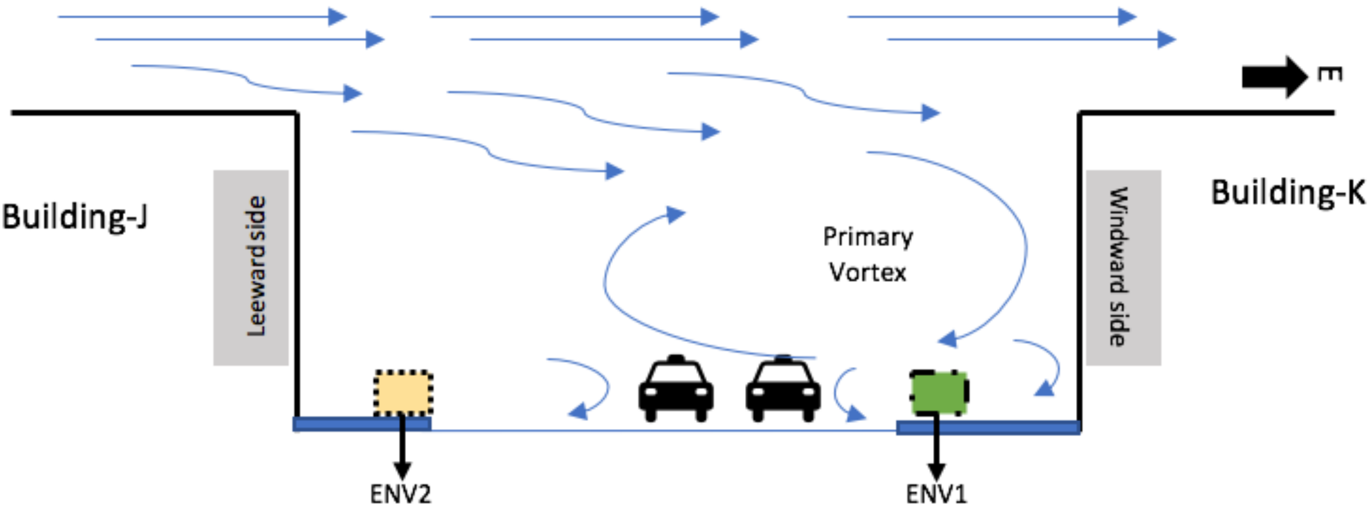

Fig-4 Wind dispersion at SC-1 (dotted and chain line represent front and rear side of the section)

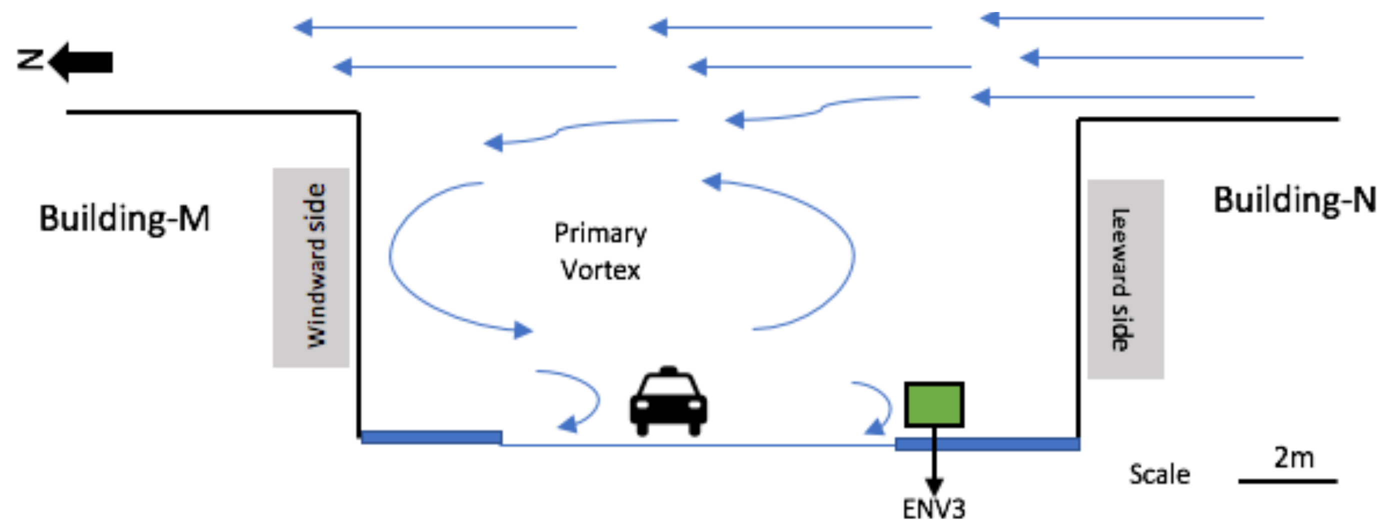

Fig-5 Wind dispersion at SC-2

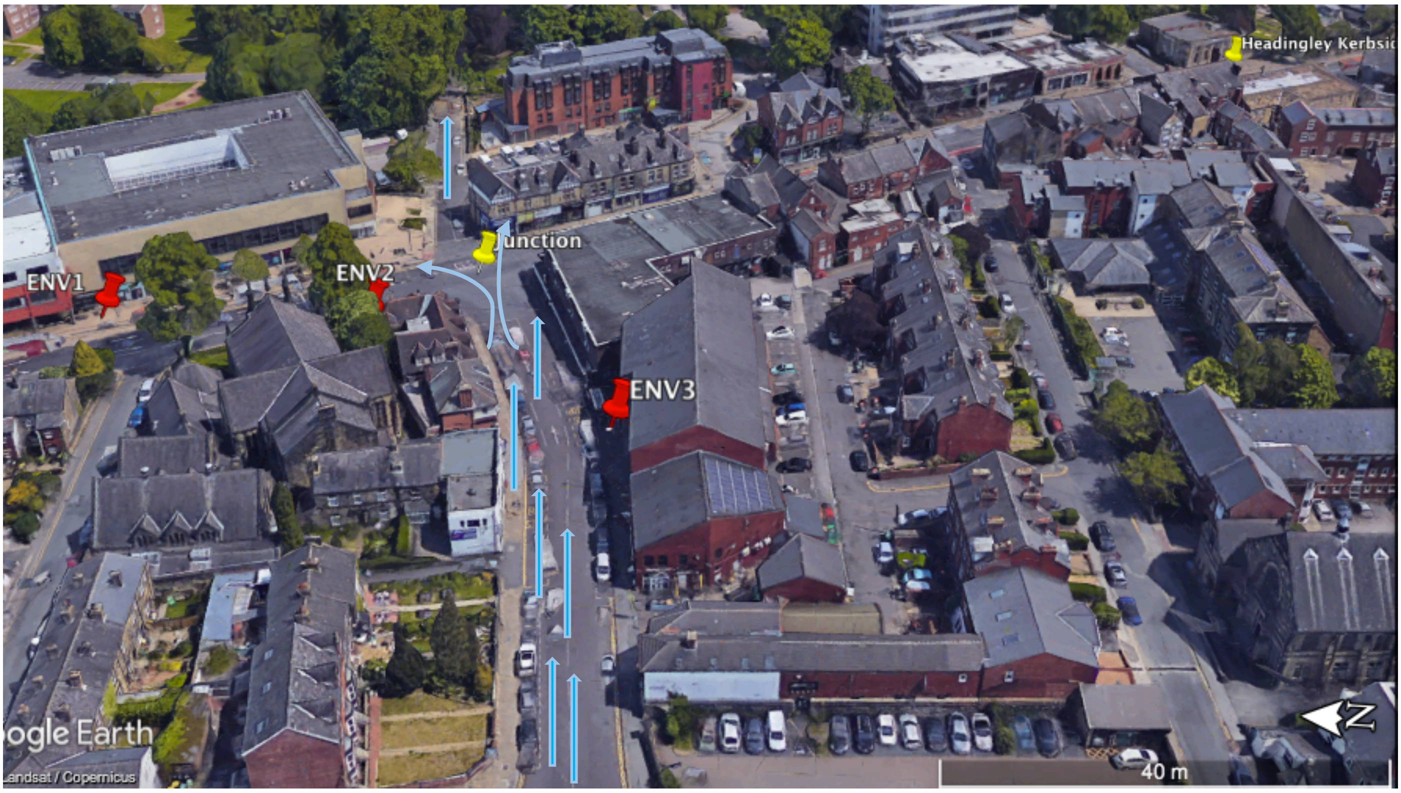

Fig-6 Pollution channeling when wind flow through street canyon (GoogleEarth, 2018)

Fig-6 shows westerly wind flows indicated by blue arrows through SC-2 on road B6157. Prevailing westerly winds can carry the pollutants along with turbulence induced by moving vehicles and channeling them towards the junction and ENV-3 (Solazzo et al., 2008)

<u>Background Site</u>

ENV-4 is located in residential area as shown in fig-1 within 50m radius. There are no busy streets or high-rise buildings which can influence recordings due to street canyon or traffic induced turbulence. Also, it is assumed there are no other local source of pollution and fuel used for commercial and domestic purpose is controlled, making it desirable to record background pollution. Presence of trees around the site which can influence the readings as they can absorb pollutants or resuspend them from rain/falling of leaf (DEFRA, 2010).

AURN Site

Fig-7 Headingley kerbside site AURN location (GoogleEarth, 2018)

Grid reference for AURN site is latitude 53°81'99.72"N longitude 1°57'63.61"W, pollutants measured are Nitric oxide (NO), NO_2, Nitrogen oxides as nitrogen dioxide (NO_X) and Particulate Matter (PM_{10} and $PM_{2.5}$) starting from 17th Feb'08 (DEFRA, 2019b). It is located at a distance of 172m from the study junction towards south on A660.

Materials

Background windspeed and direction are measured at 35m height meteorological mast 4 km south (postcode: LS10 1BD) of the study junction. Traffic flow is measured with inductive loops (2 per lane) measuring deviation in loop magnetic field in presence of vehicle from its calibrated reference field (GoldenRiver M661) (Tate et al., 2009;FHA, 2016).

NO_X and NO_2 is computed by Chemiluminescent analysers. Ozonator is used to supply ozone to NO resulting in formation of excited NO_2 and oxygen. Excited NO_2 molecule than emits light which is proportional to NO concentration. Subtracted value of which from the inlet mixture (NO and NO_X) indicates NO_X (DEFRA, 2017). This method can sometimes compute zero or negative values which is not the case but a limitation. Ozone is measured with UV analysers as per APIM400E standard (Tate et al., 2009).

All the plots are produced using the openair (Carlsaw, 2018) package in open source software 'R' (R Team, 2008).

Data Overview

Year:2008	NO2				
	ENV-1	ENV-2	ENV-3	ENV-4	AURN
Min (ppb)	0.9	0	2.5	0.2	0
Max (ppb)	213	123.1	150.5	86.9	140
Mean (ppb)	30.8	30.9	25.43	11.7	25.1
StdDev (ppb)	20.4	18.4	16	9.4	14.5
Variance (ppb)	212.1	123.1	148	86.7	140
Data collection rate (%)	94.88	83.53	90.54	88.99	92.84

Table-1 Brief statistical overview of all sites

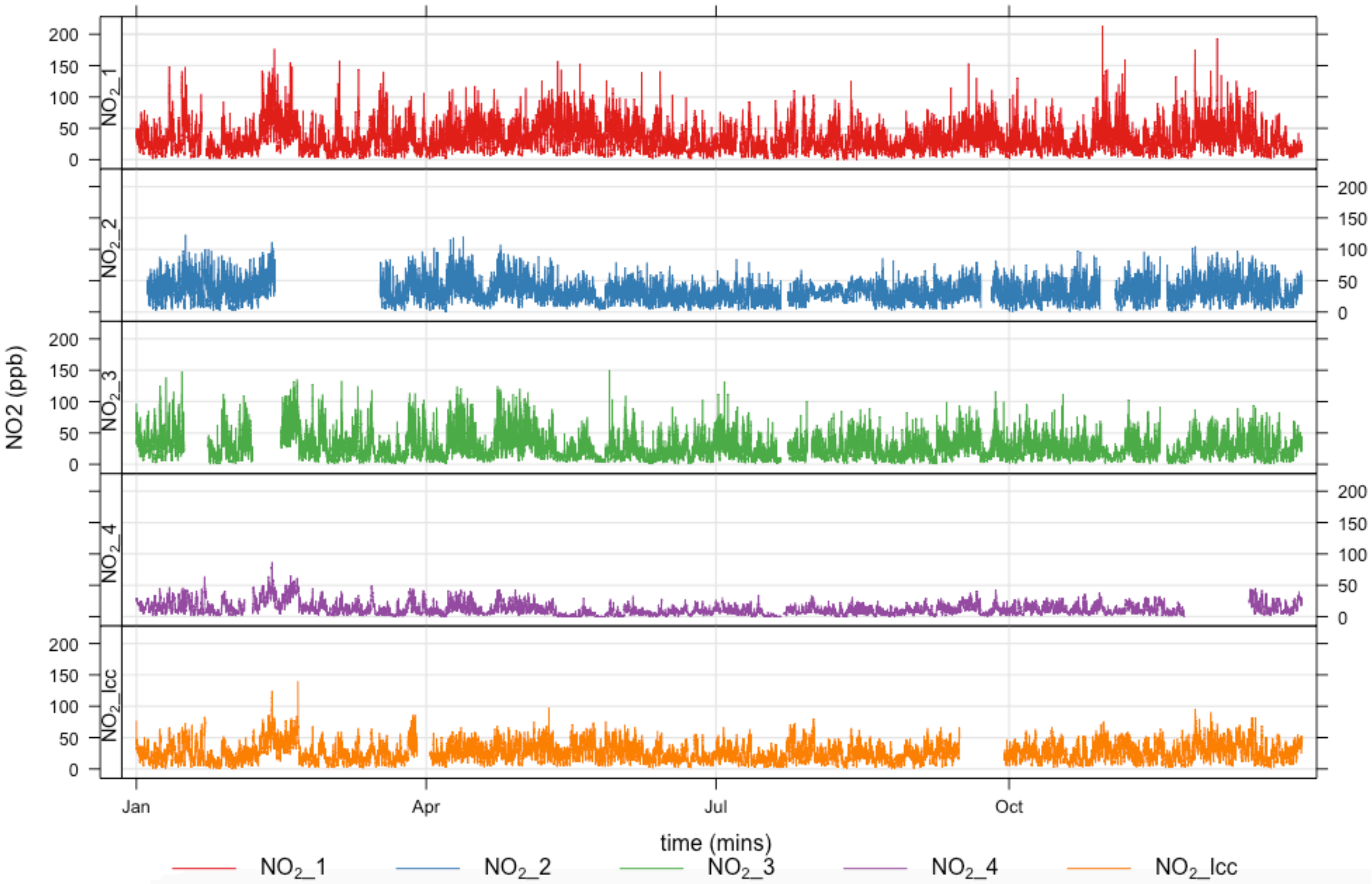

Fig-8 Time series for NO_2 (ppb) concentration at sites ENV-1, ENV-2, ENV-3, ENV-4 and AURN represented by NO_2_1, NO_2_2, NO_2_3, NO_2_4 and NO_2_lcc

From Table-1, ENV-1 accounts for highest levels of pollution and variance but mean for ENV-2 is also very similar making it equally bad site with maximum recording of 123.14 ppb and lower data collection rate. ENV-3 and AURN are marginally better with reduced mean in comparison to ENV-1 and ENV-2.

Data collection rate for site ENV-2 and ENV-4 is lower compared to 90% standard (Clark et al., 2012) however it can be deemed sufficient enough for this report. Instances of recording value of 0 ppb by ENV-2 and AURN can be attributed as an error from calibration or a result from method used to calculate as discussed above.

Data loss in period of April and September for AURN site can be attributed to 6 monthly Quality Assurance/Quality Control (QA/QC) checks undertaken to account for drift over time, replacement of consumables and checks of zero air generator/calibration gases. Also, the requirement for fortnightly manual calibration can account for short interval data loss on ENV-1 and ENV-2 in July and August (Clark et al., 2012). Other sites are also subject to similar DEFRA QA/QC checks and similar reasons can be attributed for data loss. (Tate et al., 2009).

Data Analysis

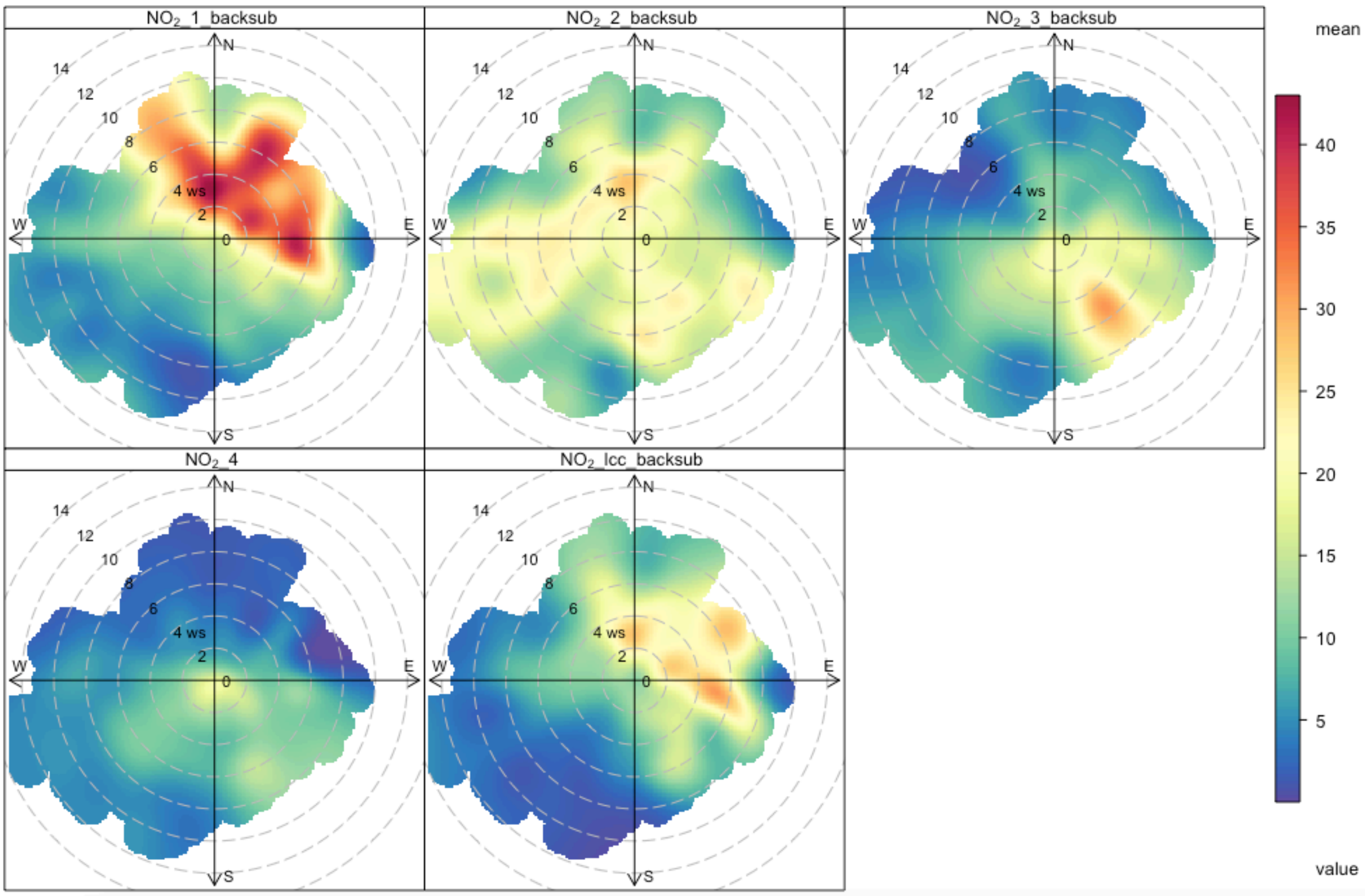

Fig-9 Bivariate polar plot for NO_2 (ppb) concentration for ENV-1, ENV-2, ENV-3, ENV-4 and AURN represented by NO_2_1_backsub, NO_2_2_backsub, NO_2_3_backsub, NO_2_4 and NO_2_lcc_backsub. (background subtracted for all sites except ENV-4)

Fig-9 Polar plots represents concentration of pollutant varying by wind speed and wind direction. For site ENV-1 Northern and north eastern winds contribute to higher concentration at the site. The northern winds can channel the pollutants from vehicle emissions through SC-1 towards ENV-1. Easterly winds will result in primary vortex formation on leeward side of ENV-1 forcing pollutants towards ENV-1 increasing concentration by similar mechanism as shown in fig-4 for westwardly winds.

For site ENV-2, as explained for ENV-1 the channeling effect can be responsible for increased concentration at site resulting from northern and southern winds channeling through SC-1 and SC-3 respectively with mechanism represented in fig-6. While, westwardly winds would result in building up of higher concentration due to location on leeward side as shown in fig-4. However, it is less in comparison to ENV-1 and could be due to formation of corner eddies and dispersion to street B6157 and wind turbulence created by vehicle flow as there is at least traffic moving in one direction in contrast to ENV-1.

For site ENV-3, the southern winds result into results into increase in concentration due to ENV-3 located on leeward side as explained in fig-5 and bus stop in vicinity can further trap pollutants on leeward side. The south eastern winds can carry pollution from traffic south of junction on A660 and partially dispersing into B6157 resulting into higher concentration in contrast to south western. Also, contribution from eastern winds can channel the pollutants from vehicle emissions moving across the junction towards ENV-3.

For AURN site, the polar plot is very similar to ENV-1 except the concentrations are lower which could be no junction being located in nearby vicinity resulting in different traffic flow patterns.

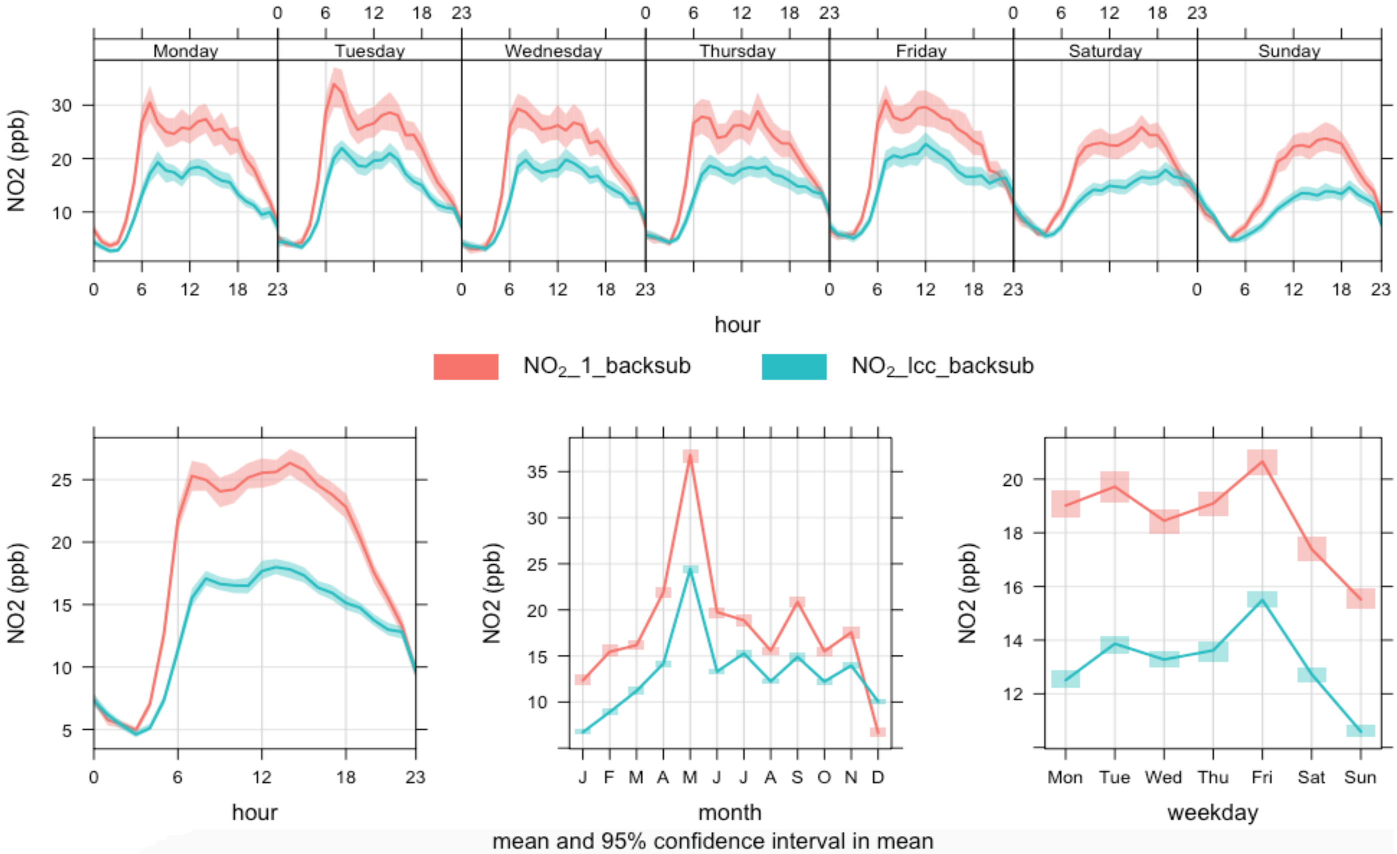

Fig-10 Time Variation plot for NO_2 (ppb) concentration at ENV-1 and AURN represented as NO_2_1_backsub and NO_2_lcc_backsub respectively for year 2008 with background concentration subtracted.

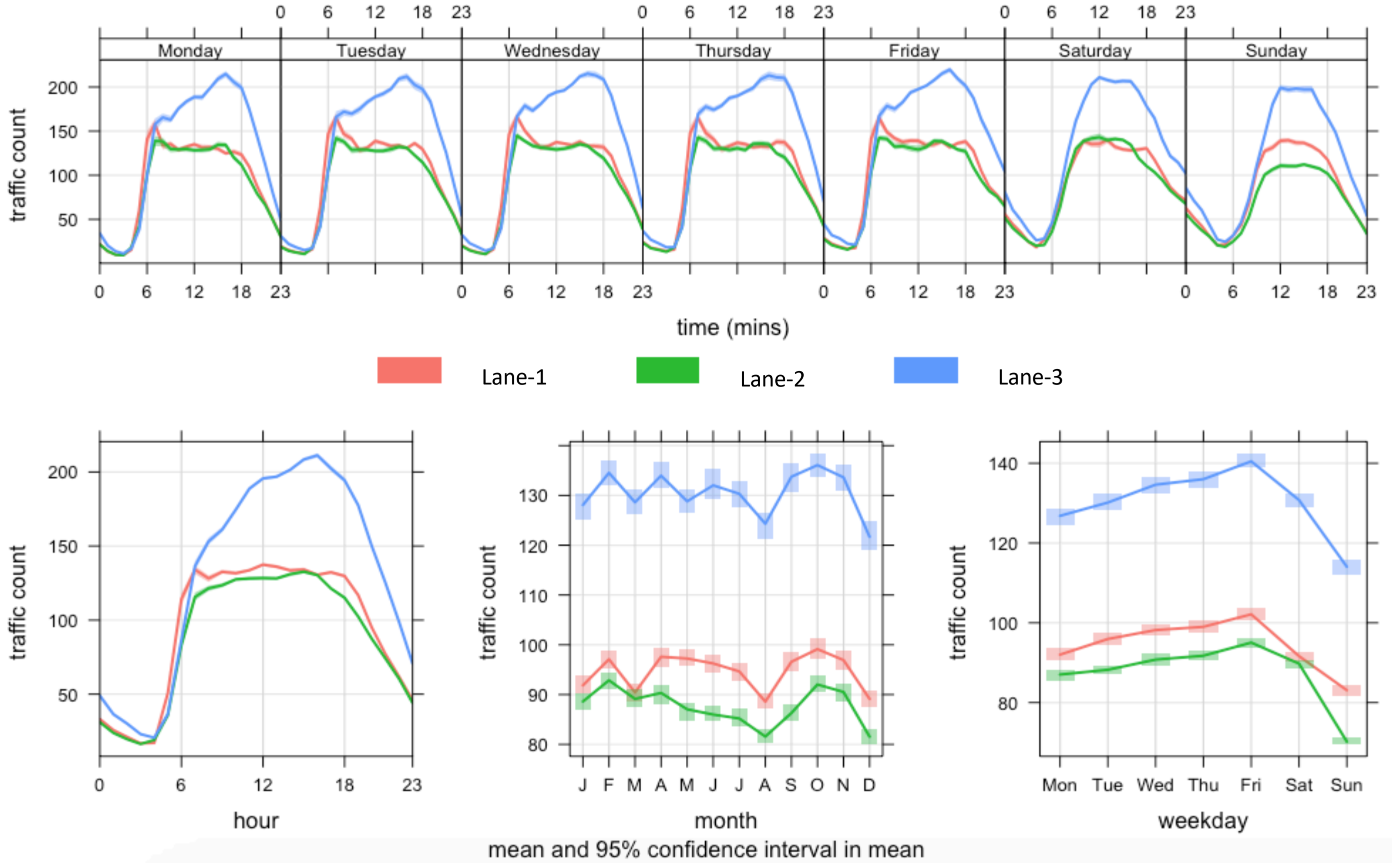

Fig-11 Time Variation plot for traffic flow on A660 road for lane-1, lane-3 and lane-3

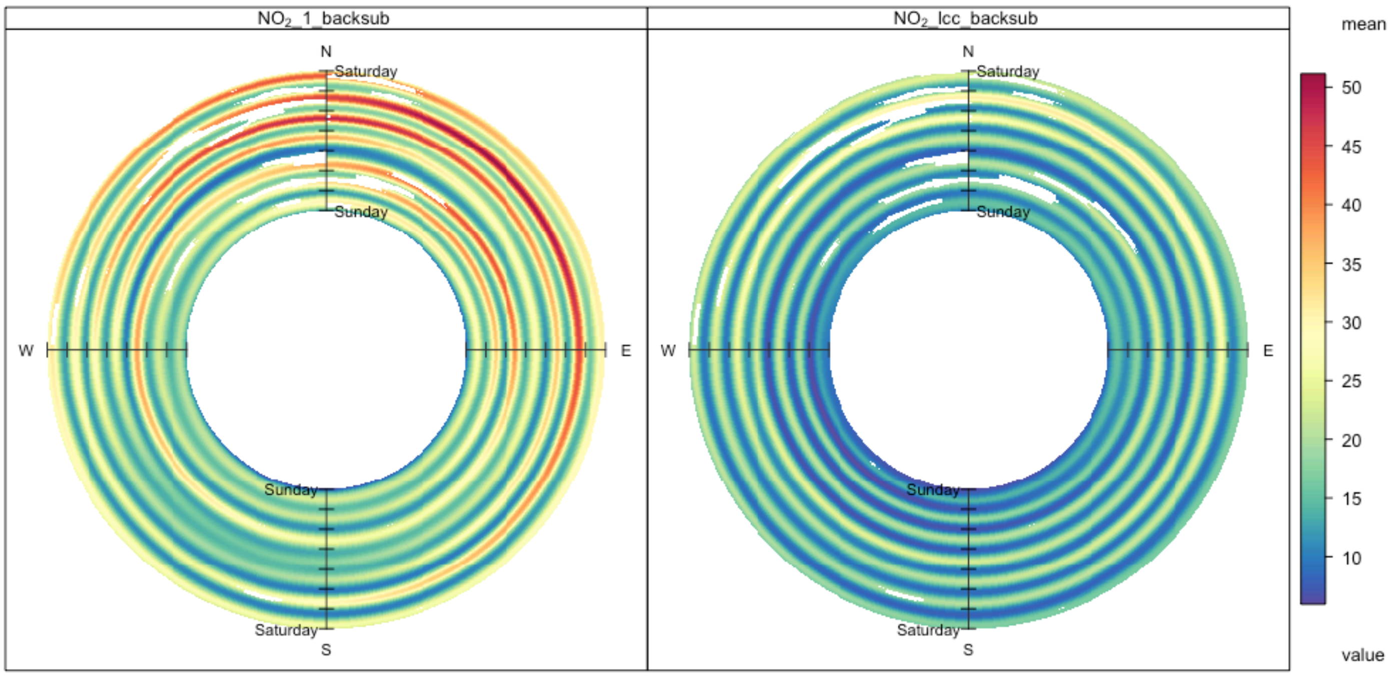

Fig-12 Polar Annulus plot for NO_2 (ppb) concentration at wind speed less than 1.5 m/s with weekday temporal variation represented by NO_2_1_backsub and NO_2_lcc_backsub for site ENV-1 and AURN respectively (background concentration subtracted)

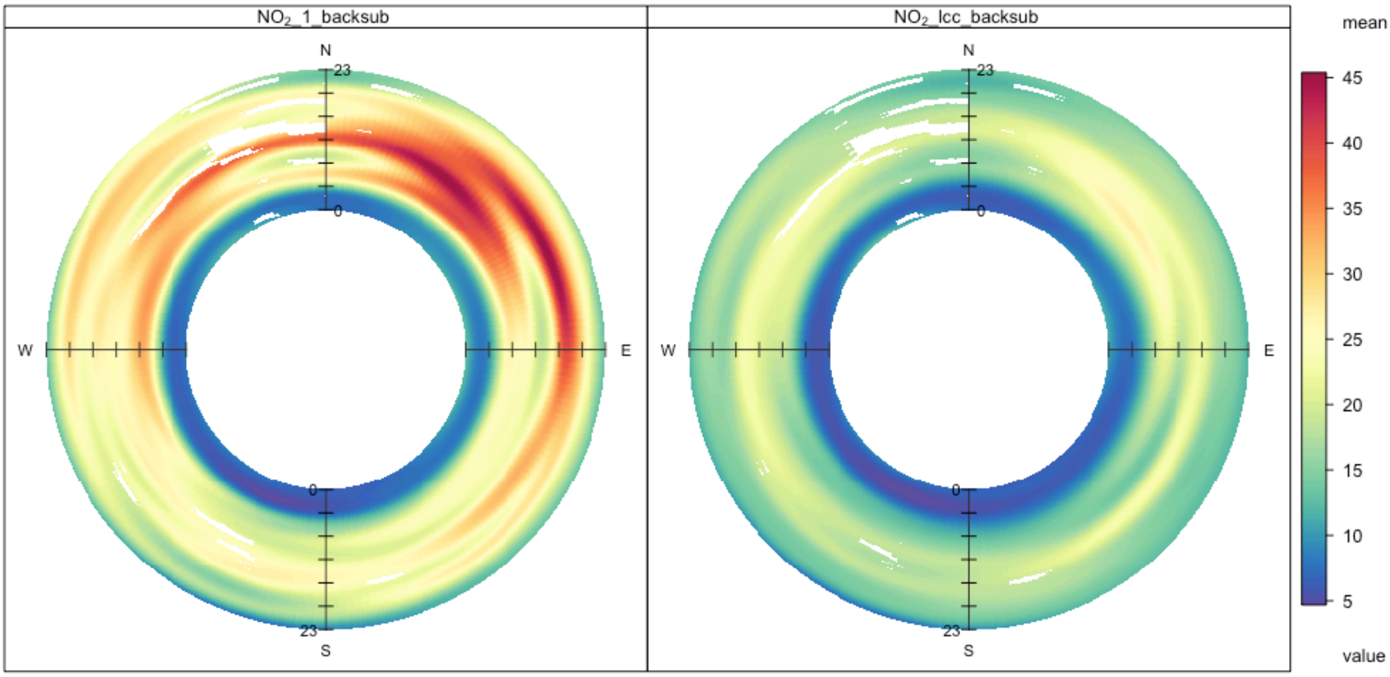

Fig-13 Polar Annulus plot for NO_2 (ppb) concentration and wind speed less than 1.5 m/s with hourly temporal variation represented by NO_2_1_backsub and NO_2_lcc_backsub for site ENV-1 and AURN respectively.(Background concentration subtracted)

Fig-10 and fig-11 represents plot of day of the week variation, mean hour of day variation and a combined hour of day for the day of the week and a monthly plot for NO_2 concentration and traffic flow respectively. There is a strong evidence of higher concentration on weekdays compared to weekends at ENV-1 and AURN sites. Also, hourly traffic count in fig-10 closely represents the change in pollutant concentration in fig-11, staying relatively high at and in between AM/PM peak than the rest of the duration.

Fig-12 and Fig-13 represent polar annulus plot for ENV-1 and AURN site which represents change in NO_2 concentration by wind direction and a time period (weekday and hourly) with subset data of wind speed less than 1.5 m/s. Both polar annulus plots confirm similar trend of higher concentration during weekdays and hours of traffic movement. Also, similar concentration profile at lower wind speeds irrespective of wind direction can be a result of diurnal wind flow pattern being more prominent at SC-1 compared to AURN site indicating different thermal effects of airflow in vicinity which could be a result of congestion and slow moving traffic (Liu et al., 2012).

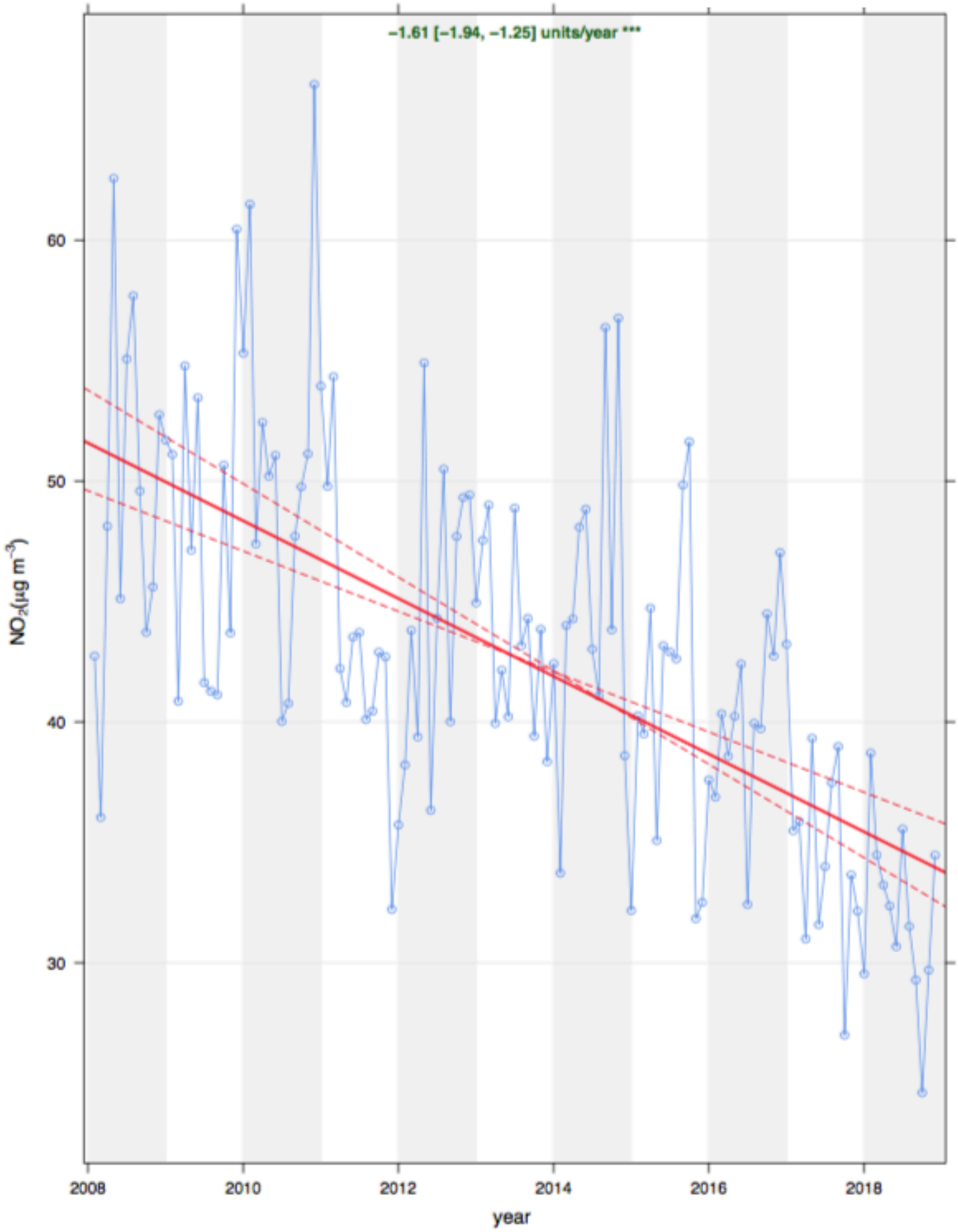

Fig-14 Trend in NO_2 from 2008 to 2018 with deseasonalised monthly mean concentration. *** indicate trend is significant at 0.001 level.

Fig-14 shows NO_2 concentration trend reducing by 1.61 ug/m^3 per year for given period, solid red line is the trend estimate and dashed lines shows 95% confidence intervals. 95% confidence interval in the trend is ranged between -1.94 to -1.25 μg/m^3.

Fig-15 represents the change in vehicle fleet from 2008 to 2018. One contribution to reducing trend of NO_2 could be result of vehicle fleet getting cleaner with stringent emission standard. However, Carslaw and Rhys-Tyler, (2013) have shown from PEMS (Portable Emission Monitoring System) measurements of approximately 70000 vehicles in London that actual emissions can be highly variable and confidence on its contribution should be cautioned.

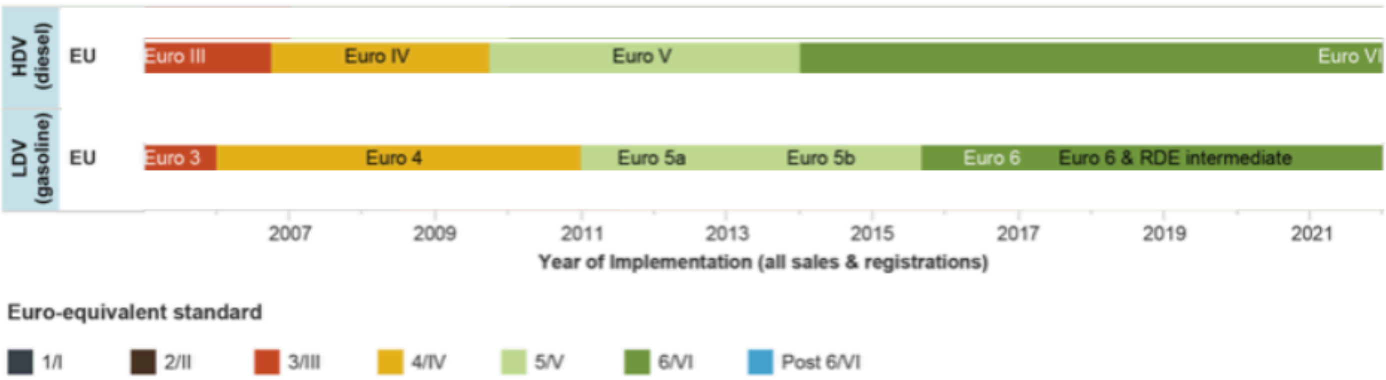

Fig-15 Emission change time line (He, 2016)

Further, along with many national strategies, locally addition of 35 hybrid buses in 2012-14, retrofitting 146 buses from EURO 3&4 to EURO 5, Implementation of three park and ride sites in 2014, 3 fold increase from 2013 to 2015 in hybrid/private hire vehicle fleet and promotion/deployment of cycling infrastructure since 2000 are actions in Leeds which can be attributed to overall reduction (LCC, 2018).

There is a possibility of noise in the data for years 2011 and 2014 where measurements are one-sided. Both can be attributed to number of factors like calibration, but data being ratified for those years it is likely to be due to change in maintenance responsibilities or transfer of ownership within government and different ratification method used. AURN was commissioned on 17th Feb'08 and thus trend is not accounting data for first 47 days of year 2008. Also, 2018 data ratification report is not available requiring last year data to be treated with caution.

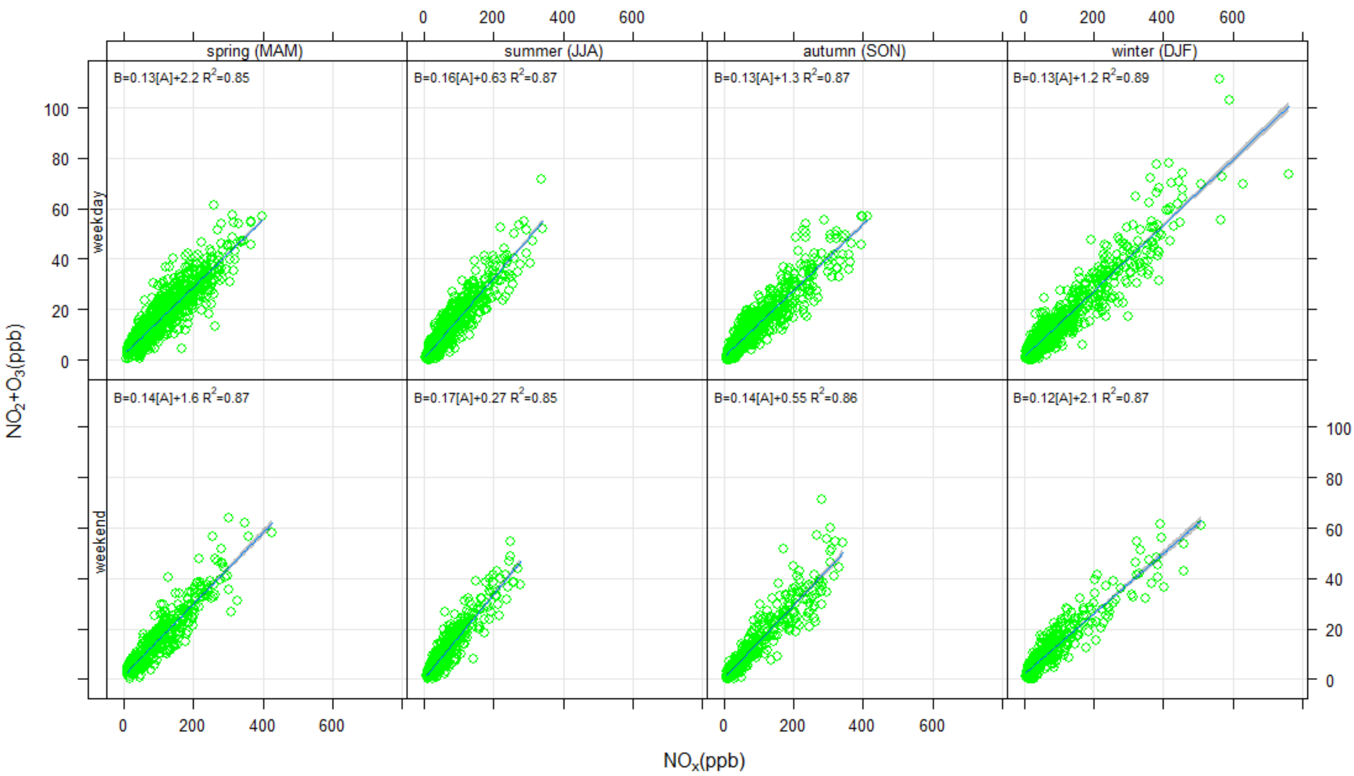

Fig-16 Scatter plot of hourly NO_2+O_3 vs NO_X split by season and weekday-weekend for year 2008 (A and B indicate NO_2+O_3 and NO_X respectively in line equation)

Using the total oxidant approach (Carslaw and Beevers, 2005) which requires measured NO_2, NO_X and O_3 for background and kerbside sites and difference between total oxidant (NO_2 +O_3) and NO_X with slope of this relation indicating primary NO_2 contribution in fig-16. It is evident NO_2 concentration increases with increase in NO_X and NO_X is one of the pollutants from diesel combustion (Reşitoğlu et al., 2015) and ozone being an atmospheric gas can be indicated there is NO_2 contribution from vehicles apart from local NO-O_3 chemistry and background indicated by regression line with similar slope for weekdays and weekends for different seasons.

Conclusion/Future Work

Above sections indicate interaction between street canyons, traffic flows, wind speed and wind direction can influence the concentration at monitoring sites. Location of ENV-1 and AURN in street canyon on windward side recording different concentration values is influenced from type of traffic flows and difference in street canyons. Also, channeling of pollutants in street canyon from vehicle emissions can influence the concentration values as seen in case of ENV-3. Street canyon's roof profile and aspect ratio can influence if pollutants can be ventilated out or trapped by formation of primary vortex influencing concentration at sites (Xie et al., 2005). Further work should include additional pollutants PM_{10}/$PM_{2.5}$ and influence different roof shapes in same street canyons on pollutant concentration near and away junctions which can help influence future policy/standard for street/housing design to avoid trapping of pollutants (Takano and Moonen, 2013). Such efforts can further drive down the long term trend along with implemented actions discussed above and planned actions like Clean Air Zone (Tubby, 2018).

References:

Carlsaw, D. 2018. openair project || open-source tools for the analysis of air pollution data || NERC knowledge exchange project || Home. *The OpenAir Project*. [Online]. [Accessed 20 March 2019]. Available from: http://www.openair-project.org/.

Carslaw, D.C. and Beevers, S.D. 2005. Estimations of road vehicle primary NO2 exhaust emission fractions using monitoring data in London. *Atmospheric Environment*. **39**(1), pp.167–177.

Carslaw, D.C. and Rhys-Tyler, G. 2013. New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK. *Atmospheric Environment*. **81**, pp.339–347.

Clark, T., Eaton, S., Gray, S., Hector, D., Loader, A., Madle, A., Stacey, B., Stratton, S., Telfer, S. and Yardley, R. 2012. LSO_manual_2012_Part_A_Issue_1_final.pdf.

COMEAP 2015. COMEAP_The_evidence_for_the_effects_of_nitrogen_dioxide.pdf.

DEFRA 2017. *Air Pollution in UK 2016* [Online]. London: Department of Environment, Food and Rural Affairs. [Accessed 23 March 2019]. Available from: https://uk-air.defra.gov.uk/assets/documents/annualreport/air_pollution_uk_2016_issue_1.pdf.

DEFRA 2019a. Home- Defra, UK. [Accessed 20 March 2019]. Available from: https://uk-air.defra.gov.uk/data/data_selector.

DEFRA 2019b. Site information- Defra, UK. [Accessed 22 March 2019]. Available from: https://uk-air.defra.gov.uk/networks/site-info?site_id=LED6.

DEFRA 2010. What impact do trees have on air pollutant concentrations? - - Local Air Quality Management Support - Defra, UK. [Accessed 9 December 2018]. Available from: https://laqm.defra.gov.uk/laqm-faqs/faq105.html.

FHA 2006. Chapter 2, Traffic Detector Handbook: Third Edition—Volume I - FHWA-HRT-06-108. [Accessed 24 March 2019]. Available from: https://www.fhwa.dot.gov/publications/research/operations/its/06108/06108.pdf.

GoogleEarth 2018. Overview. [Accessed 16 December 2018]. Available from: https://www.google.com/intl/en_uk/earth/.

He, H. 2016. China's latest step forward on vehicle emissions regulation | International Council on Clean Transportation. [Accessed 22 March 2019]. Available from: https://www.theicct.org/blogs/staff/latest-step-forward-on-china-vehicle-emissions-regulation.

LCC 2018. *15.Air Quality Background Paper 2018.pdf* [Online]. Leeds: Leeds City Council. [Accessed 20 March 2019]. Available from: https://www.leeds.gov.uk/Local%20Plans/Publication%20Draft%20Plan%20Supporting%20Documents/15.Air%20Quality%20Background%20Paper%202018.pdf.

Liu, J., Luo, Z., Zhao, T. and Shui, J. 2012. Ventilation in a Street Canyon under Diurnal Heating Conditions. *International Journal of Ventilation*. **11**(2), pp.141–154.

R Team 2008. R: The R Project for Statistical Computing. [Accessed 20 March 2019]. Available from: https://www.r-project.org/.

Reşitoğlu, İ.A., Altinişik, K. and Keskin, A. 2015. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy*. **17**(1), pp.15–27.

Solazzo, E., Cai, X. and Vardoulakis, S. 2008. Modelling wind flow and vehicle-induced turbulence in urban streets. *Atmospheric Environment*. **42**(20), pp.4918–4931.

Takano, Y. and Moonen, P. 2013. On the influence of roof shape on flow and dispersion in an urban street canyon. *Journal of Wind Engineering and Industrial Aerodynamics*. **123**, pp.107–120.

Tate, J., Ropkins, K., Goodman, P., Oates, C., Chen, H., Bell, M., Tomlin, A., Balogun, A. and Smalley, R. 2009. THE INFLUENCE OF TRAFFIC CONGESTION, SYNOPTIC AND IN-STREET WINDS ON NO2 CONCENTRATIONS AROUND A CONGESTED INTERSECTION: A MEASUREMENT STUDY *In*: UK: Institute for Transport Studies.

Tubby, J. 2018. *2018 Air Quality Annual Status Report (ASR)* [Online]. Leeds: Leeds City Council. [Accessed 22 March 2019]. Available from: https://www.leeds.gov.uk/docs/Air%20Quality%20Annual%20Status%20Report%202018.pdf.

Wood, C.R., Arnold, S.J., Balogun, A.A., Barlow, J.F., Belcher, S.E., Britter, R.E., Cheng, H., Dobre, A., Lingard, J.J.N., Martin, D., Neophytou, M.K., Petersson, F.K., Robins, A.G., Shallcross, D.E., Smalley, R.J., Tate, J.E., Tomlin, A.S. and White, I.R. 2009. Dispersion Experiments in Central London: The 2007 DAPPLE project. *Bulletin of the American Meteorological Society*. **90**(7), pp.955–970.

Xie, X., Huang, Z. and Wang, J. 2005. Impact of building configuration on air quality in street canyon. *Atmospheric Environment*. **39**(25), pp.4519–4530.

Yazid, A.W.M., Sidik, N.A.C., Salim, S.M. and Saqr, K.M. 2014. A review on the flow structure and pollutant dispersion in urban street canyons for urban planning strategies. *SIMULATION*. **90**(8), pp.892–916.