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Quantifying the contribution of periodicity and national holidays to air pollution levels in the United Kingdom using a decomposable time series model

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ABSTRACT

This paper quantifies the impact of periodicity and national holidays on air pollution levels in the United Kingdom using a decomposable time series forecasting model. The analysis focuses on nitrogen dioxide (NO_2) concentrations, with data sourced from the Automatic Urban and Rural Network and Air Quality England networks between January 2017 and December 2023. The Prophet model developed by Meta is used to identify, quantify, and appropriately remove the temporal periodicities in air pollution concentration, demonstrating how annual holidays such as Christmas, and one-off events, such as the state funeral of Elizabeth II and the London Marathon, influence local air pollution in isolation. The findings provide empirical evidence supporting widely held assumptions around national holidays and show some localised reductions in NO_2 concentrations during major events, with contextual variation also observed. For example, the state funeral of Elizabeth II shows a reduction in 21.15 μgm^{-3} compared to a median reduction of −2.43 μgm^{-3} outside of London for urban traffic sites. This paper emphasises the need for localised air pollution mitigation policies and demonstrates the utility of large, complete, and publicly available datasets coupled with modern forecasting tools in environmental research.

1. Introduction

1.1. Motivation

Air pollution is the leading causes of economic disadvantage from environmental factors (Stanaway et al., 2018; Lomborg, 2020). Transport, especially in urban environments, is a major contributor to air pollution concentrations (O'Driscoll et al., 2018; Sayegh et al., 2016; Pastorello and Melios, 2016; Colvile et al., 2001). Oxides of nitrogen (NO_X) formed from the combustion of hydrocarbon fuels (Zeldvich, 1946) and specifically NO_2 which is formed in the catalytic converters of modern diesel cars (Alvarez et al., 2008). NO_2 is generally regarded as a major contributor to a range of different poor health outcomes (COMEAP, 2015; WHO, 2013; Zhang et al., 2011; EEA, 2008; Kampa and Castanas, 2008; Breslow and Goldsmith, 1958). These negative health outcomes include cancer (IARC, 2013), cognitive function and mental health (Power et al., 2011, 2016; Roberts et al., 2019), and respiratory disease (Santus et al., 2012) such as asthma (Zheng et al., 2015; Orellano et al., 2017); pneumonia (Nhung et al., 2017); and chromic pulmonary obstructive disease (COPD) (DeVries et al., 2017). It can increase both cardiovascular and respiratory system problems (Brunekreef and Holgate, 2002). Exposure to air pollution can result in a reduction in lung function amongst children (Gauderman et al., 2004), a reduction in cognitive ability and depression, affecting both children and adults (Fonken et al., 2011; Gatto et al., 2014) and an equivalent life loss equating to ≈5879 deaths at typical ages in London (Walton et al., 2015). Other pollutants such as Ozone (O_3) (Lippmann, 1989; Chen et al., 2007; Nuvolone et al., 2018; Peden, 2024) which is produced as a secondary pollutant as NO_2 reacts with sunlight (Jaroszyńska-Wolińska, 2010), and fine particulate matter ($PM_{2.5}$) (Rovira et al., 2020; Roberts et al., 2019; Feng et al., 2016), which is formed both as part of the combustion process and through secondary processes have been shown to have negative health outcomes on the exposed public. The level of exposure to air pollution and its subsequent negative effects will only be exacerbated by the current global trend of urbanisation (Gu et al., 2021) as the demand for both transport and space will increase.

The concentration of various air pollutants have been shown to be affected by ambient weather conditions (Monks et al., 2009; Stull, 2012; Grange and Carslaw, 2019) suggesting the presence of significant and directionally predictable periodic variability. Ambient temperatures are seasonal, and this component should be expected in air

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pollution data. Seasonal periodic trends in air pollution concentrations have been demonstrated non-quantitatively for PM_{10} and $PM_{2.5}$ in Munir et al. (2017), which shows the apparent periodic variation of fine grade particulate matter ($PM_{2.5}$) over the course of a year but does not propose quantitative component contributions for these periodicities. These trends are also observable in the ratified data from the AURN network of publicly available air pollution monitoring sites in the United Kingdom (DEFRA, 2024), for example, Fig. 3 shows ratified NO_2 data from Bradford Mayo Avenue between January 2017 and December 2023 with maxima and minima (anti-)correlating with the yearly temperature maxima and minima being visible without any data processing applied.

The volume of traffic at a given location is also known to be the major contributing factor in urban air pollution concentration levels nearby (Kendrick et al., 2015; Sayegh et al., 2016). Traffic flow often has a daily and weekly periodic component, particularly in an urban context. These are caused by predictable changes in traffic demand such as morning and afternoon weekday peaks caused by commutes, off-peak during the night, and inter-peak during the day, as well as reduced demand at some sites during the weekend (de Dios Ortúzar and Willumsen, 2024).

Rapid changes in transport network demand have been shown to statistically significantly reduce the concentration of NO_2 in urban environments, as evidenced by the reduction in air pollution concentrations observed during the COVID pandemic lockdown (Lee et al., 2020; Ropkins and Tate, 2021). Unexpected or non-periodic changes in demand for the road infrastructure may result in congestion, which produces more air pollution per vehicle than non-congested traffic (WHO, 2006), or more free-flow traffic which may reduce air pollution due to fewer vehicle kilometres being travelled. Testing the impact of traffic flow changes on air pollution requires known events of a great enough magnitude to separate them from the natural variance of the system. Known and documented changes in demand for transport network caused by known one-off events can be used as test cases to understand and quantify the impact on air pollution concentration levels of planned short-term modifications and unpredicted shocks to the transport network.

Leisure travel has been shown to be a significant factor in CO_2 emissions in the European Union (EU) (Laroche et al., 2023). The entitlement of time off work over public holidays may also drive changes in travel behaviour over these periods (Gössling and Peeters, 2015). Travel and leisure behaviour preferences are often shared amongst similar socio-economic groups (LaMondia et al., 2010). Friends and family have been shown to be a major contributing factor to travel decision making as well (Griffin et al., 2024; Gitelson and Kerstetter, 1995). Anecdotally, UK residents are aware that the behaviour of people changes around national holidays. Many people travel to see family and many other people stay at home when they may have otherwise travelled. These behavioural changes do not just occur on day of the holiday either, with people often travelling up to a few days before Christmas (Ecke et al., 2024) for a range of reasons, leading to unusual demand on the transport network. A holiday event can be considered similar to a broad-scale experiment in telecommuting and therefore these events offer an opportunity to test the impact of behaviour change over a short time-period on air pollution concentrations.

1.2. Aims and objectives

This paper aims to demonstrate application of big-data methods and modern forecasting tools to unpick the complex temporal variations observed in ambient NO_2 concentration, and to empirically quantify the impact of one-off events on NO_2 concentrations in the Great Britain and Northern Ireland (the UK). This paper will assess and quantify the various periodic temporal components of NO_2 concentration time series data using the Prophet forecasting model developed by Meta (Taylor and Letham, 2018). The paper will assess and evaluate the impact of air pollution on known and repeated holidays such as Christmas Day, New Year's Day and national holidays, as well as events that may cause unusual variation to transport demands. These events include the predictable yearly travel days leading to Christmas, one-off nation-wide events such as the Coronation of King Charles III and the state funeral of Elizabeth II, and a known and large localised event, the London Marathon. The paper will extract a contribution value for the NO_2 contribution for each day of interest, isolated from the general trends and daily, weekly and hourly variations. The paper will also investigate the differences and similarities between the greater London area and the rest of the United Kingdom to determine whether different regions and transport provisions within them may impact the overall change in concentration levels.

Initially the paper will identify and quantify yearly, weekly and daily components of air pollution concentrations using Prophet's decomposable time-series methods. Longer-term trends will be identified using Prophet's breakpoint methods. The paper will then isolate these periodic components and longer-term trends, and use the residual values to more accurately assess the contribution to air pollution concentrations of various national holidays and other days of atypical transport demand requirements in Great Britain and Northern Ireland.

2. Materials and methodology

2.1. Air pollution data

Air pollution data was sourced from the Automatic Urban and Rural Network (AURN) sensors located around the United Kingdom and from the Air Quality England network. These sites measure hourly concentration of a range of different pollutants depending on the site. This paper focuses on the concentration of NO_2 because it is the most widely reported air pollutant in the AURN network and is of greatest interest to policy developers as they have strict limit values that they are legally obliged to meet.

2.1.1. Air pollution data sources

The AURN network is managed by the United Kingdom (UK) Department for Environment, Food and Rural Affairs (DEFRA) and is the largest air quality monitoring network in the UK. It is also the primary data source for reporting the compliance of air quality objectives. The UK-wide coverage is shown in Fig. 1(a) and the London coverage is shown in Fig. 1(b) The data is collected hourly and is disseminated to the general public through a range of web-based channels and the R package "openair". A full description of the network and some tools can be found at https://uk-air.defra.gov.uk. Sites are classified as one of Urban Background, Urban Traffic, Rural Background, Urban Industrial, Suburban Background and Suburban Industrial. This paper focuses its analysis on Urban Background and Urban Traffic as these are the sites most likely to be affected by changes in population behaviour. Urban traffic sites are those that are in built-up areas and close enough to traffic for it to be considered the main influencing factor on air pollution levels. Urban background sites are those which are in a built up area but are not influenced by a single factor, source or road, but by a combination of all upwind sources and hence more representative of urban areas (Lee et al., 2020). As of 1 May 2024 the AURN consists of 175 sites across the UK and Ireland.

The Air Quality England (AQE) network is a resource for local air quality information, funded and hosted by Ricardo Energy and Environment and designed to help local authorities and private sector customers fulfil their duties within the local air quality management framework (https://airqualityengland.co.uk). The London coverage of the AQE network is shown in Fig. 1(c). Data from AQE was used in the in-depth analysis of the London Marathon event in Section 3.3.4. The AQE dataset has more sites in London than the AURN network and hence offers a higher spatial resolution than would be achievable using the AURN data for the same area. The AQE dataset was subset by those

Table 1
Air quality England site codes used for London Marathon analysis.

BN2	BN1	CT4	CD009
CD010	HK010	HK013	HK011
HK006	HK009	HF5	HG005
LHRBR	T55	LHR2	T54
HIL1	HIL5	HI3	SIPS
HI1	HS5	HS4	HS9
HS8	HS7	HS6	NEW04
KC4	KC5	KC3	HF4
SBC01	CT3	TH004	TH001
TH002	WL4	WL1	WL5

categorised as being in Greater London, those that are currently running and those that measure NO_2. There were 39 sites meeting these criteria and these sites were all used for the analysis of the London Marathon event. The site IDs for the selected sites are shown in Table 1.

2.1.2. Time period selection

The analysis spanned from January 1 2017, to December 31 2023, excluding the years 2020 and 2021. The analysis requires the data to span multiple years because doing so can remove the potential confounding factor of one-off weather conditions. Weather effects such as street canyoning (DePaul and Sheih, 1986; Caton et al., 2003; Xie et al., 2005) can significantly affect the ambient concentration so relying on models or using data that was not collected at the exact same location can introduce false results into the analysis. The start point of 2017 was selected as it would both capture the introduction of the more effective (e.g., García-Contreras et al., 2021) Euro 6c, 6d-temp and 6d passenger car vehicles, Euro VI heavy-duty vehicles, and provide enough years for meaningful analysis of the repeating holidays given the lockdown exclusions. The lockdown exclusions were essential to remove holidays that were significantly impacted by the COVID-19 lockdown in the UK, as the pandemic altered people's behaviour around these dates leading to fewer than normal journeys being made, making the data from these years unreliable (Ropkins and Tate, 2021). By selecting this date range, the study incorporated multiple complete and unaffected years, ensuring that the holidays analysed reflected typical patterns without the confounding effects of the lockdowns. Additionally, aligning the data to begin on January 1 and conclude on December 31 ensured a consistent yearly cycle and minimised the presence of unratified data. These methodological decisions were aimed at reducing external interference and enhancing the reliability of the analysis. By ensuring that the data encompassed full calendar years and excluded periods of anomalous behaviour, the methodology maximised the likelihood of identifying reliable signals and drawing accurate conclusions from the data.

2.1.3. Site selection

Understanding and differentiating the differing local contexts is critical in understanding the impact of travel decisions on NO_2 concentration. London is well-understood to be an outlier in the UK transport context. The subsidised and centralised provision of public transport, and policies restricting personal car use such as congestion charging and the Ultra Low Emission Zone (ULEZ) in London make transport decisions, particularly those related to mode choice, different from the rest of the UK. The Urban Background and Urban Traffic AURN sites for this study were further separated into two subsets to account for the geographical difference: those in the greater London area (GLA) and those outside it. The site subset categorisation was based on the *zone* parameter of the provided site metadata. The AURN site codes for the two GLA subsets are shown in Table 2. The sites not shown in 2 comprise the non-GLA subset. This further disaggregation was applied to identify differences where region may be important. Events such as the funeral of Elizabeth II have a significant and direct impact on the transport behaviour in London that would not be expected elsewhere. The impact on behaviour elsewhere is an indirect consequence of potentially people staying at home to watch.

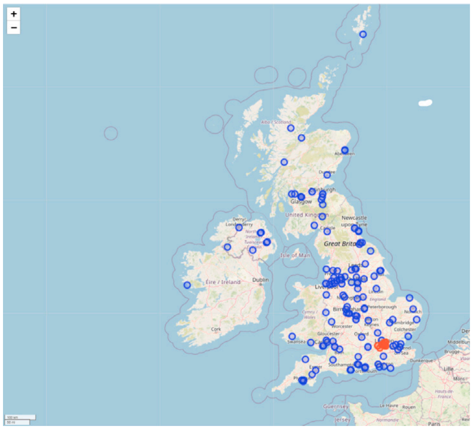
Table 2
AURN sites within the GLA by site type.

Urban background	Urban traffic
CLL2	CA1
HG4	HG1
HIL	MY1
HP1	SG5
KC1	TH2
TED2	
HORS	

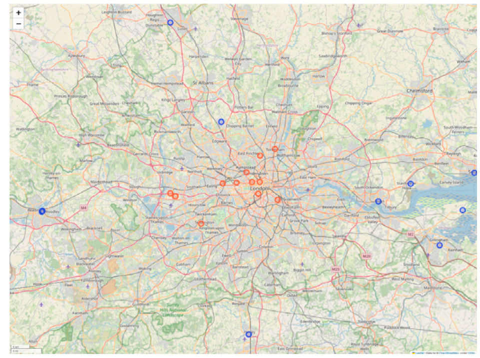
2.2. Forecasting tool

Decomposable time series methods and breakpoint analysis are able to isolate important structural variations in time series data consistently and empirically. They achieve this by using time space to frequency space transformations such as Fourier transformations and various wavelet transformations. These transformations reveal structures in frequency solution-space that may be filtered and transformed back into the time solution-space. The Prophet tool (Taylor and Letham, 2018) created by Meta was chosen to determine the impact of holidays on air pollution trends because it combines Fourier time series decomposition and break point analysis with individual days of interest in a professional and open-source python and R package, making the work verifiable and transferrable across common data science languages. The default settings were used for this analysis to aid in repeatability and transferrability. The decomposition of the time series is useful for making future predictions but can also be used to understand previous behaviour if some external influencing factors, in this case weather and travel behaviour, contribute to the time series. This methodology has been used in a range of different use cases including tourism recovery during COVID (Fotiadis et al., 2021), epidemic trends (Wang et al., 2020) and oil production forecasting (Ning et al., 2022), indicating multi-disciplinary relevance. Some attempts have been made to forecast air pollution concentrations using the Prophet model (Hasnain et al., 2022; Shen et al., 2020; Gladkova and Saychenko, 2022), though these papers focus on predicting future air pollution concentration values rather than isolating different component contributions or using the model as a diagnostic tool for understanding historical events.

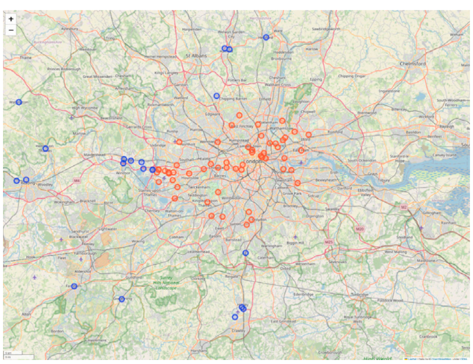
The Prophet tool is typically used for projecting future values however it has some use in analysing previous trends. The Prophet tool breaks down the time series into three main components: trend, seasonality and holidays, and uses a decomposable time series (Harvey and Peters, 1990) to determine the relative contribution of each of them to the overall time series. The trend component isolates the overall direction in the time series and is generally used for predicting future values. Isolating the trend from the periodic and one-off components of the time series is useful as it allows the various different components to be more accurately assessed and quantified. Seasonality components of transport-related data can be further broken down into daily, weekly, and yearly periodic components. Traffic flow influences the daily and weekly periodicities as there is typically less flow at weekends than on weekdays, and less flow during off-peak and inter-peak times than during AM and PM peak traffic flows. Yearly trends in air pollution are dominated by ambient weather conditions as the interaction of NO_2 and photons ($h\nu$) creates Ozone (O_3) and secondary pollutants, as well as the impact of atmospheric boundary layer changes (Dupont et al., 2016). Two sample outputs from the Prophet model are shown in Fig. 4: one for air pollution (Fig. 4(a)) and one for traffic (Fig. 4(b)). The overall trend, followed by the holiday, yearly, and weekly components for the time series, are shown in individual panels. This study primarily focused on the impact of holidays, which, after the seasonality and trend of the time series were removed, gives some indication of the relative impact of the event on air pollution concentration levels at each site, accounting for observed periodic trends.



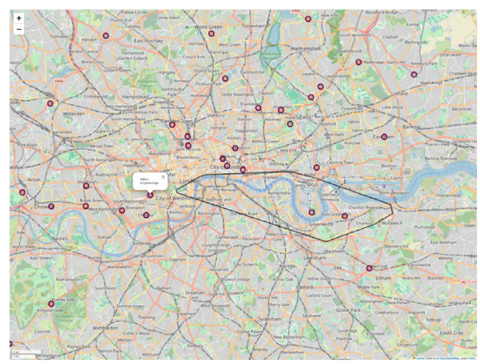
(a) A map of the United Kingdom showing the location of all AURN sites. The sites which form the GLA data subset are coloured orange and the sites which form the rest of the data set are coloured blue.



(b) A map of London and its surrounding area showing the location of all AURN sites. The sites which form the GLA data subset are coloured orange nad the sites which form the rest of the data set are coloured blue



(c) A map of London and its surrounding area showing the location of all AQE sites. The sites which form the GLA data subset are coloured orange nad the sites which form the rest of the data set are coloured blue



(d) A map showing the extent of the London marathon and potentially relevant AQE sites. The extent of the London marathon route is indicated by the grey poly-line and the location the sites are shown as purple circles. The location of a site of particular interest, Knightsbridge, is highlighted

Fig. 1. Maps showing the areas and points of interest for this paper. The figures are created using OpenStreetMap data, licensed under the Open Data Commons Open Database License (ODbL) by the OpenSreetMap Foundation (OSMF).

2.3. National holidays

National holidays were added based the *holidays* package for Python[1] for the UK as well as three additional days that were deemed relevant to transport. The holidays were New Year's Day, New Year's Day (observed), Good Friday, May Day, Spring Bank Holiday, Christmas Day, Christmas Day (observed), Boxing Day and Boxing Day (observed). The holiday dates are not consistent across multiple years with the same holidays falling on different dates depending on the calendar. Additionally, when a holiday naturally falls on Saturday or Sunday another (observed) holiday is added to the holiday schedule. The observed date is also considered on a year-by-year basis and is labelled as (observed) in the analysis.

The additional days were Christmas Travel 1, Christmas Travel 2 and Christmas Eve, which were 22, 23 and 24 December respectively. The days in the lead-up to Christmas were considered interesting for people studying transport and its effect on air pollution as they are days when more people than usual may be expected to travel differently, ahead of Christmas in the UK. No value for the air pollution component was calculated for the days between boxing day, or boxing day observed and new year's day. A notable exception from this list is Bonfire night. Bonfire night is typically a time where air pollution might be expected to be high due to many people having bonfires and

[1] https://github.com/vacanza/python-holidays/.

setting off fireworks across the UK. These events are more likely to be observed in the $PM_{2.5}$ and PM_{10} concentration measurements due to the nature of the emission source, and analysing these is beyond the scope of this paper.

The London Marathon is the largest marathon in the world and occupies a significant portion of the Greater London Area (GLA). The dates of the London Marathon included in this study are available online and through official organisation channels. The London marathon non-elite start is typically scheduled for Sunday 9:30–11:30 with runners being required to finish 8 h after the last starter crosses the start line, meaning the cutoff time is 19:30. People who have not finished by then may continue but need to use the pavement. Disruption can be expected between Thursday and Monday around Westminster, and less in other areas. Fig. 1(d) illustrates the extent of the area occupied by the marathon. The area was calculated using a GPX trace of the marathon route, which was downloaded from https://www.plotaroute.com/route/1476748 with each record considered a point. The GPX data was converted into GeoJSON, and a convex hull was calculated using the *unary union convex hull* method of the GeoPandas Python package (Jordahl et al., 2021). A convex hull is the *"smallest convex polygon containing all the points in a geometry"* and is a fair representation of the area directly affected by the London marathon.

3. Results

3.1. Forecasting case study - Bradford Mayo Avenue

A case study is presented to demonstrate the functionality of the Prophet forecasting model. The Bradford Mayo Avenue site is chosen for the case study as it represents a location that is both close to a residential area and adjacent to a well-used road, with two lanes of traffic running in each direction. The site also sits within, but on the edge of, the clean air zone introduced in Bradford on 26 September 2022. The site's location in decimal latitude and longitude is (53.77, −1.76). Fig. 2 shows the site in context. Air pollution concentration data for the case study was taken between 1 January 2017 (00:00) and 31 December 2023 (23:59). This range was chosen because it spans a long enough period to show trends and also demonstrates the impact of COVID-19 lockdowns on the overall trends. The data as downloaded from the AURN portal is shown in Fig. 3. The Prophet model was run using its default configurations and with national holidays added as detailed in Section 2.3. The default configuration was chosen as it would not induce over-fitting or over-smoothing. The decomposition of this data is shown in Fig. 4(a).

The output of the Prophet forecast model Fig. 4(a) shows five panels with the trend, holidays, yearly, weekly and daily components from top to bottom. The x-axis shows the relevant time intervals, and the y-axis shows the component for each time period as well as the one-off contributions from each national holiday at this site. The top panel in Fig. 4(a) shows the general decrease in NO_2 concentration at the BDMA site since 2017, with a predictable drop in concentration during mid-2020, corresponding to the COVID 19 lockdown period. A clean air zone was introduced in Bradford on 26 September 2022 which coincides with the final decreasing trend, though no causal link is claimed from this work and doing so is beyond the scope of this paper.

Supplementary automatic traffic count (ATC) data was collected at a site on the A6177 Rooley Lane in Bradford to better demonstrate the link between traffic flow and air pollution. The ATC site is on the same link of the Bradford road network and is east of the air pollution monitoring site. The traffic flow at the ATC site is broadly representative of the traffic flow at the air pollution monitoring site. The ATC data covers the same span as the air pollution data but is measured at 15 min intervals. The Prophet forecasting tool was applied to this data set in the same way as it was to the air pollution concentration data set. The component analysis generated by the Prophet tool is shown in Fig. 4(b). The reduction in trend component observed in Fig. 4(b) during

Fig. 2. Figure showing the location of the Bradford Mayo Avenue site for context. The air quality monitoring site is the green cabinet across the road from the photograph viewpoint and is centred in the yellow circle. The image was captured in July 2023 and sourced from Google Maps.

the COVID lockdown period and returning to near baseline levels after demonstrates that travel behaviour changed significantly. The observed change in travel behaviour is evidence of the need to remove this time interval from the further holiday analysis.

The ATC component plot directionally agrees with the shapes of the NO_2 component plots when considering weekly and daily trends. The R^2 coefficients for the relationship between the daily and weekly ATC and NO_2 concentrations are 0.88 and 0.93. Strong weekday contributions and weaker weekend contributions as well as clear reductions during off-peak daily time periods are observed in both traffic and air pollution decompositions. The inter-peak period is less clearly observable in the traffic data however this may be because there is no true inter-peak period at this site and it remains busy from the AM rush to the off-peak. The yearly panels do not correlate as well over the summer which is an expected outcome. The summer trough in NO_2 does not have a similar trough in traffic count because NO_2 is converted to O_3 in the presence of sunlight, with no comparable mechanism present for vehicle count. The influence of cold start and cold running on selective catalytic reduction (SCR) catalytic converters further inhibits their effectiveness and may contribute to an increase in NO_2 concentrations during colder times of the year (Matthaios et al., 2019). The contribution due to holidays also shows strong reductions. The trend of traffic flow from the end of 2022 to the beginning of 2024 shows an upwards trend compared to a downwards trend for the air pollution concentration. This may indicate some reduction in absolute concentrations due to the implementation of the Bradford Clean Air Zone around this period but may be due to slight differences in the ATC site location compared to the air pollution site.

3.2. Overall trends

The sites for Greater London urban traffic and urban background are used to demonstrate the yearly, weekly and daily periodicities in air pollution concentration data. The selected sites are detailed in 2. The raw data was processed using Prophet as outlined in Section 2.2. A general additive model for yearly component of the air pollution concentration of NO_2 ($\mu g\ m^{-3}$) was calculated for all site in each subset to show the overall trend. A $y = 0$ line is also added to improve the clarity of the figure.

Fig. 5 shows the different periodic temporal trends for GLA urban traffic and urban background sites. Figs. 5(a) and 5(b) shows the yearly

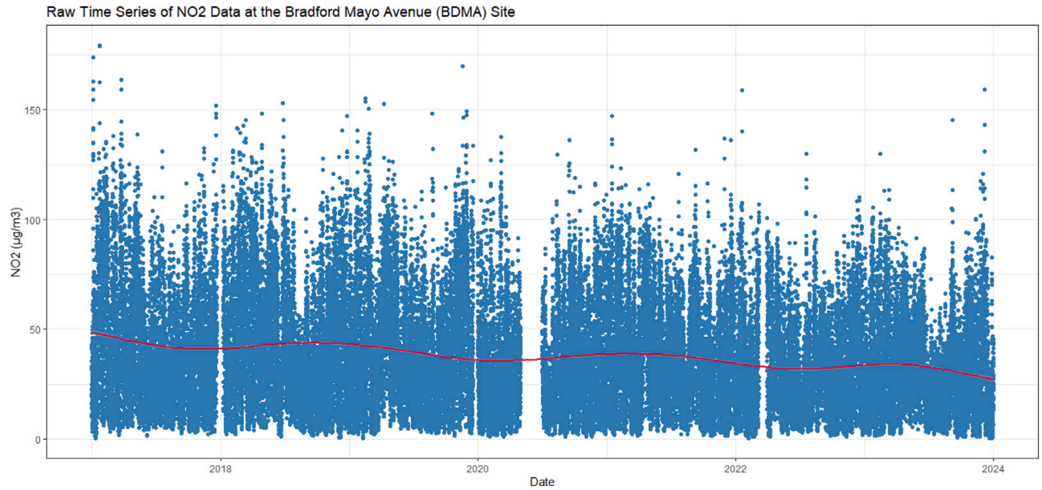
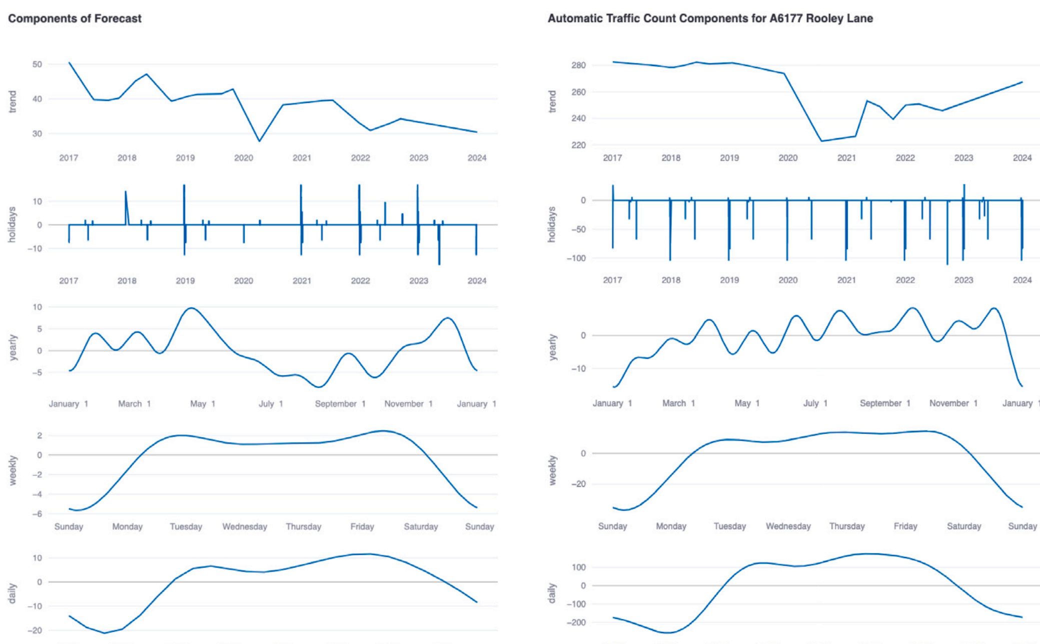


Fig. 3. Figure showing the raw timeseries data for NO_2 concentrations for the Bradford Mayo Avenue Site (AURN Code BDMA) over the study period 2017–2024 with the COVID 19 pandemic data included where available. Some data is missing from the original data source during mid-2020. These data are used as the input for the time series decomposition. A GAM model is fitted in red to demonstrate how the data might be modelled without decomposing the time series into its periodic components.



(a) (b)

Fig. 4. Decomposed Time Series Data for NO_2 Concentrations (a) and ATC Traffic Counts (b) over the study period (2017–2024) with COVID-19 lockdown interval data shown for completeness. The daily, weekly and yearly panels show the time series decomposition for these time intervals. The trend panels show the segmented linear trend based on breakpoint analysis with the temporal periodicities removed. The holidays panels show the remaining component of the NO_2 concentration.

periodic components of the urban background and urban traffic sites in the GLA respectively. The figures show a shape with a negative contribution in the warmer summer months, and a positive contribution in the cooler winter months which is in line with expectations. For the urban background sites, the peak (≈16 μg^{-3}) in winter is greater than the trough (≈ – 15 μg^{-3}) in the summer but the general trend indicates that the peak in winter is less than the trough in summer. This indicates that whilst general trends are useful and directionally correct, the specific context of any site remains important to assessing and predicting concentrations. This trend is also present in the urban traffic sites, though it is not as pronounced. This suggests that proximity to traffic is still an important factor, even though meteorological factors are strongly impacting the trends.

Figs. 5(c) and 5(d) show the weekly periodic components of the urban background and urban traffic sites in the GLA respectively. Over the weekly time period the forecasting model suggests a reduction in

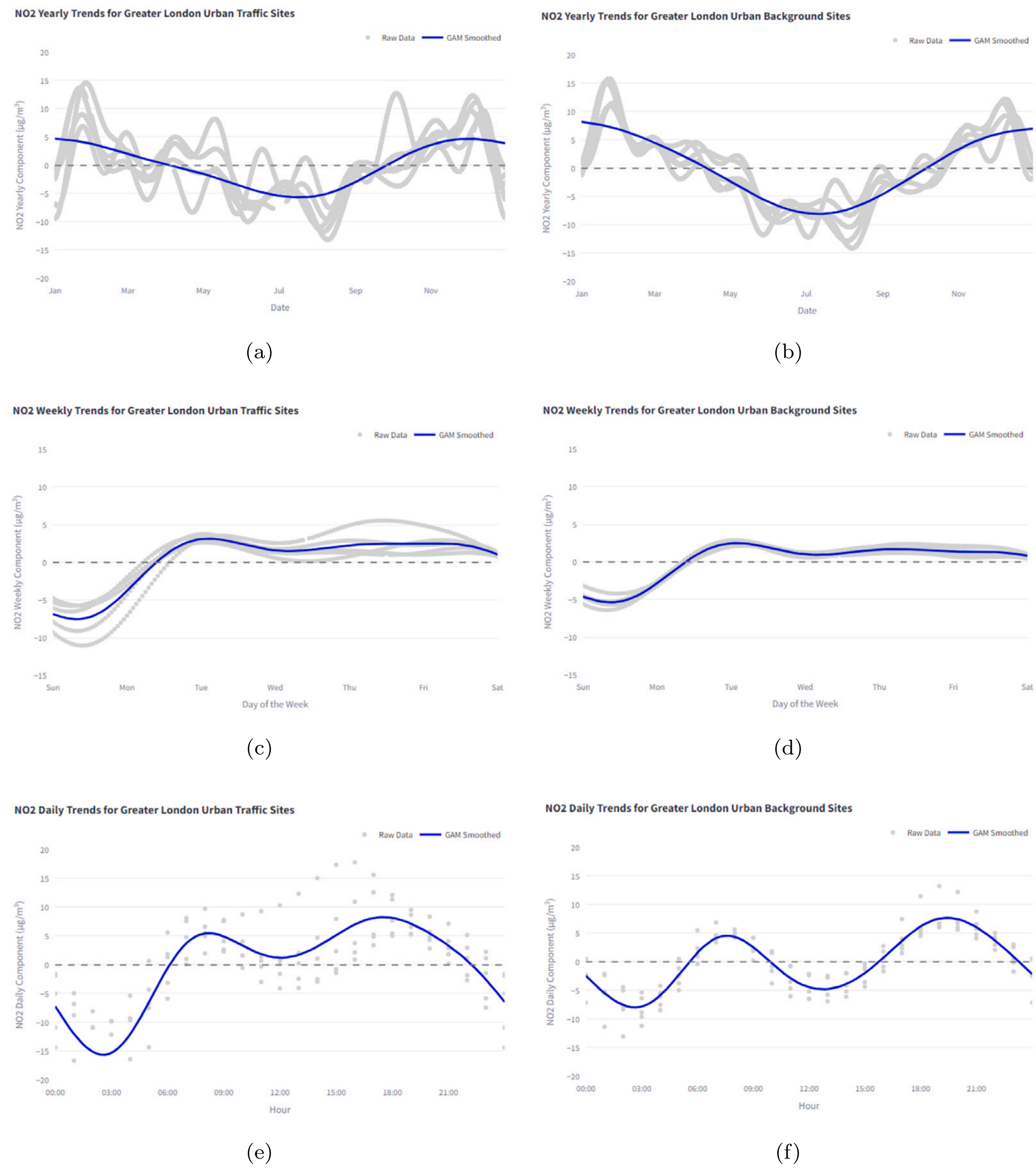


Fig. 5. Trends in NO_2 concentration at urban traffic sites (a, c, e), and background sites (b, d, f) in Greater London (yearly, weekly, daily). In all cases, grey traces show raw data; blue line is GAM smoothed trend-line.

ambient air pollution on Sundays both at Urban Background and Urban Traffic sites. This is likely due to a reduction in demand for the transport infrastructure on Sunday. The reduction on Sundays is between -5 μg m^{-3} and -10 μg m^{-3} at Urban Traffic sites but between -3 μg m^{-3} and -6 μg m^{-3} at Urban Background sites. The larger reduction at traffic focused sites further suggests that this reduction is significantly driven by the use of transport during these times. Additionally, this suggests that whilst there may be some reduction in traffic related pollution on a Sunday, the GLA transport systems remain just as active during Saturdays as they do for the duration of the working week.

Figs. 5(e) and 5(f) show the daily periodic components of the urban background and urban traffic sites in the GLA respectively. Over the daily time period the forecasting model suggests that air pollution trends follow anticipated traffic use trends. The AM and PM peaks are observable alongside an inter-peak (IP) period and an off-peak period during the night at between 02:00 and 05:00, when demand for transport systems is at its lowest. As with the weekly time period, these trends are most strongly observed in the Urban Traffic sites, suggesting that transport is a significant factor in the periodic variation. The off-peak contribution is ≈ -15 μg m^{-3} at the Urban Traffic sites compared to ≈ -8 μg m^{-3} at the urban background sites. Urban background sites experience a slightly negative component of air pollution during the IP period that is not seen for most of the Urban Traffic sites.

3.3. Impact of holidays on air pollution

The results of the holiday components are visualised as box plots. The *y*-axis holidays are ordered chronologically with the first holiday in the year positioned at the top of the *y*-axis. Annual events are shown in blue, events that occurred in 2022 are shown in red, and events that occurred in 2023 are shown in yellow. The NO_2 concentration component for each site and for each holiday are used to calculate the median and inter-quartile range (IQR) which are shown in the solid box, and the whiskers are 1.5 × IQR. Outliers and potential outliers are plotted as solid and white dots respectively. Individual sites are not plotted if they are not outlier candidates. The results of this analysis are shown in Fig. 6. Figs. 6(a) and 6(b) show the components for the greater London area and Figs. 6(c) and 6(d) show the components for those sites not in the greater London area. The box plot visualisation shows the variation seen across the UK for both subsets of the AURN network sites.

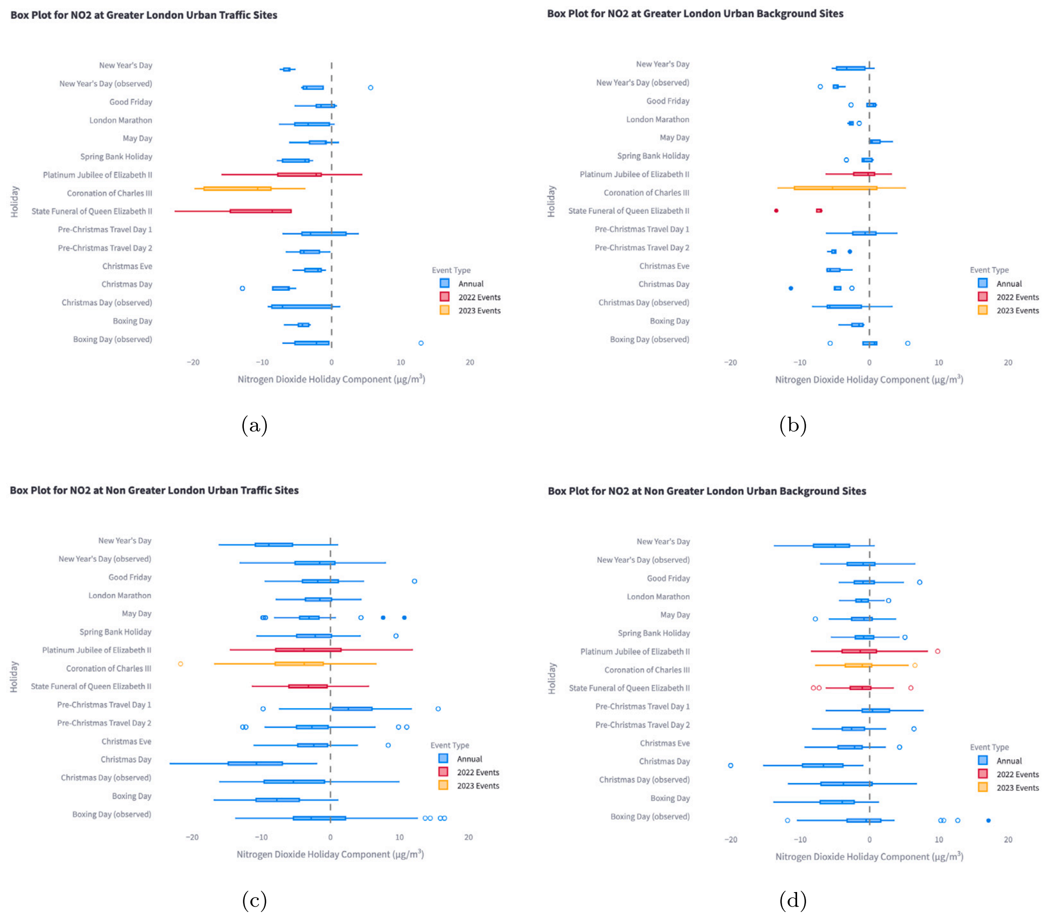


Fig. 6. Box Plots of NO_2 Concentration Components for Urban Traffic and Background Sites Across Specified Holidays in the GLA and non-GLA subsets of the AURN network. The vertical lines indicate medians, boxes represent the interquartile ranges, white points are potential outliers, and solid points are confirmed outliers.

3.3.1. Annual national holidays

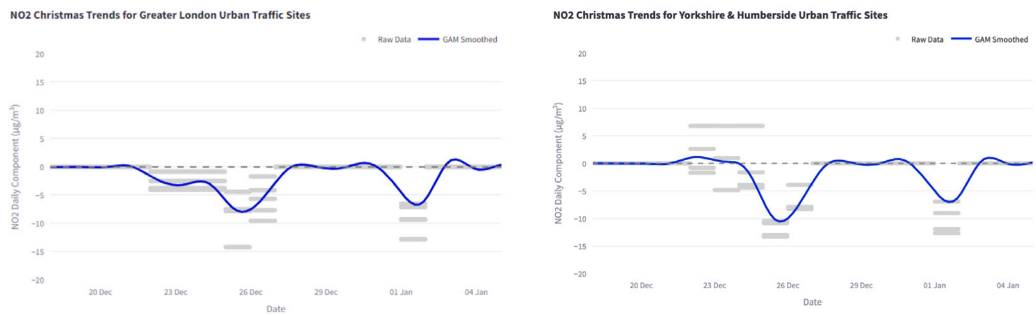
National holidays in the UK are days where schools and most institutions are closed, and although it is not a legal requirement, many people are not required work. Some sectors such as retail may operate on reduced hours or not trade at all. May Day, or the early May holiday has origins in pagan fertility rituals. The current bank holiday was instituted in 1978 by Michael Foot, the then leader of the British Labour Party. It falls on the first Monday of May every year. There is evidence in a reduction in NO_2 concentration at the GLA urban traffic sites and there is evidence of an increase in concentration at the GLA urban background sites. There is some evidence of a small reduction in component concentration level at non-GLA urban traffic sites as the 3rd quartile is below zero. There is no significant evidence of a difference at non-GLA urban background sites. The median May Day bank holiday component for the GLA Urban Traffic sites is -2.10 μg m^{-3} and -3.39 for non-GLA sites. The highest non-GLA site is Portsmouth Anglesea Road (POAR) with a component of 13.83 μg m^{-3} and the lowest non-GLA site is Widnes Milton Road (WSMR) with a component of -16.34 μg m^{-3}.

The May Day national holiday for GLA sites is an example of an inversion between the Urban Traffic sites and the Urban Background sites. The IQR for Urban Traffic sites is completely negative and the IQR for Urban Background sites is completely positive. This effect may be caused by a displacement of activity away from main roads and economic centres to areas that would typically expect less intense activity on the same day. This trend is less clear outside of London, suggesting that less publicly accessible activities are available beyond the GLA. More detailed usage data including pedestrian and active travel mode (bicycles and similar) counts as well as event metadata are required to confirm or reject this hypothesis and doing so is beyond the scope of this paper.

The UK spring bank holiday was originally observed on Whitsun in the UK but was moved to the last Monday in May as part of the Banking and Financial Dealings Act 1971. There is strong evidence of a reduction in component concentration at the GLA urban traffic sites as the entire inter-quartile range is below zero and there are no outliers. There is no strong evidence of a reduction at the GLA urban background sites as the inter-quartile range falls either side of zero. The median concentration component is less than zero for non-GLA urban traffic sites but the interquartile range includes positive values, as well as two outlier sites, Glasgow Kerbside and Aberdeen Wellington Road (GLA4 and ABD8 respectively). The inter-quartile range for the spring bank holiday fall either side of zero so despite the median value being negative, there is no evidence to suggest a large and systematic reduction in NO_2 concentration occurs at non-GLA urban background sites. There is one outlier site Belfast Centre (BEL2) identified with a concentration component of 5.62 μg^{-3}.

Good Friday is a Christian holiday and is recognised as a national holiday in the UK. It is the Friday before Easter. The date varies from year to year and between the Julian and Gregorian calendar. In Western Christianity, using the Gregorian calendar, Easter falls on the first Sunday after the spring equinox. The variability in observed date is accounted for in this analysis. There is no conclusive evidence of any consistent trend in the variation in emission component identified in either the urban traffic or urban backgrounds in the GLA site subset or the non-GLA site subset. The IQR falls within zero for all of these measurements.

The air pollution concentration change in response to the discussed national holidays varies depending on the holiday. The cultural significance of these holidays is likely to be influential in the changes



(a) (b)

Fig. 7. Christmas Period Trends of Urban Traffic Sites in Greater London (a) and Yorkshire/Humberside (b). The grey traces show the raw data for each site, and the blue line is a GAM smoothed trend-line.

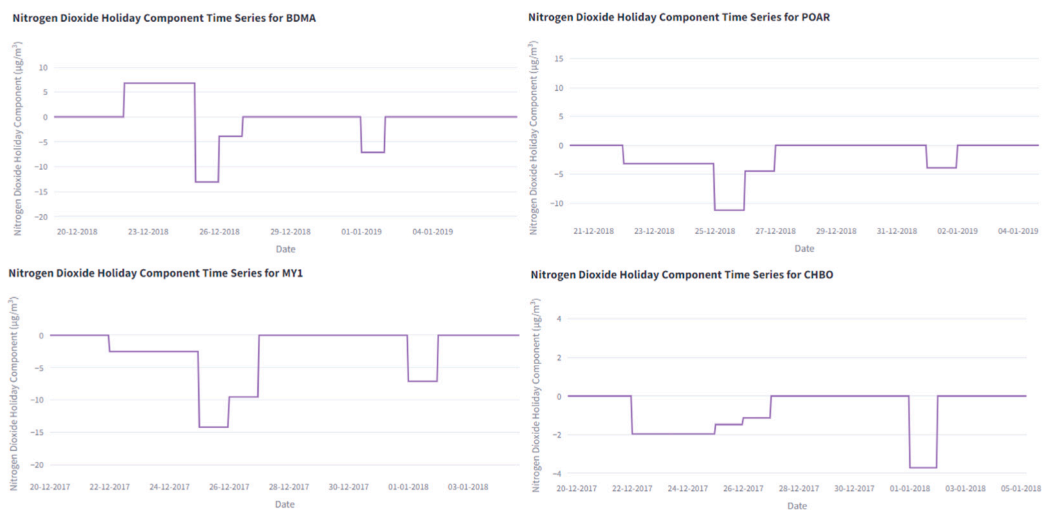


Fig. 8. Figure showing the components over the Christmas period for three individual sites. The sites are Bradford Mayo Avenue (BDMA), Portsmouth Anglesea Road (POAR), Marylebone Road (MY1) and Chilbolton Observatory (CHBO).

in behaviour. Holidays that are a day off work for most people, the bank holidays, have a more significant change in air pollution compared to holidays with a singular and religious significance. One could hypothesise that as religion becomes less important in peoples' lives, the holidays become less strictly observed and the behaviours observed on these days become more similar to a representative day. Consequentially, the difference in NO_2 concentrations observed on these days compared to representative days would become smaller.

3.3.2. Christmas

The Christmas period is different for everyone as different working patterns facilitate different behaviours and with some employees being more generous with time off than others. For most people it is time off work and for many this includes travelling unusual distances to be with friends, family, or going on holiday. This disrupted travel behaviour can be hypothesised to impact the air pollution concentrations. Figs. 7(a) and 7(b) show the regional trends in the GLA and Yorkshire and Humberside respectively. The trend analysis for the Christmas period, defined in this study as between 18 December and 5 January show different trends depending on the type of site observed. Urban Background sites show a decrease in NO_2 concentration in the run up to Christmas, with a contribution of between ≈ 0 μg m^{-3} and ≈ -5 μg m^{-3} in the pre-Christmas travel days. The contribution over this period at Urban Traffic sites is mixed, with some sites seeing a negative components and others seeing positive components. The Christmas Day and Boxing Day components are strongly negative as might be predicted, and the New Year's Day period is also strongly negative. More so than Christmas Day in some cases.

There is some evidence of air pollution displacement outside of the GLA, where the component of NO_2 concentration increases in the lead up to Christmas, likely being caused by changes in travel behaviour. This is demonstrated in the top left panel in Fig. 8, which shows the components for the Bradford Mayo Avenue (BDMA) site, but as demonstrated in the other panels, this is not a general trend. This feature is not observed consistently across the UK, and it may be hypothesised that different employment sectors or general working behaviours are accounting for this difference, with different allowances for time off over the period contributing to different travel requirements. It may also be hypothesised that different communities may behave differently during the Christmas period.

Four individual sites were investigated further to show the range of differences over the Christmas period. The concentration components for Marylebone Road (MY1), Bradford Mayo Avenue (BDMA) and Rural Background site Chilbolton Observatory (CHBO) were extracted for the Christmas period. The MY1 site is a site located close to four lanes of traffic, two in each direction in the centre of London, UK. Likewise, the BDMA site has the same road configuration, although in a slightly less built-up environment. The CHBO site is a background site to serve as a control to clarify the causal impact of holidays on air pollution. The CHBO site shows a slight decrease in pollution over the Christmas period, of around -2 μg m^{-3}. This is comparable to the reduction observed at the POAR and MY1 sites and suggests that the reduction observed on these days is not causally linked to the changes in traffic behaviour. The control is directionally different from the BDMA site, suggesting that its observed component is likely driven by local factors rather than nationwide factors.

3.3.3. One-off national holidays

The platinum jubilee of Elizabeth II was the celebration of the 70th anniversary of Elizabeth II and was the first celebration of its kind for the British monarchy. It was marked with an additional national holiday on 3 June 2022 in the UK and the spring bank holiday was moved to 2 June, creating the jubilee bank holiday weekend for national celebration. The jubilee weekend was expected to boost the British economy by £1.2bn (Travel Weekly, 2022). Despite the significant changes to the calendar and expected behavioural changes there is no strong evidence of any significant change in air pollution due to the events. There is a negative median component for both GLA and non-GLA urban traffic sites, suggesting that a small number of people may have altered their driving behaviours, but this may be offset by other changes leading to more pollution. The range in pollution components is quite high outside the GLA suggesting that the response to the jubilee national holiday was driven by local factors rather than systematic national factors. The greatest decrease was observed at London Marylebone Road (MY1) with a reduction of -15.62 μg m^{-3} and the greatest increase was observed at Southwark A2 Old Kent Road (SK5). The greatest decrease outside of London was Shaw Crompton Way (CW) in Oldham, with a reduction -12.69 μg m^{-3}.

The State Funeral of Queen Elizabeth II occurred on Monday September 19 2022 and was held at Westminster Abbey, London, UK. The event was a significant departure from normal Monday behaviour in London and across the UK and a once in a generation event with around 28 million people watching across 50 channels in the UK. The funeral generated significant global interest with an estimated that 4 billion people watching it worldwide. The funeral began at 11:00 and at 12:15 a procession from Westminster Abbey to Wellington Arch left for Windsor Castle. At 15:00 the funeral procession arrived in Windsor Castle. Around 1 million people (an equivalent of $\approx 10\%$ of the London population) watched the event on the streets of London and extra public transport services were made available to access it. The day was designated as a national holiday in the UK with many shops, workplaces and schools closed. Analysis of the air pollution concentration at sites within the GLA showed a consistently significant reduction in NO_2 concentration across all measured sites in London, as shown in Figs. 6(a) and 6(b), and the components are shown in Table 3. It is likely that this reduction was caused by significant reduction in activity. The greatest reduction at urban traffic sites was observed at site MY1, where a component reduction of -19.85 μg m^{-3} was estimated. The greatest reduction at urban background sites was observed at site London Hillingdon (HIL), where a component reduction of -11.68 μg m^{-3} was estimated. This site was in the direction of the funeral procession from London to Windsor but not on the exact route. This point was considered an outlier.

The highest change in air pollution concentration was observed at site MY1, Marylebone Road. This site is known to be one of the most highly polluted roads in the UK (Hicks et al., 2021) and is therefore a site with a high potential for generating observable changes. It is also the closest Urban Traffic site to the funeral procession. The London Westminster Urban Background (HORS) site did also return a reduction in the component of air pollution concentration observed but not enough to be considered an outlier.

Figs. 6(c) and 6(d) show a less significant and consistent trend across the rest of the UK compared to the GLA. It is likely that this was caused by the significant change in behaviour by people in and around London, as well as many people choosing to watch the television coverage of the procession and ceremonies. The greatest urban traffic site was observed at Bradford Mayo Avenue (BDMA) where a component increase of 6.61 μg m^{-3} was estimated. The smallest change at an urban traffic site was observed at Widnes Milton Road (WSMR) where a component decrease of -9.78 μg m^{-3} was estimated. A potential positive outlier was identified at Bristol St Pauls (BRS8) 6.37 μg m^{-3} and a potential negative outlier was identified at Manchester Picadilly (MAN3) -7.14 μg m^{-3} was observed.

The trend in NO_2 air pollution components at sites across the rest of the country is less clear, with significant variation observed. The five sites with the greatest reduction in NO_2 concentrations for both site types analysed are shown in Table 4. The median Urban Traffic component was -2.43 μg m^{-3}, compared to the GLA median value of -7.96 μg m^{-3}, and the median Urban Background component was -0.50 μg m^{-3}, compared to the GLA median value of -5.95 μg m^{-3}. This suggests that despite the event being a national holiday, the impact from an air pollution perspective was primarily felt within the GLA.

The coronation of Charles III took place on Saturday 6 May 2023 at Westminster Abbey, London. A 1.3-mile procession from Buckingham palace started at 10:20, taking approximately 40 min, and a second returning procession occurred on the day of the coronation. Around the UK, pubs were open until 1:00, and approximately £3.8m was spent by local authorities to celebrate the event (Open Democracy, 2023). The median component for GLA urban traffic sites was negative and the maximum of $1.5 \times IQR$ range was also below zero. The median component change was also negative for GLA urban background sites, suggesting some reduction in emissions compared to a normal Saturday London-wide. The non-GLA urban traffic sites were mostly negative although there are some positive values within the expected range. The non-GLA urban background sites show the same trend as the non-GLA urban traffic sites, although the difference is less pronounced.

3.3.4. London marathon

The analysis of the AURN sites shown in Fig. 6 suggests that a significant reduction in NO_2 concentration is observed for urban traffic sites in the GLA, and also for the urban background sites in the GLA as the inter-quartile range for each subset is below zero. There is also some evidence to indicate a reduction in NO_2 concentration at non-GLA urban background sites though the lack of influencing factors suggest that this is likely an artifact of the analysis.

The component of NO_2 on the day of the London Marathon for all Air Quality England sites was plotted as a box-plot in Fig. 9. The median value is -1.29, and the first and third quartiles are -3.50 and 1.34 respectively. Two negative outliers were identified at sites RBKC Knightsbridge (KC3) and Hammersmith Town Centre (HF5), and one positive outlier was identified at site Haringey Wood Green (HG005). The inter-quartile range falls either side of zero for these sites suggesting that no trend across the London area was present. The negative outlier values at KC3 was -14.29 μg m^{-3} and HF5 was -13.23 μg m^{-3}. The positive outlier value at HG005 was 9.10 μg m^{-3}. The KC3 site is located close to The Mall, where the marathon ends and is likely to be heavily influenced by changes in travel behaviour both on the day of the event and the days leading up to it. The HG005 site is located relatively close to the marathon area compared to some sites and is close to Alexandra Palace, an entertainment and sports venue in north London. There is no clear reason why this site would have an abnormally high pollutant concentration component caused by the London Marathon, so this outlier may be caused by unknown external factors.

4. Conclusions

The work in this paper has both policy and methodology implications in the field of air pollution study. From a policy perspective, the impact of various public holidays, and hence potential one-off events, has been rigorously quantified using a new and innovative analysis technique. From a methodological perspective this technique may be applied beyond the demonstrated use case, expanding into the realm of public health and impact assessment.

The link between transport use and NO_2 concentrations in the UK has been further validated, with strong correlation observed between traffic flow and NO_2 concentrations where expected, and no correlation where it is not expected. The observed correlation between traffic flow and ambient NO_2 concentrations suggest that changes in traffic

Table 3
Component of air NO_2 concentrations (μg m^{-3}) due to the state funeral of Elizabeth II at urban sites inside the GLA.

Site code	Site name	Site type	Concentration
CA1	Camden Kerbside	Urban Traffic	−8.19
HG1	Haringey Roadside	Urban Traffic	−12.97
MY1	London Marylebone Road	Urban Traffic	−21.15
SK5	Southwark A2 Old Kent Road	Urban Traffic	−4.16
TH2	Tower Hamlets Roadside	Urban Traffic	−0.4.18
CLL2	London Bloomsbury	Urban Background	−6.68
HG4	London Haringey Priory Park South	Urban Background	−5.68
HIL	London Hillingdon	Urban Background	−11.72
KC1	London N. Kensington	Urban Background	−5.63
HORS	London Westminster	Urban Background	−5.95

Table 4
Components of air NO_2 concentrations (μg m^{-3}) due to the state funeral of Elizabeth II at urban sites outside the GLA. The lowest five sites and the median value for each site type is shown.

Site code	Site name	Concentration
BEL1	Belfast Sockman's Lane	−9.73
WSMR	Widnes Milton Road	−9.64
BOLD	Oldbury Birmingham Road	−9.10
HOPE	Stanford-le-Hope Roadside	−9.10
OX	Oxford Centre Roadside	−4.18
Median	Urban Traffic	−2.43
MAN3	Manchester Picadilly	−7.12
THUR	Thurrock	−6.42
SEND	Southend-on-Sea	−5.89
SOUT	Southampton Centre	−5.54
BDMP	Borehamwood Meadow Park	−4.74
Median	Urban Background	−0.50

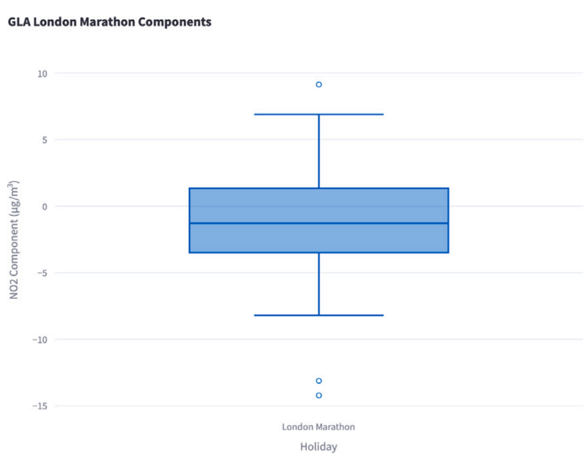


Fig. 9. Figure showing a box plot of the extracted components for all Air Quality England sites for the London Marathon. The median value of the component is shown as a horizontal line through the blue box. Potential outliers are shown as white dots extending beyond the top and bottom fences.

flow levels impact NO_2 concentration and that this change can be measured using the proposed methodology. Predictable daily, weekly and yearly periodic trends are observed reliably and repeatedly across a range of diverse and disparate set of air pollution monitoring sites across the UK. Periodic component contributions have been identified and extracted from the underlying trend using the Prophet forecasting tool. The contributions for each temporal component are empirically measured and quantitatively assessed. These results are in line with less quantitative assessments and confirm the previously understood seasonal periodicity in NO_2 pollution concentrations. This confirms the validity of Prophet as a useful tool in analysing air pollution data.

One-off holidays have been shown to impact air pollution concentrations in a varied but mostly predictable manner. Some anecdotal assumptions have been clarified but there are few clear and generalised trends that can be observed and quantified consistently across all sites and regions in the UK. With the exception of Christmas day, which has a negative component at all sites measured, every holiday has some instance of a positive component or negative component observed for at least one site. This further indicates that NO_2 pollution, whilst a global concern, is a local problem and policy designed to mitigate it must focus on the local factors causing and influencing it.

The results from the London Marathon analysis suggest that even large-scale events do not have an observable impact on air pollution except in the areas very close to the event itself, and even then only in certain circumstances. The sites that are close to the finish line, which is a significant point of disruption, have shown some significant reduction in air pollution, but no significant change was shown when the AQE air pollution network was considered in its entirety. This is important knowledge for those planning major events and who are concerned with those events' impact on NO_2 pollution.

The results from this analysis are of direct interest to organisers and policy makers in the UK however the conclusions drawn from this are transferrable worldwide. The confirmation of the link between transport and air pollution, along with the demonstration that shorter timescale events can meaningfully impact NO_2 concentration, will allow planners to better understand the impact their events have on air pollution and hence public health. The significant variation across site locations indicates that whilst it may not be possible to directly predict the level of concentration change, it is possible to measure it retroactively and therefore plan accordingly for future events.

This study presents a comprehensive analysis of the impact of periodicity and national holidays on air pollution levels in the United Kingdom, specifically focusing on nitrogen dioxide (NO_2) concentrations. Utilising the Prophet forecasting tool, the research provides novel insights into how various time-based factors influence air pollution, supporting both anecdotal and scientifically established trends. The study's methodology, leveraging the Prophet model, proves to be a robust approach for decomposing and understanding NO_2 time series data and quantifying underlying trends. The ability of the model to isolate the effects of holidays from underlying trends and seasonal variations offers a valuable tool for environmental researchers and policymakers. This approach allows for more precise quantification of the impact of specific events and periods on air pollution, facilitating targeted interventions, or more effective impact assessment of historical events such as the Bradford tyre fire in 2023 (https://www.bbc.co.uk/news/articles/cg33m1gkm4do), other industrial fires, or bonfire night activities.

The findings highlight several important aspects of air pollution dynamics. Firstly, the identification and quantification of the contribution of daily, weekly, and yearly periodic components to NO_2 concentration time series align with previous studies and underscores the significant role of traffic and weather patterns in shaping air pollution levels. The observed daily peaks corresponding to AM and PM rush hours, weekly reductions during weekends, and seasonal variations align with expected patterns driven by human activity and meteorological conditions. The replication and quantification of these key results validates the new methodology and allows for the robust quantification of one-off event contributions to ambient NO_2 concentration.

The analysis of national holidays shows some evidence of reductions in NO_2 concentrations during these periods, particularly on Christmas Day and New Year's Day, and is able to quantify their impact. These holidays are examples of significant and unusual, though not unpredictable, reductions in vehicular traffic as people stay home or travel less, leading to decreased emissions. The state funeral of Elizabeth II and the London Marathon also demonstrated localised reductions in NO_2 levels, underscoring the influence of large-scale events on local urban air quality, but the results from the London Marathon analysis suggest that the impact of these events remains very localised. The observed changes in NO_2 concentration provide a quantitative expectation for the reduction in NO_2 that might be expected if policies such as car free city days or similar initiatives to boost telecommuting were introduced in any given location and provide practical means for deriving an expected value in locations where the analysis has not been performed.

The results of this analysis demonstrate that there is very limited spatial homogeneity in the impact of relatively consistent behavioural changes on NO_2 concentration and this should be of considerable interest to air pollution policy practitioners and suggests that national level policy should have flexibility and account for local context. This result is important beyond the UK. The impact of holiday is different between different regions. Greater London, with its dense population and high traffic volumes, exhibited more pronounced reductions in NO_2 during holidays compared to other regions. There are many differences between London and the rest of the UK. These include a modern, multimodal and well-funded public transport network and strict clean air zone and congestion charging. Cycling infrastructure is also well funded meaning people may be more likely to choose active travel modes than in other areas where the cycling infrastructure is less well developed or other external differences such as weather, topography or attitude to cycling culture induce different travel mode choices. These factors significantly impact the transportation decisions made by people within the GLA and consequentially impact the local NO_2 concentration. There are also significant economic differences with 22% to 25% of the GDP created in London compared to $\approx$13.4% of the population. The access to more economic resource may impact the ability and/or desire for individuals to choose more environmentally friendly options when purchasing vehicles, or purchase newer vehicles more frequently, leading to faster fleet turnover and a higher percentage of the newest and cleanest vehicles on the road. These regional differences underscore the importance of localised air pollution mitigation strategies that take into account the both the needs of the population and the ability of the population to pay. Policies and interventions must consider the specific context and characteristics of each area to be effective. The results also suggest that while holidays and major events can lead to temporary reductions in air pollution, the broader trends driven by daily and seasonal patterns remain dominant. This indicates that long-term air quality improvements require sustained efforts beyond temporary reductions achieved during holidays.

This work demonstrates the value of big-data methods and modern forecasting tools in environmental research. The successful application of the Prophet model demonstrates its potential for broader applications in air quality management and other environmental studies. By providing a clear and repeatable method for analysing time-series data, this approach can be adapted to investigate other pollutants and environmental variables and has the potential to reveal presently unknown relationships in high temporal resolution environmental data sets. This paper contributes to a deeper understanding of how temporal variability and national holidays affect air pollution levels in the United Kingdom and shows how the impact of holidays and one-off events can be quantified in other contexts where high-resolution air pollution data is available. The results show the need for localised and context-specific air pollution mitigation policies. The methodological advancements presented here offer a valuable tool for future research, enabling more precise and targeted analyses of environmental data. As urbanisation and traffic demand continue to grow, such insights will be crucial for developing effective strategies to improve air quality and public health.

5. Future work

The methodology presented in this paper is flexible and transferrable to other research questions in the air pollution discipline and opens up multiple avenues for further study. This work reports results for NO_2 concentrations however there are direct measurements such as fine particulate matter ($PM_{2.5}$), ozone (O_3) and other volatile organic compounds, and aggregate statistics such as air quality index (AQI) that this method may also be applied to, given a sufficiently rich data set. Expanding the analysis to cover these extra species requires larger data sets than are currently publicly available in the UK. This methodology may also be used to determine the impact of short events such as short-term road closures, major accidents, and sports events on air pollution levels. This additional information will allow policy and programme designers to better assess the environmental impact of their plans.

This work may encourage other authorities to use time-series decomposition methods on their locally sourced data to gain greater insight into their locale. The method is transferrable beyond the demonstrated UK context and may be applied in any region where reliable air pollution concentration data and event data is available at hourly resolution. Lower resolution periodicities may be observed if hourly data is not available, but daily or monthly resolution data may be. The methodology can be expanded to include multi-day events. World Car Free Day is celebrated on 22 September with organised events being held in some cities and quantifying its impact on air pollution may be an interesting future use case of this methodology if high-quality air pollution and meteorological data is available.

This paper has some limitations that are worthy of discussing for future study. The analysis does not consider the weather conditions at the site. This is an important limitation as wind speed and wind direction can impact the concentration of NO_2 through the mechanism of street canyoning. Boundary layer effects may also influence the NO_2 concentration on any given day and this would not necessarily be captured by considering yearly weather trends alone. Whilst prevailing wind conditions may be generally extracted from local meteorological sites or modelled at the AURN site, there remains the potential for error to be added leading to incorrect results. This is of particular concern to the events which are one-off as they cannot have multiple examples to remove this effect. This paper mitigates this by extending the analysis over multiple years however researchers without access to an extended data set would be advised to ensure accurate and local meteorological data is introduced as an additional regressor to the Prophet model if replicating or extending this research.

Transport and air pollution adjacent problems may also be tackled using a robust and repeatable methodology. Additional data sets may be added to the analysis pipeline to shed further light on the links between air pollution and potential causal and resultant factors. For example, replacing holidays with known air pollution events and using these as trigger days in time-series data sets related to public health may allow for a higher confidence in the causal link between air pollution and negative health outcomes to be demonstrated, and in a more local context. If a causal link between air pollution and, for example, increased hospital admissions can be demonstrated then the consequences for air pollution research would be significant.

CRediT authorship contribution statement

Christopher E. Rushton: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **James E. Tate:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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