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Impact of SARS-CoV-2 variants on mobility and air pollution in the United Kingdom

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HIGHLIGHTS

- Wildtype SARS-CoV-2 had more impact on mobility and air pollution than alpha and delta variants.
- Majority of detected peak events in mobility and COVID-19 fall outside lockdown periods.
- The frequency of extreme records decreased with each dominant variant.
- NO2 continued depletion likely a result of reduced commuting.

ABSTRACT

During the two years following the first case of COVID-19 in the United Kingdom, cycles of social restrictions were imposed to control the spread of the virus. These measures curtailed social contact and halted commercial and recreational activities affecting levels of air pollutants. As society adapted, restrictions eased and pollution gradually returned to baseline levels. However, resurgence in COVID-19 cases from new variants created a protracted and challenging path back to ‘normality’. In this study, we retrospectively look back at the two years of COVID-19 and its prevalent variants, and examine the government response and its impact on mobility and air pollution. Results from a peak detection algorithm show peak events in mobility and COVID-19 deaths during variants periods decreased significantly from the wildtype COVID-19, despite the high contagiousness of these variants. Pollution levels remained below baseline with periods of significant increase for O3, while NO2 levels remained depleted, likely as a result of reduced traffic congestion as home office schemes have been maintained. Our findings suggest mobility and pollution return to baseline levels as immunity to COVID-19 increases.

1. Introduction

The worldwide measures administered to control the COVID-19 pandemic led to dramatic socioeconomic changes across the globe.

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As the spread of the virus was predominantly based on human close contact, mobility became an important indicator for prevention and to measure the implementation of social restrictions. Mobility restrictions were, at least initially, based on limited evidence of effectiveness (Oh et al., 2021). However, as cases spread throughout the world, reducing mobility from public gatherings and other non-essential activities was proven successful to decrease COVID-19 transmission (Tran et al., 2020). Restrictions in mobility fluctuated in response to the spread of novel variants of COVID-19, and the development of vaccines and gradual acquiescence of herd immunity influenced how lax or tight mobility restrictions were, as well as the community’s response.

In an effort to aid governments and researchers, technology companies such as Google and Apple disclosed their anonymised, aggregated mobility data. This represented an opportunity to trace pollution levels associated with anthropogenic activities. Numerous studies have quantified these changes in different countries, supported by monitored data and satellite imagery (Higham et al., 2021; Li and Tartarini, 2020; Broomandi et al., 2020; Jain and Sharma, 2020). Reductions in particulate matter (PM), nitrogen dioxide (NO2), and carbon monoxide (CO) were reported as a result of lockdown measures (Li and Tartarini, 2020; Bao and Zhang, 2020). In contrast, ozone (O3) recorded increments linked to changes in air chemistry and meteorological factors (Kerimray et al., 2020; Dantas et al., 2020; Xu et al., 2020). Research considering meteorological parameters confirms that reductions in mobility have had a significant effect; ‘de-weathered’ data (i.e., removing meteorological influence) has shown these significant decreases to be associated to changes in mobility (Mohajeri et al., 2021).

Considering how COVID-19, mobility, and air pollution interlace (Zalakeviciute et al., 2020; Filonchyk et al., 2020), we propose the effects of COVID-19 on the environment can be categorised by its variants and the specific measures to control them. In this study, we question if the most widespread COVID-19 variants showed significant differences in mobility restrictions and pollution. A similar approach was reported by Akter et al. (2022) in reviewing the indirect environmental effect of preventative measures to control the spread of different variants of COVID-19. To our knowledge, a linkage between control measures for each variant, environment and mobility variables has not been studied.

In this work we present a temporal distribution of social restrictions for the case of United Kingdom (UK), alongside COVID-19 historical cases, the surge of new variants, and vaccinations. The impacts of the pandemic and government decisions are then linked with pollution and mobility changes. The connections found in this study can be compared with findings from other regions around the world, to measure to what extent the societal and environmental responses to COVID-19 variants differed internationally.

2. Materials and methods

2.1. Data sources

COVID-19 data for the different regions of the UK were obtained from the official source UK Coronavirus Dashboard (GOV.UK, 2022). The observed metrics (as published in the dashboard) were: a) COVID-19 cases by specimen date (cases); b) people vaccinated by vaccination and published dates (all vaccines administered in the country), and c) daily national statistics office (NSO) deaths by death date (deaths). Information on COVID-19 variants and their prevalence for all available genotyped cases was obtained from the variants of concern technical briefing 32 (UKHSA, 2022a).

A record of events in the UK involving lockdown restrictions, was compiled from public records, news reports, and analysis of the Institute for Government (IFG, 2022), to quantify the effects of public health measures on mobility. These events are classified according to their potential impact on mobility as: a) new restrictions, b) restrictions lifted or eased, c) alerts announced by the government in media outlets, and d) positive news and encouraging messages to the citizens. This distinction was performed following on the IFG classification, and further expanded from a comprehensive analysis of public information. A full list of the considered events can be found in Appendix A.1.

Mobility records of 267 areas in the UK were sourced from Google Community Mobility Reports (Google LLC, 2022). Daily values were obtained for the categories:

- Retail and recreation (RTR)
- Grocery and pharmacy (GRP)
- Transit stations (TRS)
- Workplaces (WKP)
- Residential (RSD)

These aggregated, anonymised data show how busy certain places are based on the users with location history activated on devices with a Google account. The analysed categories represent, to an extent, the citizens’ behaviour in response to social restrictions. From the five categories presented, four (RTR, GRP, TRS, and WKP) indicate the number of visits to related places, such as restaurants, commercial centres, train stations, and office buildings. RSD, on the other hand, shows a change in the time spent at home. The baseline is the median value for the corresponding day of the week during the 5-week period of January 3rd to 6th February 2020. In addition, we considered the changes reported by the Department for Transport (DfT) in their COVID-19 transport use statistics (DfT, 2022). This dataset presents the change in traffic (TRF) from March 2020, as a percentage of the equivalent day in the first week of February 2020, for cars (CAR), light commercial vehicles (LCV) and heavy goods vehicles (HGV).

Pollution data were sourced from the Automatic Urban and Rural Networks (AURN) from the Department of Environment, Food and Rural Affairs (DEFRA). Ground-level measurements with 1-hour frequency were obtained for NO2, O3, PM10, and PM2.5. Meteorological data for temperature (TEM), relative humidity (RH), and wind speed (WS) were sourced from the Met Office MIDAS Land and Marine Surface Station Data.

2.2. Data analysis

To evaluate overall trends throughout the COVID-19 pandemic, daily averages were created from hourly data for weather and pollution variables, averaging all the data points from different locations (DEFRA and MIDAS stations, and mobility areas). COVID-19 data were aggregated nationally and compared against a two-year time series. To further analyse changes, z-score values are calculated for COVID-19, mobility, and pollution, following the formula:

\[
\text{baseline}_i = \frac{X_i - \mu_{\text{baseline}}}{\sigma_{\text{baseline}}}
\]

where \(X_{\text{baseline}}\) is the mean of values from baseline period, and \(\mu_{\text{baseline}}\) is standard deviation of values from baseline period. For pollution data, the baseline is derived by averaging daily measurements from 2017 to 2019 to create a 365-day array of values. This baseline is also used to calculate daily and yearly percentage changes in pollution levels during 2020 and 2021.

Furthermore, an identification of significant events was performed using a peak detection algorithm based on z-scores for real-time series data (Brakel, 2020) for the full details. For the detection of peaks, the studied variables were grouped in the following categories: a) COVID-19: cases and deaths, b) mobility: RTR, GRP, TRS, WKP, RSD, CAR, LCV and HGV, c) pollution: NO2, O3, PM10 and PM2.5, and d) weather: TEM, RH and WS. Following the peak identification, a resampling was performed based on the absolute values of the peaks separated in periods of three-months to account for seasonal differences. The dominant periods of COVID-19 variants were investigated spatially in contrast with pollution, weather, and mobility variables. To connect peak events with regions within the UK, a
3. Results and discussion

3.1. COVID-19 events & data

The standardised values for daily COVID-19 cases, mortality, and vaccinations are presented in Fig. 1a. As virus sequencing became widely available, it became possible to map distinct variants and their prevalence. The overall predominance, considering number of total cases, was held by the alpha variant within the sample of genotyped cases. The overall predominance, superseded in January 2022 by the variant omicron in January 2022 (UKHSA, 2021; UKHSA, 2022b).

Mortality from COVID-19 reached one of its highest points between March and May 2020 (Fig. 1a). Simultaneously, virus mutations led to the origin of the alpha variant, which caused about 50,000 cases per day in the winter 2020–2021. This wave in cases led to a second increase in mortality similar to the observed in spring 2020. The devastating effect of the alpha variant and an increase of cases after winter holidays, prompted the tightening of restrictions in January 2021. At the same time, new variants beta and gamma were detected in the UK, raising public concerns on the efficacy of the new-developed vaccines against novel changes in the virus sequence (Roberts, 2021). Favourably, most new variants composed a tiny fraction of cases in the country. However, the rate of infections resulted in another highly contagious variant: delta, in the summer of 2021.

Despite its high transmissibility, deaths from delta variant were less widespread than those from their predecessors, which reflected changes in the immunity of the population and the adaptation of social restrictions that prevented vulnerable people from contracting the virus. This was particularly protective when the omicron variant became dominant in December 2021, and cases rose to the highest level since the start of the pandemic. This meant daily cases of over 150,000 in late-December 2021 (UKHSA, 2022c). The results of the vaccination campaign, which by the 15th of December 2021 reached a coverage of 90.6 % of the first dose, 83.3 % of the second dose and 63.3 % of the population with a booster injection (UKHSA, 2022d), were reflected in a stark contrast between the pattern of cases and deaths reported by the NSO.

Fig. 1c shows a visual representation of events and actions to tackle the pandemic in the UK. These events were categorised based on their potential influence on mobility COVID-19 events by category. Hence, global and national announcements regarding the severity of the pandemic, without enforcing social restrictions, were considered alerts that could reduce social mixing. On the other hand, announcements preceding the easing of restrictions and success stories are classified as positive events that could lead to an increase in mobility. The first wave of deaths from the wildtype COVID-19 led to the implementation of the first national lockdown. As the death wave decreased, positive news and ease of restrictions took place, and a summer of relative ‘freedom’ was observed. Starting the autumn of 2020, a slight increase in COVID-19 cases was countered with new restrictions that continued until the beginning of December, when restrictions were eased to allow holiday celebrations. Cases quickly rose and restrictions were tightened by the end of 2020. Restrictions continued while another wave of cases and deaths was recorded in the winter 2020–2021. The first vaccination campaign materialised, becoming the first step of a roadmap to end restrictions presented in February 2021. By March 2021 the second wave of deaths had dissipated and consequently restrictions continued to lift throughout 2021. Alerts were issued in response to the omicron variant and a fourth wave of cases -in a more resilient, vaccinated population-took place, resulting in new restrictions that lasted a relative short period of time.
3.2. Mobility changes

The standardisation of mobility trends published by Google is presented in Fig. 2. The effects of events shown in Fig. 1c can be indirectly linked to mobility changes in Fig. 2a. Thus, events categorised as alerts or restrictions can be related to an increase in the time spent at home, reducing the values of the other categories. The most significant changes in mobility, signalled with max/min points in Fig. 2a, were observed during the first wave of cases with the wildtype SARS-CoV-2, and the alpha variant.

In the spring 2020, the first national lockdown recorded a significant increment in RSD. Initial restrictions focused on reducing social interaction in public spaces, encouraging companies to shift to home-office schemes, reducing WKP significantly. Similarly, leisure activities and public transport were reduced. This is supported by the COVID-19 transport statistics, with a 45 % reduction in traffic (TRF). Restrictions were lifted in most of the country in the summer of 2020, with the exception of local lockdowns in Leicestershire, and RSD returned to baseline levels while RTR, TRS, and WKP increased. Particularly, the increase in RTR was driven by the program Eat Out to Help Out, which aided the retail industry recovery after the first lockdown (HM Revenue & Customs, 2020). RSD increased significantly during the winter 2020–21, when the third wave of cases hit the UK and Tier-4 restrictions were implemented as the alpha variant became dominant. RSD went back to baseline levels during the spring of 2021 and reduced even further in the summer, after vaccines campaigning and easing of social restrictions. In contrast with RSD, RTR and WKP increased above the baseline levels, a trend that continued until December 2021, when alerts were issued, and restrictions were imposed to control the spread of the omicron variant. To compare the effects of restrictions between each dominant variant, mobility z-scores were averaged according to the periods of predominance:

- Wildtype: 31-January (first UK case) to mid-December 2020,
- Alpha: mid-December 2020 to May 2021, and
- Delta: June 2021 to mid-December 2021.

Hence, taking into account seasonal & yearly changes, mobility values from February 2020 (beginning of dataset) to May 2020 (P1-WT: wildtype 1st half) can be compared against alpha period a year later (P3-alpha: February to May 2021), and those from June to December 2020 (P2-WT: wildtype 2nd half) can be contrasted with delta period a year later (P4-delta: June to December 2021).

Fig. 2b shows the comparison of the two dominant variants versus P1-WT and P2-WT to evaluate the effects of restrictions of these two variants versus the measures taken for the original virus a year prior. As observed in Fig. 2a, mobility changes reached maximum points at the beginning of the pandemic. This is supported by an average of 1 z-score reduction in P1-WT, with traffic observing the lowest value. In contrast, RSD showed an increase of over 0.9 z-score on average. The highest reductions in mobility are recorded for P1-WT. Its equivalent period in 2021, P3-alpha, did not observe significant reductions, but increases over the baseline were only recorded slightly for GRP and TRF. These increases differed little from P2-WT, during which most categories, excepting TRF, remained slightly below the baseline. The equivalent period to P2-WT corresponds to P4-delta, during which cases increased considerably without reducing mobility. Unexpectedly, mobility values during this highly contagious variant were the highest recorded for all periods. This comparison highlights the importance of government measures to control the pandemic. After almost a year of successive strict restrictions, ‘lockdown fatigue’ hit the population, and by the end of 2021, the RSD category recorded values significantly above the baseline levels. As no sole factor influences mobility, the observed mobility changes are multifactorial phenomena involving social restrictions and public health, and the increased confidence and herd immunity from the vaccine administration also played a role in the ‘recovering’ of mobility.

3.3. Ground-level air pollution changes

UK nationwide pollution values are presented in Table 1, with a percentage change versus the baseline to estimate the effect of lockdown restrictions on air quality. The highest change (25.8 %) was observed for NO2 in 2020, followed by a reduction of 20.4 % in 2021. PM2.5 followed with a reduction of 10.8 % in 2020, and 11.0 % in 2021, a similar trend to PM10, while O3 levels increased significantly in 2020 (9.7 %) and remained above the baseline in 2021 (5.7 %).

The standardisation from baseline is presented in Fig. 3a. As reported in previous studies (Acosta-Ramírez and Higham, 2022; Abdullah et al., 2020), meteorology played a huge role in the regional air pollution during the pandemic (details of wind speed, relative humidity and temperature in the UK during each variant can be found in Appendix B1). However, the effects of a drastic reduction in mobility can be seen in the sudden changes during strict lockdown periods. One of the most dramatic changes reported globally was the reduction in NO2 following the decrease in anthropogenic activities, mainly traffic. In the UK, traffic accounts for 49 % of NOx emissions (DEFRA, 2004), and the first national lockdown with its consequent reduction in mobility is reflected in a 38 % reduction in NO2 recorded by DEFRA stations in 155 points across the UK. Levels of NO2 increased in proportion with the levels of traffic, and peaked in the winter of 2020–21, potentially related to winter production of NO2 (DEFRA, 2004). From the spring 2021, NO2 levels remained low despite an increase of traffic above baseline levels, which could be related to reduced traffic congestion as home

![Fig. 2. Mobility records from 2020 and 2021. (a) Standard scores (z-scores) with highlighted periods of dominance of alpha and delta variants. (b) Comparison of mobility changes during periods of wildtype and variants of SARS-CoV-2. Abbreviations detailed in Data sources.](image-url)
office was further promoted in workplaces (Gatenby, 2020). The patterns observed for \( O_3 \) show an inverse relationship with \( \text{NO}_2 \) that indicate the interaction between \( \text{NO}_2 \) and \( O_3 \). As reported by Jhun et al. (Jhun et al., 2015), \( \text{NO}_2 \) acts as a quencher of \( O_3 \) through \( \text{NO}_2 \) titration, and an increase in \( O_3 \) can be associated to a lower \( O_3 \) titration by \( \text{NO}_2 \). The periods of lowest \( \text{NO}_2 \) show the highest values of \( O_3 \) above the baseline. Increases in \( O_3 \) were analysed in other studies (Zoran et al., 2020) for its impact on respiratory symptoms. Aside from changes in \( \text{NO}_2 \), changes in temperature, wind, and relative humidity have been reported to associate with the observed increases in \( O_3 \) in the UK (Acosta-Ramírez and Higham, 2022). PM10 and PM2.5 show similar patterns throughout the two years of the pandemic. In the UK, fireplaces and stoves are considered the largest single source, with a 36% contribution, by DEFRA (2019). Thus, changes in residential mobility could impact the levels of regional PM. This is observed by contrasting the lockdown periods and increases in RSD presented in Fig. 3a with increases in PM10 and PM2.5. However, high variability is observed for both pollutants, which could be related to meteorology factors. Among other factors, wind speed has been found linked to PM distribution and deposition, thus, periods of high speed could result in transport and re-suspension of PM (Jones et al., 2010; Broomandi et al., 2022).

As discussed in Mobility changes, the emergence of highly contagious variants influenced the extent of social restrictions enforced in the UK. A comparison of the averaged standard scores for P1-WT and P2-WT versus P3-alpha and P4-delta is shown in Fig. 3b. The most significant reduction was recorded for \( \text{NO}_2 \) during P1-WT. The interaction with \( O_3 \) is noted as this period also observed the highest increase in \( O_3 \). However, meteorology factors such as sunlight and temperature might be involved in the excess production of \( O_3 \) (Jhun et al., 2015). Similarly, a remarkable increase in PM10 was recorded, linked to extreme wind speed events (Acosta-Ramírez and Higham, 2022). The period equivalent to P1-WT: P3-alpha, recorded levels for \( \text{NO}_2 \) close to baseline after exceedances recorded during the winter. This suggests that mobility changes of the first half of 2020 had more impact on the production of \( \text{NO}_2 \) than those recorded during P3-alpha. \( O_3 \) levels recorded a similar increase to the one observed a year prior, suggesting the role of meteorology in \( O_3 \) production, and a lesser role of \( \text{NO}_2 \) in the accumulation of \( O_3 \) during this particular period. Meanwhile, the period P2-WT covering the second half of 2020, records overall reductions in all pollutants. These values are a result of autumn and winter conditions interfering with the production and dispersion of pollutants, as well as reduced work-related-traffic as home-office became a more predominant scheme. However, mobility restrictions effect on pollution is also observed in P2-WT, as the equivalent period a year later (P4-delta & most restrictions lifted), recorded a slightly smaller reduction for all pollutants.

### Table 1

| Pollutant (\( \mu g/m^3 \)) | 2017 | 2018 | 2019 | 2020 | 2021 |
|-----------------------------|------|------|------|------|------|
| NO\(_2\)                     | 24.92| 23.81| 23.20| 17.39| 18.49|
| % change                    | 3.31 | 0.43 | -3.74 | -25.84 | -20.40 |
| \(O_3\)                      | 47.55| 50.24| 49.26| 52.79| 50.78 |
| % change                    | -2.65| 2.35 | 0.30 | 9.70 | 5.74 |
| PM2.5                       | 9.70 | 9.95 | 9.75 | 7.85 | 7.90 |
| % change                    | -1.23| 3.53 | -2.30| -10.82| -10.99|
| PM10                        | 15.50| 16.33| 16.32| 14.32| 14.10|
| % change                    | -3.28| 3.16 | 0.13 | -5.92| -7.29 |

3.4. Significant periods

To narrow down peak events during 2020 and 2021, we performed peak detection algorithm (Brakel, 2020). Detected signals are shown in Fig. 4a, where positive signals indicate significant increases above the mean and negative signals show significant decreases. A total of 369 absolute signals were identified in the 2-year period. Grouped variables reveal the majority of signals (43%) were detected for COVID-19 (cases, deaths, and vaccines), followed by 19% for traffic (CAR, LCV, HGV), pollution (\(\text{NO}_2\), \(O_3\), PM10 and PM2.5) with 17%, mobility (RTR, GRP, TRS, WKP and RSD) with 15%, and weather (TEM, WS, RH) with 7%. A frequency distribution reveals that the first trimester of 2020 recorded most of the peaks (24%), followed by the second trimester of 2020 (16%). The third trimester of 2021 recorded the lowest number of events (3%) and the remaining periods of both years recorded on average 11% of the total number of peaks.

Fig. 4a highlights the top 3 periods with peaks for each group of variables. The first group, COVID-19, recorded 66% of peaks during Jan-Mar & Oct-Dec 2020, followed by Jan-Mar 2021. Mobility recorded 65% of its signals in Jan-Mar 2020, Oct-Dec 2020, and Apr-Jun 2021. While traffic variables are related to mobility categories from Google, their top periods differed in 2020, as traffic recorded the majority of its peaks (68%) during Apr-Sep 2020 and Apr-Jun 2021, the latter period recorded a high number of peaks for both mobility and traffic. Interestingly, peaks in COVID-19 and mobility are more abundant in the periods outside of strict lockdowns, except for peaks in RTR, while pollution, traffic and weather peaks were abundant during the first national lockdown, and peaks in pollution were recorded during the second lockdown. By the third lockdown, peak frequency is reduced, indicating the recovery of all variables leading to a lesser detection of extreme events. On the other hand, pollution recorded 59% of its total peaks in Apr-Sep
2020 and Oct-Dec 2021; while 80 % of weather peaks were recorded in Apr-Jun 2020, Jan-Mar 2021, and Jul-Sep 2021.

Overall, the following categories share top periods:

– COVID-19 and mobility have 50 % and 51 % of their peaks, respectively, in Jan-Mar & Oct-Dec 2020. All COVID-19 signals are positive.

– Mobility and traffic share the period Apr-Jun 2021, with increase in RTR, LCV and HGV, as well as decreases associated with bank holidays.

– Pollution and traffic recorded 49 % and 39 % of their peaks, respectively, from Apr-Sep 2020. The majority of increases correspond to PM10 and PM2.5, as well as LCV.

– Weather recorded 28 % of its peaks, particularly increases in temperature and wind speed, in Apr-Jun 2020, matching with pollution top 1 period.

A comparison between variant periods is shown in Fig. 4b. Overall, the period with majority of peaks is P1-WT (131 absolute signals), followed by P2-WT (71), P3-alpha (37) and P4-delta (31), which reflects the adaptation of the society to the pandemic and the lifting of restrictions. Mobility categories recorded the most significant decreases during P1-WT, with a few positive signals regarding increases in RSD. The equivalent P3-alpha period recorded a small amount of decreases in mobility, with the majority of them related to bank holidays. On the other hand, pollution did not record significant peaks in this period. By contrasting with the values in Fig. 3b (higher standard scores on average for O3 and PM10), the lack of peaks detected during P3-alpha indicates that levels of pollution remained relatively constant through the weeks, and that their higher levels were not derived from isolated events. With regards to P2-WT, traffic increases accounted for more than 20 peak events, related to the reopening of the economy reflected in the increases in mobility during this period (RTR and TRS) and the demand of goods and services associated with LCV. This period recorded an increase in pollution peak events, particularly, related to PM2.5, followed by PM10. Decreases were also observed for these two pollutants, suggesting a relation with wind speed and pollutant dispersion. P4-delta recorded minimal number of peaks in mobility and weather, and a slight increase in pollution peak events. Pollution events were detected for NO2 and PM2.5 primarily, likely associated with winter conditions and anthropogenic sources (DEFRA, 2004; DEFRA, 2012).

3.5. Spatial distribution

To pinpoint the locations and potential sources of the peak events, a spatial representation was performed for P1-WT, P2-WT, P3-alpha and P4-delta. This representation was achieved by interpolating the data available from different locations within the UK: Google Mobility areas, local authorities COVID-19 data, and DEFRA stations. Mobility categories covering >70% of signals were selected: RTR, WKP, and RSD. These variables were contrasted with COVID-19 cases. Similarly, pollution data for NO2 and particulate matter were considered as they represented >90% of the recorded pollution increases.

3.5.1. COVID-19 and mobility changes

COVID-19 distribution of cumulative cases is shown in Fig. 5a-e. During P1-WT, the first wave of deaths was recorded and cases increased to reach over 250 thousand by May (UKHSA, 2022c). Hotspots were focused on Yorkshire and North East region and continued during P2-WT, however the scale increased drastically as cases reached 2 million by mid-December 2020, when alpha variant superseded wildtype SARS-CoV-2. During P3-alpha, hotspots remained in the largest cities of the UK and cases exceeded 4.5 million. Cases continued increasing during P4-delta variant, reaching 11 million by mid-December 2021, when delta was superseded by omicron (UKHSA, 2022b). Mobility changes during variant periods are presented in Fig. 5e-p. WKP (Fig. 5e-h) showed a significant reduction for the majority of the country during P1-WT. As companies adapted to a ‘new normality’ and home office became prevalent, WKP continued depleted during P2-WT.
with an average reduction of 35%. The most significant reduction was observed for London, Luton and Reading areas. By 2021, during P3-alpha, WKP continued depleted to a lesser extent (−26% on average), with more areas increasing visits to office spaces and hotspots in East Midlands and West Midlands. London area continued showing reductions 30%. This pattern remained during P4-delta, with hotspots expanding and through East Midlands, Wales, North West, and South West. RTR (Fig. 5i-l) was one of the hardest-hit by the pandemic. Of official closures of non-essential businesses were reflected in >50% reduction in RTR category during P1-WT. While some events eased restrictions and allowed businesses to recover (Fig. 1c), RTR continued depleted in P2-WT. After the deployment of vaccination campaigns in January 2021, the roadmap to lift restrictions was followed and P3-alpha recorded increasing levels of RTR. During P4-delta, most restrictions were lifted and RTR returned to -and exceeded- baseline levels, mostly on the coastal areas of North West and Wales, as well as Scotland, Cardiff, and Norwich. On the other hand, RSD (Fig. 5m-p) was expected to increase, as staying at home was the safest way of preventing the spread of COVID-19 on its early stages. During P1-WT RSD increased gradually, reaching its highest point in the first lockdown, with hotspots around London, Bristol, Edinburgh, and Glasgow. By P2-WT hotspots reduced in size, remaining London and Bristol and the majority of the country showing smaller increases in time spent at home. This is related to the easing of restrictions observed in Fig. 1c, and the increases on RTR and WKP. RSD continued reducing to reach baseline levels in the majority of the country during P3-alpha, however some areas remained with positive increases that averaged 7%. This trend continued during P4-delta, with London area remaining with increases in RSD, and an average increase of 6% in the country.

### 3.5.2. Pollution levels

The spatial distribution of pollution data is presented in Fig. 6. During P1-WT, NO₂ levels (Fig. 6a) were reduced across the country, while maintaining hotspots in the most densely populated areas (Glasgow, Edinburgh, Newcastle, Liverpool, Manchester, Sheffield, Birmingham, Cardiff, Bristol, and London). The drop of 38% in NO₂ versus the baseline is linked to traffic reduction and work-related mobility in urban areas (Calafio et al., 2022). Its equivalent period in 2021, P3-alpha, shows an increase on the size of the hotspots and levels of NO₂ surpassing 15 μg/m³, showcasing the impact of restrictions lifting. In contrast, PM2.5 and PM10 levels (Fig. 6e, i) were higher in the South East, South West and Midlands regions during P1-WT. Similarly, a connection between the temperature peaks (Fig. 4a) and PM could exist, promoting the photochemical reactions between precursors of PM2.5 (Wang and Ogawa, 2015). The meteorology role is supported by a similar distribution recorded on the P3-alpha with similar levels of PM2.5 and lower PM10. While no peak events in wind speed or temperature were found during P3-alpha, the peaks found in RH could indicate abrupt fluctuations that have been shown to have a positive correlation PM2.5 concentration (Zhang et al., 2017). P2-WT shows an increase in NO₂ around the hotspots observed in P1-WT, reflecting the reopening of the economy and the connections between densely populated cities and surrounding areas. As the economy continued reopening, NO₂ levels returned to -and exceeded- baseline levels, with an average country-wide value of 16 μg/m³. The same period in 2021, during P4-delta, observed increases in the size of hotspots in the south, covering more cities, and reductions

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**Fig. 5.** COVID-19 and mobility contour plots during each variant period. Multi-resolution cubic interpolation (Higham and Brevis, 2019). (a, e, i, m) P1-WT, (b, f, j, n) P2-WT, (c, g, k, o) P3-alpha, and (d, h, l, p) P4-delta. Changes in scale between variables highlighted with grey frame. Abbreviations detailed in section Data sources.
in the hotspots in the north. The shrinking of some NO₂ hotspots in P4-delta is likely related to the overall reductions in NO₂ levels shown in Fig. 3b.

PM levels showed a different distribution during P2-WT, with PM2.5 levels higher around South East region, particularly London area, and hotspots in Sheffield and Leeds, while the lowest levels were recorded around Edinburgh. PM10 recorded smaller hotspots than PM2.5, including the cities of Swansea, Cardiff, Bristol, London, and Southend-on-Sea, as well as some areas in East Midlands and Yorkshire. A year after, during P4-delta, PM10 shows a similar distribution of pollution. The only hotspot in PM10, for both P3-alpha and P4-delta, was recorded on Swansea, which could be related to the increase of traffic reported in Fig. 2b, as the Swansea station is located near a busy dual-carriage way. It is noteworthy that surrounding roads underwent comprehensive roadworks during P4-delta, potentially affecting traffic and pollution levels on this particular site (DEFRA, 2022; Harries, 2021).

4. Conclusions

Initial UK lockdown restrictions led to significant changes in mobility related to workplaces, recreational activities and time spent at home. These changes resulted in traffic declines, and influenced domestic energy consumption and anthropogenic sources of pollution, ultimately affecting air quality. The most significant reductions in mobility within workplaces and traffic were observed during the first period, wildtype SARS-CoV-2. Peak event frequency reduced as the pandemic progressed, with mobility returning to baseline levels in response to fewer and shorter social restrictions while delta variant recorded the highest number of cases before omicron. Meanwhile, mortality decreased in response to increased immunity of the population. This strengthened resilience prompted the return to baseline levels of mobility with a reduction of 90 % in mobility peaks during delta in contrast with its counterpart SARS-CoV-2 wildtype.

The majority of peak events in pollution correspond to particulate matter, particularly PM2.5, whose peaks intercalate with isolated wind speed increases. Pollution peaks share significant periods with traffic, with peaks from light commercial vehicles likely related to an increased demand in goods and services, including home deliveries. Particulate matter hotspots are located in the south of the UK, associated with regional meteorology, while NO₂ hotspots are located within the largest cities, with overall expansion during alpha variant and peak increases during delta. While winter episodes of increase were recorded in an inverse relationship with O₃, an overall depleted NO₂ concentration continued as a result of reduced commuting and traffic congestion. Pollution levels fluctuated significantly between variant periods, but their hotspot locations remained static, revealing a spatial-dependent characteristic that could be linked with regional meteorology and population density.

In essence, as the pandemic developed and new variants arose, the relationship between air quality and COVID-19 became less apparent. Our findings suggest that this relationship resulted from a combination of public and private measures and, ultimately, the communities’ response. As the general public adapted to live with the virus, mobility slowly and steadily increased, although sudden outbreaks had effect. While this paper demonstrates the impact of wildtype SARS-CoV-2 with short-term improvements of air quality, it further poses the questions: was this a one-off event? And now that the government and general public have learnt from the pandemic, will adaptations such as home office remain?

CRediT authorship contribution statement

C. Acosta-Ramírez: Investigation, Methodology, Data curation, Formal analysis, Visualisation, Software, Writing - original draft. J.E. Higham Conceptualisation, Writing - review & editing, Supervision.

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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### Appendix A. COVID-19 events by category

| Date          | Event                                           | Category                      |
|---------------|-------------------------------------------------|-------------------------------|
| 31/12/2019    | First cases Wuhan                              | Alert announcement            |
| 30/01/2020    | NCOV-19 declared PHEIC                         | Alert announcement            |
| 16/03/2020    | Stop non-essential travel                      | Restrictions introduced       |
| 23/03/2020    | First lockdown UK                              | Restrictions introduced       |
| 25/03/2020    | Coronavirus Act 2020                           | Alert announcement            |
| 26/03/2020    | Measures come into force                       | Restrictions introduced       |
| 16/04/2020    | Lockdown extended                              | Restrictions introduced       |
| 30/04/2020    | Prime minister announces ‘we are past the peak’| Positive announcement        |
| 10/05/2020    | Conditional plan lifting lockdown               | Restrictions eased            |
| 01/06/2020    | Phased reopening schools                        | Restrictions eased            |
| 15/06/2020    | Non-essential shops reopen England             | Restrictions eased            |
| 25/06/2020    | Relaxing 2 meters social distancing rule       | Restrictions eased            |
| 29/06/2020    | Local lockdown in Leicestershire               | Restrictions introduced       |
| 04/07/2020    | UK first local lockdown comes into force       | Restrictions introduced       |
| 04/07/2020    | More easing of restrictions in England         | Restrictions eased            |
| 18/07/2020    | Local authorities can enforce social distancing | Alert announcement           |
| 11/05/2020    | People advised to wear face coverings          | Alert announcement            |
| 28/05/2020    | Test and tracing systems go live               | Alert announcement            |
| 03/06/2020    | Eat Out to Help Out                            | Restrictions eased            |
| 14/06/2020    | Restrictions eased further                      | Restrictions eased            |
| 14/09/2020    | Rule of six                                    | Restrictions introduced       |
| 22/09/2020    | New restrictions in England                    | Restrictions introduced       |
| 30/09/2020    | More restrictions                              | Restrictions introduced       |
| 14/10/2020    | Three tier system                              | Restrictions introduced       |
| 05/11/2020    | Second national lockdown                        | Restrictions introduced       |
| 01/09/2020    | Majority schools England reopen                 | Restrictions eased            |
| 31/10/2020    | UK reaches 1 million COVID-19 cases             | Alert announcement            |
| 24/11/2020    | Three households can meet                      | Restrictions eased            |
| 02/12/2020    | Second lockdown ends & England goes into strict 3-tier | Restrictions introduced |
| 15/12/2020    | PM says Christmas rules will be relaxed        | Positive announcement        |
| 19/12/2020    | Tougher restrictions for some areas            | Alert announcement            |
| 21/12/2020    | Tier 4 comes into force                        | Restrictions introduced       |
| 26/12/2020    | More areas into Tier 4                         | Restrictions introduced       |
| 04/01/2021    | Restrictions will tighten                      | Alert announcement            |
| 06/01/2021    | Third national lockdown                         | Restrictions introduced       |
| 15/02/2021    | Hotel quarantine                               | Restrictions introduced       |
| 22/02/2021    | Roadmap to end lockdown                        | Positive announcement        |
| 08/03/2021    | Schools in England reopen                       | Restrictions eased            |
| 29/03/2021    | Outdoor gatherings 6 people allowed             | Restrictions eased            |
| 12/04/2021    | Non-essential shops reopen                     | Restrictions eased            |
| 17/05/2021    | 30 people allowed to mix outdoors              | Restrictions eased            |
| 14/06/2021    | Last step to lifting lockdown delayed           | Alert announcement            |
| 19/07/2021    | Most legal limits on social contact removed     | Restrictions eased            |
| 14/09/2021    | England's winter plan for COVID                 | Alert announcement            |
| 08/12/2021    | Plan B against Omicron                         | Alert announcement            |
| 10/12/2021    | Face masks compulsory                          | Restrictions introduced       |
| 15/12/2021    | COVID pass mandatory                           | Restrictions introduced       |

Fig. A.1. List of events considered as potential influencing factors in mobility behaviour in the UK.
Appendix B. Meteorology patterns

Fig. B.1. Meteorology records from 2020 and 2021. (a) Standard scores (z-scores) from baseline with highlighted periods of dominance of alpha and delta. (b) Comparison of meteorology variables during periods of wildtype and variants of SARS-CoV-2.

Fig. B.2. Meteorology contour plots during each variant period. Multi-resolution cubic interpolation (Higham and Brevis, 2019). (a, e) P1-WT, (b, f) P2-WT, (c, g) P3-alpha, and (d, h) P4-delta.

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