Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
The effect of COVID-19 lockdown on atmospheric total particle numbers, nanoparticle numbers and mass concentrations in the UK

Said Munir a,*, Haibo Chen a, Richard Crowther b

a Institute for Transport Studies, Faculty of Environment, University of Leeds, Leeds, LS2 9JT, UK
b Team Leader (Environmental Advisory), Transport Strategy, Leeds City Council, Leeds, LS1 1UR, UK

ARTICLE INFO

Keywords:
- Nanoparticles
- Total particle number
- COVID-19 lockdown
- PM 10 and PM 2.5
- Machine learning

ABSTRACT

The main aim of the COVID-19 lockdown was to curtail the person-to-person transmission of COVID-19. However, it also acted as an air quality intervention. The effect of the lockdown has been extensively analysed on NO 2, O 3, PM 10 and PM 2.5, however, little has been done on how total (TPN) and nanoparticle numbers (NPN) have been affected by the lockdown. This paper quantifies the effect of the lockdown on TPN and NPN in the UK, and compares how the effect varies between rural, urban background and traffic sites. Furthermore, the effect on particle numbers is compared with particle mass concentrations, mainly PM 10 and PM 2.5. Two approaches are used: (a) comparing measured levels of the pollutants in 2019 with 2020 during the lockdown periods; and (b) comparing the predictions of machine learning with measured concentrations using business as usual (BAU) scenario during the lockdown period. P 100 (particle size ≤ 100 nm) increased by 39% at Chilbolton Observatory (CHO) and decreased by 13% and 14% at London Honor Oak Park (LHO) and London Marylebone Road (LMR), respectively. Particles from 101 to 200 nm (P 200) showed a similar trend to P 100, however, average levels of particles 201–605 nm (P 605) decreased at all sites. TPN, PM 10 and PM 2.5 concentrations decreased at LMR and LHO sites. Estimated PM 10, PM 2.5 and TPN decreased at all three sites, however, the amount of change varied from site to site. Pollutant concentrations increased back to pre-pandemic levels, suggesting more sustainable interventions for permanent air quality improvement.

1. Introduction

Air pollution is a serious environmental issue affecting human health globally, especially in large urban areas. According to Lelieveld et al. (2020), air pollution contributed to 8.8 million deaths worldwide in 2015. Air pollution is reported to affect lung function, cause respiratory infections, aggravate asthma, and result in ischaemic heart disease, stroke and neurodegenerative conditions (WHO, 2021; Landrigan, 2017). Long-term exposure to air pollution affects people of all ages, however, it is particularly harmful to the young, elderly and people with existing health conditions (Khallaf, 2011).

To decrease the adverse effect of air pollution on human health, various interventions are implemented from time to time to cut emissions and reduce atmospheric concentrations of air pollutants in urban areas. Normally, in the UK air quality interventions are implemented at the scales of local authorities. According to the Department for Environment, Food and Rural Affairs (DEFRA, 2020), an air quality intervention is a deliberate measure aimed at improving air quality. An intervention may be primarily aiming at other outcomes but it could also indirectly affect air pollution. The COVID-19 pandemic provided an opportunity for such an intervention. To curtail the person-to-person transmission of COVID-19, the UK government implemented a lockdown on March 26, 2020, which acted as a national intervention for air quality in the UK. The lockdown restrictions included: (a) people to stay at home, except for limited purposes; (b) closing of all non-essential businesses and public venues (including community centres, libraries, and places of worship); and (c) stopping all gatherings of more than two people in public (Jephcote et al., 2021). Due to restrictions on mobility road traffic decreased abruptly and monthly-average daily traffic counts on English A-roads and motorways in April 2020 were down by 69% compared with April 2019, with a 74% reduction in light and a 35% reduction in heavy vehicles (coaches and HGVs) (Jephcote et al., 2021). Therefore, the COVID-19 lockdown improved air quality in major cities in the UK and elsewhere (e.g., Shi et al., 2021; Dacre et al., 2020; Munir...
The focus of most of the studies analysing the effect of COVID-19 lockdown on air quality has been on NO2. Brown et al. (2021) analysed the levels of NO2 concentrations at air quality monitoring stations within a distance of 500 m of nurseries, primary schools, secondary schools and colleges in England. They reported that NO2 concentrations had decreased during lockdown by 35% and 41% in the UK at background and traffic sites, respectively. According to Dacre et al. (2020) the largest decreases in NO2 concentrations associated with reduced emissions were found in urban traffic (27%) and urban background sites (14%), where NO2 concentrations were representative of local areas and thus dominated by local reduction in emissions from vehicles. Dacre et al. (2020) also reported that NO2 levels even increased at some rural and remote sites, where NO2 measurements were representative of large areas and thus dominated by the regional advection of secondary NO2 from Europe. Mohajeri et al. (2021) analysed the concentrations of NO2 and PM2.5 in four cities in the UK and reported that NO2 levels decreased by 21% in Greater London, 19% in Cardiff, 27% in Belfast and 41% in Edinburgh. The levels of PM2.5 increased by 7% in Greater London, and decreased by 1% in Cardiff, by 15% in Edinburgh and by 14% in Belfast. The reported reduction was greater in NO2 than in PM2.5 levels, which was probably because PM2.5 was also affected by non-exhaust regional sources. Also, the lockdown period was accompanied by a period of hot dry weather and easterly winds, which was likely to increase resuspension and import of PM from Europe (Munir et al., 2021). They attributed the reductions in pollutant levels to the mobility restrictions imposed by the COVID-19 lockdowns. Similarly, Higham et al. (2021) reported that NO2 concentration decreased by about 50%, whereas O3 concentration increased by 10% during the lockdown period. Jephcoat et al. (2021) analysed measurements from 129 monitoring stations in the UK and reported mean reductions of 38.3% in NO2 and 16.5% in PM2.5, whereas a positive gain of 7.6% was reported in O3 concentrations. According to their analysis, the reduction in NO2 and PM2.5 concentrations was largest at urban traffic sites and modest at the background and rural sites across the UK.

Solberg et al. (2021) analysed the effect of the lockdown measures on NO2 in Europe and reported the largest NO2 reductions in Spain, France, Italy, Great Britain and Portugal and the smallest in eastern countries (Poland and Hungary). In addition to NO2, several authors have studied the lockdown effect on ground levels ozone (O3) and PM2.5. Previously, Dunka et al. (2020), Jain and Sharma (2020), Ganguly et al., (2021), and Kumar et al. (2020) analysed the effect of lockdown on several air pollutants including PM10 and PM2.5 in India and reported considerable reduction in their concentrations. Similarly, Donzelli et al. (2021) analysed the effect of lockdown on particulate matter in Italy, Grivas et al. (2020) in Greece, Tobias et al. (2020) in Spain, and Shi et al. (2021) compared the effect of lockdown in Italy, Spain, UK, France and Germany.

Although several studies have analysed mass concentrations of PM10 and PM2.5, no study was found in the UK that focused on the effect of COVID-19 lockdown on total particle numbers (TPN) and nanoparticle numbers (NPN). This is probably due to two main reasons: (a) the data availability problem – hourly concentrations of gaseous pollutants (e.g., NO2, NO, CO, and O3) and mass concentrations of PM10 and PM2.5 are available abundantly throughout the UK, however, the data of TPN and NPN is very limited. Hourly data of TPN and monthly data of NPN were only available from three sites for the lockdown period in the UK. (b) Air quality standards according to the Air Quality Standards Regulations (AQRS) of 2013. PM10 and PM2.5 are among the regulated outdoor air pollutants, whereas TPN and NPN are not regulated. Therefore, measurements of particle number concentration are not mandatory. Although evidences suggest that particle number concentrations are probably more relevant from public health perspectives (AQEG., 2012). Nanoparticles (particle diameter <100 nm), also known as ultrafine particles are smaller in size with a much larger surface area per unit mass than the fine and coarse particles (PM2.5 and PM10). The human body inflammatory response to particles has a strong correlation with particle surface area, rather than with particle mass (Sager and Castranova, 2009). Nanoparticles can pass through the lungs alveolar membrane and reach the cardiovascular system, where they may cause toxic effects (Oberdorster et al., 2004). Therefore, nanoparticles are considered more harmful to human health due to their large surface area and tiny size. Unlike PM2.5 and PM10, the mass of a sample of nanoparticle is too small to be measured accurately by normal PM measuring methods. Ultrafine particles are, therefore, not generally measured as a mass concentration “PM0.1” in μg/m3 and are rather typically characterised by their particle number concentrations or particle number counts in units of particles per cubic centimetre (particles/cm3) or μm3 or ppm3. The main objective of this paper are: (a) To quantify the effect of COVID-19 lockdown on TPN and NPN in the UK. (b) Compare the effect of COVID-19 lockdown on NPN and TPN with PM10 and PM2.5. (c) How the effect of COVID-19 lockdown on particulate matter varies between rural, urban background and traffic sites. In this study, we used two main approaches: (a) comparing measured levels of PM10, PM2.5, TPN and NPN in 2019 with 2020 for the months when COVID-19 lockdown was in place; and (b) Employing a machine learning approach, which was used to predict the levels of these pollutants for the lockdown period in Business As Usual (BAU) scenario, and the predicted concentrations were compared with the measured levels. The model predictions are basically weather corrected pollutant concentrations, which are important for understanding the real change caused by changed in emission after removing the effect due to changes in meteorological conditions.

2. Methodology

The main aim of this paper is to analyse the effect of COVID-19 lockdown on NPN (particles/cm3), TPN (particles/cm3) and particle mass concentration of PM10 (μg/m3) and PM2.5 (μg/m3) at several air quality monitoring stations using measured and weather corrected concentrations. Meteorological data of several parameters were used from the air quality monitoring stations and from London Heathrow Airport meteorological station. The meteorological parameters used were: air temperature (temp, °C), wind speed (ws, m/s), wind direction (wd, degrees from the north), relative humidity (rh, %), atmospheric pressure (P, millibars), visibility (vis, m), precipitation (precip, mm), ceiling height (m) and dew point (dp, °C). Hour of the day (hour), day of the week (wday) and day of the year (yday) were also used to account for diurnal, weekly and seasonal variations. Julian day was used in the model to account for long term change in pollutant levels.

2.1. Air quality and meteorology data

Data of NPN was available only in monthly resolution from five air quality monitoring stations: Chilbolton Observatory, Harwell, London Honor Oak Park, London N. Kensington, and London Marylebone road. Hourly data of TPN was also available from these five sites plus Birmingham Tyburn as shown in Table 1. However, three of the sites, namely, Birmingham Tyburn, Harwell and London N. Kensington did not have data of both NPN and TPN for 2019 and 2020, and therefore were not considered for further analysis in this paper. Hourly data of mass concentrations of PM10 and PM2.5 were available for over 60 sites in the UK. All these sites also provide modelled temperature, modelled wind speed and modelled wind direction data derived from the WRF model. However, PM10 and PM2.5 data were only analysed for the sites where NPN and TPN data was available. Data of the other weather parameters (rh, P, dp, precip, vis, and ceiling height) was obtained from the London Heathrow Airport (51.479, −0.449, 25 m above mean sea level (amsl)). More details of the monitoring sites are provided in Table 1. Fig. 1 shows the air quality and meteorological stations from which data was used in this study.
2.2. Measurement techniques

Hourly TPN concentrations were measured using condensation particle counters (CPCs), TSI model 3772-CEN at Chilbolton, Honor Oak Park and Marylebone Road (AQEG, 2018). These CPCs are sensitive to particles from about 7 nm up to several μm in size and have a concentration measurement range from zero to 50,000 particles/cm$^3$. The TSI model 3773-CEN has been developed to comply with the requirements of CEN/TS 16976:2016. At all concentrations, each particle is counted individually. Particle size distributions were measured using a Scanning Mobility Particle Sizer (SMPS). This consists of a CPC (TSI model 3775) combined with an electrostatic classifier (TSI model 3080). Reference equivalent method Filter Dynamic Measurement System (FDMS) was used for measuring PM$_{10}$ and PM$_{2.5}$ at these sites, which is allowed for regulatory purposes (AQEG, 2012).

2.3. Data analysis and modelling

2.3.1. Nanoparticles, total particle numbers and mass concentrations

Monthly NPN data were downloaded from the three air quality monitoring stations: London Marylebone Road, London Honor Oak Park, and Chilbolton Observatory (Fig. 1). NPN were measured in the particle size diameter (nm) of 16.6, 17.8, 19.2, 20.6, 22.1, 23.7, 25.4, 27.4, 29.5, 31.7, 34.9, 36.6, 39.3, 42.2, 45.3, 48.7, 52.4, 56.3, 60.5, 65.0, 69.8, 75.1, 80.6, 86.7, 93.1, 107.5, 115.5, 124.1, 133.4, 143.3, 154.0, 165.5, 177.9, 191.2, 205.4, 220.7, 237.2, 254.9, 273.9, 294.3, 316.3, 339.9, 365.3, 392.5, 421.8, 453.3, 487.1, 523.4, 562.4, and 604.3. For convenience the different size ranges were aggregated into three main groups: (1) particle size $\leq$ 100 nm (P$_{100}$), (2) particle size between 101 and 200 nm (P$_{200}$), and (3) particle size between 201 and 605 nm (P$_{605}$).

As given in Table 2, the number of particles was greatest in P$_{100}$ range at all three sites with mean levels (particles/cm$^3$) of 8236, 3291 and 2156 at London Marylebone Road, London Honor Oak Park and Chilbolton Observatory, respectively. The mean P$_{200}$ ranged from 399 to 972 and P$_{605}$ ranged from 121 to 287 (Table 2). This clearly shows that most of the particles exist in the smaller particle size (P$_{100}$).

A summary of the NPN, TPN, PM$_{2.5}$ and PM$_{10}$ is presented in Table 2, showing mean concentration...
concentrations along with their standard deviations for 2019. Concentrations of all three pollutants were highest at London Marylebone Road, followed by London Honor Oak Park. The lowest levels were observed at the Chilbolton Observatory site. London Marylebone road is a busy urban traffic (roadside) site, London Honor Oak Park is an urban background site, and Chilbolton Observatory is a rural background site, which explains why particles pollution was highest at London Marylebone road and lowest at the Chilbolton Observatory site.

2.3.2. Machine learning techniques

Machine learning approaches are frequently used to evaluate the effect of different interventions on air quality in urban areas (Jephcote et al., 2021; Solberg et al., 2021). Since the beginning of the COVID-19 pandemic in late 2019, numerous studies using machine learning approaches have been published, which assessed the effect of the lockdown on air quality in urban areas in the UK and worldwide (e.g., Jephcote et al., 2021; Solberg et al., 2021; Shi et al., 2021; Collivignarelli et al., 2020). Several researchers have preferred to employ Generalise Additive Model (GAM) for such analysis as it is an interpretable supervised machine learning technique, easy to apply, and able to address the nonlinear association between the response and predictor variables (Wood, 2006, 2020; Hastie and Tibshirani, 1990). The performance of GAM is comparable to any other advanced machine learning technique, for example, Boosted Regression Trees, Random Forest and neural network (Solberg et al., 2021; Ropkins and Tate, 2021; Munir et al., 2021; Carslaw et al., 2007). Therefore, here we employed a GAM to assess how the COVID-19 lockdown has affected the levels of TPN, PM$_{10}$ and PM$_{2.5}$ in the UK. No hourly data of NPN was available, therefore, we could not model the levels of NPN.

2.3.3. Model development and validation

To model PM$_{10}$, PM$_{2.5}$ and TPN, here we used several predictors including both meteorological and temporal parameters, following the methodology of the previously published papers (e.g., Jephcote et al., 2021; Solberg et al., 2021; Shi et al., 2021). Meteorological parameters used in the models were temperature (temp, °C), wind speed (ws, m/s), win direction (wd, degree from the north), relative humidity (rh,%), atmospheric pressure (P, millibars), visibility (vis, m), dew point (dp, °C), precipitation (precip, mm), and ceiling height (ceil_hgt, m), which is the height above ground level of the lowest cloud or any other obscuring phenomena layer. Temporal parameters were hour of the day (hr), day of the week (dweek), and day of the year (yday) to represent daily, weekly and annual variations in pollutant levels. Julian day was included to account for long-term temporal trend.

It should be noted that ws, wd and temp data was available from the air quality monitoring stations, whereas the data of the other meteorological parameters were obtained from the Heathrow airport meteorological station.

GAM (PM$_{10}$ ~ s1 (ws) + s2 (wd) + s3 (temp) + s4 (P) + s5 (rh) + s6 (vis) + s7 (dp) + s8 (precip) + s9 (ceil_hgt) + s10 (hour) + s11 (dweek) + s12 (dyear) + s13 (yday))

(1)

GAM (PM$_{2.5}$ ~ s1 (ws) + s2 (wd) + s3 (temp) + s4 (P) + s5 (rh) + s6 (vis) + s7 (dp) + s8 (precip) + s9 (ceil_hgt) + s10 (hour) + s11 (dweek) + s12 (dyear) + s13 (yday))

(2)

GAM (TPN ~ s1 (ws) + s2 (wd) + s3 (temp) + s4 (P) + s5 (rh) + s6 (vis) + s7 (dp) + s8 (precip) + s9 (ceil_hgt) + s10 (hour) + s11 (dweek) + s12 (dyear) + s13 (yday))

(3)

The above three GAM models (1, 2 and 3) are used to model PM$_{10}$, PM$_{2.5}$ and TPN, respectively using several predictors. In equations (1)–(3), the terms s1 to s13 are the smoothing nonparametric functions, which relate the modelled variables with the explanatory variables. The models were fitted on randomly selected 75% training data and validated on 25% randomly selected testing data from monthly measurements of 2018–2019. Correlation coefficients (r - values) and Root Mean Squared Error (RMSE) for both trained (fitted) and cross-validated models were calculated for assessing the model goodness of fit.

2.3.4. Modelling BAU scenario

For predicting the levels of PM$_{10}$, PM$_{2.5}$ and TPN in the BAU scenario for the lockdown period, the models were fitted on 2018–2019 data and then used to predict these pollutants for March, April and May 2020. In the BAU scenario, local emission sources continue to operate as normal under the meteorological conditions observed during the lockdown period. These forecasts allow for a direct comparison with the measured data. The estimated concentrations could be considered as weather corrected, deweathered, normalised or adjusted for meteorological variability concentrations.

2.3.5. Software and packages

All data analysis and the implementation of machine learning models were performed in R programming language (R Core Team, 2021) using its core packages and several independent packages. The package ‘mgcv’ (Wood, 2020) was used to implement the GAM model, ‘openair’ (Carslaw, 2021a) was used to download air quality data and calculate correlation coefficient and RMSE for model assessment, ‘lubridate’ (Spinu, 2021) was used to edit date and add temporal variables to the dataset, and ‘worldmet’ (Carslaw, 2021b) was used to download meteorology data from the London Heathrow Airport weather station.

3. Results and discussion

3.1. Comparison of the measured data

To calculate how NPN was affected during the COVID-19 lockdown, NPN in 2019 was subtracted from those in 2020. Therefore, a positive difference indicated an increase, whereas a negative difference indicated a decrease in the number of nanoparticles during the lockdown period. Change in the number of nanoparticles during March, April and May are shown in Table 3 for the three monitoring sites. P$_{100}$ have increased by 13%, 46%, and 58% in March, April, and May, respectively at Chilbolton Observatory. In contrast, P$_{100}$ have decreased at London Honor Oak Park by 29%, 2%, and 7% and at London Marylebone Road by 18%, 15% and 9% in March, April and May, respectively. P$_{300}$ have shown a similar pattern to P$_{100}$ i.e. their number has increased at Chilbolton Observatory and decreased at London Honor Oak Park and London Marylebone Road sites. However, P$_{600}$ have shown slightly different results than P$_{100}$ and PM$_{2.5}$, as shown in Table 3 that in addition to London Hoor Oak Park and London Marybone Road, P$_{600}$ have decreased even at the Chilbolton Observatory site in April and May. On average, the number of particles has increased at the rural sites and decreased at the urban background and urban traffic sites. When we averaged changes in particle numbers for the three sites, the rural sites showed positive gains, background site showed reductions, and urban traffic showed higher reductions. The reason for this is that particle numbers at urban traffic (roadside) sites are controlled by the local
than at the rural site (CHO). Furthermore, P<sub>CHO</sub> showed that NPN has decreased more at urban traffic (LMR) site during 2020 for the lockdown period. Reduction in the ratio of LMR/lockdown. Fig. 2 clearly showed that the ratios at all sites decreased to Chilbolton Observatory (LHO/CHO) for the period of COVID-19 changes during the COVID-19 lockdown.

Again, this shows that P<sub>100</sub> are strongly related to the direct emissions from road traffic, whereas relatively larger size particles are of secondary nature i.e. secondary particles formed in the atmosphere (Rivas et al., 2020). Furthermore, P<sub>100</sub> demonstrated a greater reduction at urban traffic and urban background sites than at rural sites as shown by the ratios of LMR/CHO and LHO/CHO. This is because the levels of P<sub>100</sub> are strongly related to the direct emissions from road traffic, whereas relatively larger size particles are of secondary nature i.e. secondary particles formed in the atmosphere (Rivas et al., 2020). Furthermore, the average ratios of P<sub>100</sub>/P<sub>200</sub> (10.10) and P<sub>100</sub>/P<sub>605</sub> (37.05) were highest at London Marylebone Road, followed by London Honor Oak Park, where the ratios of P<sub>100</sub>/P<sub>200</sub> and P<sub>100</sub>/P<sub>605</sub> were 6.8 and 22.25, respectively, whereas the lowest ratios of P<sub>100</sub>/P<sub>200</sub> (6.00) and P<sub>100</sub>/P<sub>605</sub> (21.45) were observed at Chilbolton Observatory sites. Again, this shows that P<sub>100</sub> are in much larger proportion at urban traffic sites than at urban background and rural sites (Fig. 3), indicating emissions from road traffic.

Changes in TPN, PM<sub>10</sub> and PM<sub>2.5</sub> during the lockdown period were calculated by subtracting their levels in 2019 from those in 2020 (Table 4). Both PM<sub>10</sub> and PM<sub>2.5</sub> levels have decreased in all 3 months at London Marylebone road and London Honor Oak Park sites, except PM<sub>2.5</sub> in May at London Honor Oak Park site. Chilbolton Observatory showed slightly different results, where both PM<sub>2.5</sub> (22.80%) and PM<sub>10</sub> (9.10%) levels decreased in April and increased in March and May (Table 4). TPN also decreased in April at London Marylebone road and London Honor Oak Park sites. Overall, PM<sub>10</sub> and PM<sub>2.5</sub> decreased 30% emission sources, for example, emissions from the road traffic and because road traffic flow was decreased on roads in London, this directly affected the levels of NPN. Particle numbers at urban background sites are affected by the city scale emissions, whereas particle numbers at rural sites are affected by the regional scale emissions. Therefore, particle numbers at different types of environment demonstrated different changes during the COVID-19 lockdown.

Fig. 2 shows the ratio of different particle size at (a) London Marylebone road to Chilbolton Observatory (LMR/CHO), (b) London Marylebone to London Honor Oak (LMR/LHO), and (c) London Honor Oak to Chilbolton Observatory (LHO/CHO) for the period of COVID-19 lockdown. Fig. 2 clearly showed that the ratios at all sites decreased during 2020 for the lockdown period. Reduction in the ratio of LMR/CHO showed that NPN has decreased more at urban traffic (LMR) site than at the rural site (CHO). Furthermore, P<sub>100</sub> demonstrated a greater reduction at urban traffic and urban background sites than at rural sites as shown by the ratios of LMR/CHO and LHO/CHO. This is because the levels of P<sub>100</sub> are strongly related to the direct emissions from road traffic, whereas relatively larger size particles are of secondary nature i.e. secondary particles formed in the atmosphere (Rivas et al., 2020). Furthermore, the average ratios of P<sub>100</sub>/P<sub>200</sub> (10.10) and P<sub>100</sub>/P<sub>605</sub> (37.05) were highest at London Marylebone Road, followed by London Honor Oak Park, where the ratios of P<sub>100</sub>/P<sub>200</sub> and P<sub>100</sub>/P<sub>605</sub> were 6.8 and 22.25, respectively, whereas the lowest ratios of P<sub>100</sub>/P<sub>200</sub> (6.00) and P<sub>100</sub>/P<sub>605</sub> (21.45) were observed at Chilbolton Observatory sites. Again, this shows that P<sub>100</sub> are in much larger proportion at urban traffic sites than at urban background and rural sites (Fig. 3), indicating emissions from road traffic.

Changes in TPN, PM<sub>10</sub> and PM<sub>2.5</sub> during the lockdown period were calculated by subtracting their levels in 2019 from those in 2020 (Table 4). Both PM<sub>10</sub> and PM<sub>2.5</sub> levels have decreased in all 3 months at London Marylebone road and London Honor Oak Park sites, except PM<sub>2.5</sub> in May at London Honor Oak Park site. Chilbolton Observatory showed slightly different results, where both PM<sub>2.5</sub> (22.80%) and PM<sub>10</sub> (9.10%) levels decreased in April and increased in March and May (Table 4). TPN also decreased in April at London Marylebone road and London Honor Oak Park sites. Overall, PM<sub>10</sub> and PM<sub>2.5</sub> decreased 30%

| Month | Size | Site   | y2019 | y2020 | Diff | Diff (%) |
|-------|------|--------|-------|-------|------|----------|
| March | P<sub>100</sub> | CHO    | 1495  | 1682  | 187  | 13       |
| April | P<sub>100</sub> | CHO    | 2399  | 3492  | 1093 | 46       |
| May   | P<sub>100</sub> | CHO    | 2361  | 3741  | 1380 | 58       |
| March | P<sub>100</sub> | LHO    | 2824  | 2257  | –567 | –20      |
| April | P<sub>100</sub> | LHO    | 3638  | 3550  | –88  | –2       |
| May   | P<sub>100</sub> | LHO    | 3848  | 3562  | –286 | –7       |
| March | P<sub>100</sub> | LMR    | 8515  | 6964  | –1551| –18      |
| April | P<sub>100</sub> | LMR    | 6407  | 5459  | –948 | –15      |
| May   | P<sub>100</sub> | LMR    | 6637  | 6021  | –616 | –9       |
| March | P<sub>200</sub> | CHO    | 295   | 326   | 31   | 11       |
| April | P<sub>200</sub> | CHO    | 585   | 753   | 168  | 29       |
| May   | P<sub>200</sub> | CHO    | 405   | 426   | 21   | 5        |
| March | P<sub>200</sub> | LHO    | 415   | 379   | –36  | –9       |
| April | P<sub>200</sub> | LHO    | 706   | 635   | –71  | –11      |
| May   | P<sub>200</sub> | LHO    | 544   | 463   | –81  | –15      |
| March | P<sub>200</sub> | LMR    | 949   | 729   | –220 | –23      |
| April | P<sub>200</sub> | LMR    | 1039  | 796   | –243 | –23      |
| May   | P<sub>200</sub> | LMR    | 789   | 641   | –148 | –19      |
| March | P<sub>505</sub> | CHO    | 107   | 137   | 30   | 28       |
| April | P<sub>505</sub> | CHO    | 249   | 234   | –15  | –6       |
| May   | P<sub>505</sub> | CHO    | 138   | 97    | –41  | –30      |
| March | P<sub>505</sub> | LHO    | 167   | 158   | –9   | –5       |
| April | P<sub>505</sub> | LHO    | 375   | 246   | –129 | –34      |
| May   | P<sub>505</sub> | LHO    | 195   | 129   | –66  | –34      |
| March | P<sub>505</sub> | LMR    | 272   | 224   | –48  | –18      |
| April | P<sub>505</sub> | LMR    | 423   | 247   | –176 | –42      |
| May   | P<sub>505</sub> | LMR    | 251   | 153   | –98  | –39      |

Fig. 2. Ratios of nanoparticle numbers: (a) LMR/CHO; (b) LMR/LHO; (c) LHO/CHO, where LMR stands for London Marylebone Road, LHO for London Honor Oak, and CHO for Chilbolton Observatory.
and 50% at London Marylebone road, and 18% and 10% at London Honor Oak Park, respectively. However, PM$_{10}$ increased by 8% and PM$_{2.5}$ decreased by 4% at Chilbolton Observatory. So, London Marylebone road (roadside) showed greater reduction compared to London Honor Oak Park (urban background), and no or little reduction was observed at Chilbolton Observatory rural site. TPN have decreased 53% and 30% at London Marylebone road and London Honor Oak Park sites, respectively. Due to missing data, the change in TPN at Chilbolton Observatory site was not calculated. The reason for this is that particle pollution at urban traffic (roadside) sites are controlled by the local emission sources, for example, emissions from the road traffic and background sites are affected by the city scale emissions, whereas particulate matter at rural sites are affected by the regional scale emissions. Therefore, particle pollution at different types of environment demonstrated different changes during the COVID-19 lockdown.

### 3.2. Machine learning results

The model results could be considered as weather-corrected air pollution changes. Firstly, the model was validated by using an independent dataset, which was not included in training the model. Correlation coefficient and RMSE values were calculated for the model assessment using both training and tested data. The model performance did not get worse for the independent dataset, showing a good model transferability. The values of correlation coefficients and RMSE showed did not get worse for the independent dataset, showing a good model transferability. The values of correlation coefficients and RMSE showed acceptable model performance (Table 5). Table 6 presents the difference between predicted and observed values.

After validation, the model was retrained using 2018 and 2019 data and then used to predict PM$_{10}$, PM$_{2.5}$ and TPN for the month of March, April and May 2020 for the three sites. Predicted and measured levels of PM$_{10}$, PM$_{2.5}$ and TPN are higher than the measured levels, indicating that pollutants levels have decreased during the lockdown period.

The modelling results (Table 6) showed that the concentrations of PM$_{10}$, PM$_{2.5}$ and TPN decreased at all three sites, however, the amount of change varied from site to site. PM$_{10}$, PM$_{2.5}$ and TPN levels decreased.

### Table 4

Total particle numbers (TPN) and PM$_{10}$ and PM$_{2.5}$ mass concentrations and their difference between 2020 and 2019 (2020–2019). No TPN data was available for Chilbolton Observatory for year 2019. LMR stands for London Marylebone Road, LHO for London Honor Oak Park and CHO for Chilbolton Observatory.

| Month | Pollutant | Site | 2019 | 2020 | diff | Diff (%) |
|-------|-----------|------|------|------|------|----------|
| March | PM$_{10}$ | LMR  | 23.71| 16.61| –7.10| –29.96  |
| April | PM$_{10}$ | LMR  | 32.26| 22.01| –10.25| –31.77  |
| May   | PM$_{10}$ | LMR  | 19.59| 14.12| –5.48| –27.95  |
| March | PM$_{2.5}$| LMR  | 16.13| 8.45 | –7.68| –47.60  |
| April | PM$_{2.5}$| LMR  | 25.82| 13.67| –12.15| –47.06  |
| May   | PM$_{2.5}$| LMR  | 15.14| 7.04 | –8.10| –53.52  |
| March | TPN       | LMR  | 26,249| NA  | NA   | NA      |
| April | TPN       | LMR  | 25,534| 12,108| –13,426| –53    |
| May   | TPN       | LMR  | 11,718| NA  | NA   | NA      |
| March | PM$_{10}$ | CHO  | 11.77| 13.15| 1.38 | +11.74  |
| April | PM$_{10}$ | CHO  | 24.69| 22.44| –2.25| –9.10   |
| May   | PM$_{10}$ | CHO  | 9.78 | 11.87| 2.09 | +21.33  |
| March | PM$_{2.5}$| CHO  | 8.25 | 8.51 | 0.27 | +3.26   |
| April | PM$_{2.5}$| CHO  | 18.85| 14.56| –4.30| –22.80  |
| May   | PM$_{2.5}$| CHO  | 6.60 | 7.05 | 0.44 | +6.73   |
| March | PM$_{10}$ | LHO  | 9.99 | 8.83 | –1.17| –11.66  |
| April | PM$_{10}$ | LHO  | 22.24| 14.61| –7.63| –34.32  |
| May   | PM$_{10}$ | LHO  | 8.32 | 7.56 | –0.77| –9.24   |
| March | PM$_{2.5}$| LHO  | 14.72| 13.80| –0.92| –6.25   |
| April | PM$_{2.5}$| LHO  | 29.56| 21.86| –7.70| –26.06  |
| May   | PM$_{2.5}$| LHO  | 12.59| 13.05| 0.46 | 3.62    |
| March | TPN       | LHO  | 11,703| 3066| NA   | NA      |
| April | TPN       | LHO  | 12,966| 8447| –4,519| –30    |
| May   | TPN       | LHO  | 8189| NA  | NA   | NA      |

### Table 5

Comparison of fitted and cross-validated models for predicting PM$_{10}$, PM$_{2.5}$ and TPN.

| Modelled pollutants | Fitted/Cross-validated | R - value | RMSE |
|---------------------|------------------------|-----------|------|
| PM$_{10}$           | Fitted                 | 0.83      | 8.55 |
|                     | Cross-validated        | 0.83      | 7.36 |
| PM$_{2.5}$          | Fitted                 | 0.84      | 7.05 |
|                     | Cross-validated        | 0.82      | 6.98 |
| TPN                 | Fitted                 | 0.88      | 7852 |
|                     | Cross-validated        | 0.88      | 7975 |
by 33.05%, 43.42% and 50.32%, respectively, at London Marylebone Road site. PM$_{10}$ and PM$_{2.5}$ decreased by 1.98%, 15.53% at Chilbolton Observatory, however, due to missing data of TPN in 2018 and 2019, the model could not predict TPN for the lockdown period. PM$_{10}$, PM$_{2.5}$ and TPN decreased by 20.49%, 26.19% and 16.18%, respectively, at London Honor Oak Park. The reductions in all three pollutant concentrations were highest at the London Marylebone Road site, followed by the London Honor Oak Park. Chilbolton Observatory experienced the least reduction in PM$_{10}$ and PM$_{2.5}$ concentrations. The model results showed that the increase in TPN and mass concentrations at Chilbolton Observatory when comparing measured data in 2019 and 2020 were probably caused by the changes in meteorological conditions.

4. Discussion

In London during the first lockdown, on average private driving, public transport and walking trips decreased by 69%, 86% and 78%, respectively (Mohajeriet al., 2021). However, the levels of pollutants did not experience similar reductions, which showed nonlinear relationship between mobility and pollutant concentrations. In addition to emission sources, pollutant levels are affected by the meteorological conditions, which vary from time to time. To normalise for the variations in meteorological parameters, in machine learning techniques several meteorological parameters were used. So, basically the model predicts that if there was no lockdown (BAU), what the pollutant levels would have been. Fig. 5 shows the Hysplit back trajectory during the lockdown period for April in 2019 and 2020. Back trajectories are used for understanding the origins of air masses, which can significantly affect the type and levels of air pollutants. This shows that it is not just the local reduction in the emission amount that affects the air pollutants but also the wind direction, speed and other meteorological parameters. An increase in particles pollution at rural sites could be partly related to sudden changes in wind speed, direction and their origin that bring different air masses from outside over large parts of the UK or even from the EU countries (Fig. 5). However, there was a positive association between mobility reduction and the levels of mass and particle concentrations at the roadside and urban background concentrations.

Jephco te et al. (2021) reported an average reduction of 12.6% in PM$_{2.5}$ concentrations in London. Furthermore, they reported higher reductions of PM$_{2.5}$ at urban background and urban traffic sites than the suburban and rural sites. According to Jephco te et al. (2021), four out of 47 sites experienced an overall rise in PM$_{2.5}$ concentrations. The four sites included the Chilbolton Observatory site, which is a rural background site and experienced 4% increase during the lockdown period. Overall, the findings of Jephco te et al. (2021) are in agreement with the current study. It was previously reported that Easterly winds from Central and Eastern Europe were loaded with high pollutant emissions and caused pollution episodes in the UK, especially in London and southern England (Pope et al., 2016; Graham et al., 2020). Episodes of PM$_{2.5}$ concentrations from 8th to 12th and 15th to April 17, 2020 were associated with easterly air flow from Eastern and Central Europe (Jephco te et al., 2021). This showed that meteorology plays an important role in controlling the levels of air pollution and therefore has the following implications:

1. Even if emissions are cut from road traffic, emissions from area and point sources and changes in meteorological conditions may still contribute to air pollution episodes;
2. The effect of changes in weather needs to be carefully considered, when quantifying long term trends, especially in view of the climate change and global temperature rising;
3. For a sustainable air quality improvement, the contribution of continental air masses to UK air quality needs to be considered, which emphasises the need for national and international collaboration. Only local efforts alone will have limited impacts on air quality.

No paper was found on the effect of lockdown intervention on particle numbers in the UK. However, several studies were conducted in other countries. For example, Shen et al. (2021) analysed the impact of lockdown measures on particle numbers in Italy. They reported that during the lockdown period the primary particle numbers of size 10–25 and 25–50 nm reduced by 66% and 34%, respectively at a regional background site in Ispra, Italy. However, they reported that lockdown had no effect on particle numbers at an urban background site in Modena, Italy. New particle formation frequency slightly increased compared to the same period in 2016–2019 in Ispra. However, the particle growth rates were lower during the lockdown at both sites compared to other periods. Shen et al. (2021) showed that significant decrease in traffic flow had little influence on particulate pollution levels in the Po Valley in Italy, which probably suggested that in addition to road traffic, other sources and processes also impacted particle numbers and mass concentrations. According to Shen et al. (2020) the particle number concentrations of nanoparticles decreased by approximately 40% during the lockdown period compared to the pre-lockdown in Beijing, China. However, they reported that accumulation mode particles increased by approximately 20% as several polluted episodes contributed to secondary aerosol formation. Similarly, Kanawade et al. (2020) analysed the effect of COVID-19 lockdown on particle number in India and reported that the number concentrations of particles <3 nm did not decrease, however, the number concentrations of particles >10 nm diameter decreased by 85% during the lockdown compared to the BAU scenario. It probably showed that the reduction in primary anthropogenic emissions did not inhibit the formation of particles <3 nm. Dinoi et al. (2021) analysed submicron particle concentrations, in the size range from 10 nm to 800 nm and found that particle numbers decreased by 19% in Lecce and 7% in Lamezia Terme, Italy during the lockdown period. The above studies were carried out in different cities around the world having different weather and emission conditions and therefore direct comparison with the UK would not make much sense. Rivas et al. (2020) carried out a source contribution in four European Cities including London, and concluded that the main emission sources were photonucleation, traffic emissions and secondary particle formation, however, the contribution of each source differed at each site. Therefore, the change in particle concentrations reported in different

---

Table 6

| Site                     | Pollutant | Observed (min, max) | Predicted (min, max) | Difference (min, max) | Diff (%) (min, max) |
|--------------------------|-----------|---------------------|----------------------|-----------------------|---------------------|
| London Marylebone Road  | PM$_{10}$ | 17.58 (0, 79.8)     | 26.26 (0, 56)        | -8.68 (36, 51)        | -33.05 (321, 499)   |
|                          | PM$_{2.5}$| 9.73 (0, 72.3)      | 17.50 (2, 44.55)     | -7.76 (31, 35)        | -43.42 (123, 675.23) |
|                          | TNC       | 11,958 (1186, 30,107) | 24,073 (0, 46,858)  | -12115 (-37273, 11,253) | -50.32 (-912, 529) |
| Chilbolton Observatory   | PM$_{10}$ | 15.84 (0.58, 130)   | 16.16 (-2, 36)       | -0.32 (-22, 117)      | -1.98 (-98, 236)    |
|                          | PM$_{2.5}$| 10 (0.24, 76)       | 11.91 (-3, 30)       | -1.85 (-20, 47)       | -15.53 (-222, 350)  |
|                          | TNC       | 6334 (260, 27,081)  | NA                   | NA                    | NA                  |
| London Honor Oak Park    | PM$_{10}$ | 16.29 (0.73, 82)    | 20.49 (-5, 52)       | -4.20 (-30, 32)       | -20.49 (-132, 775)  |
|                          | PM$_{2.5}$| 10.37 (0.35, 67)    | 14.20 (-4, 40)       | -3.83 (-26, 33)       | -26.19 (-77, 546)   |
|                          | TNC       | 9479 (681, 57,197)  | NA                   | NA                    | NA                  |
cities during the lockdown was different quantitatively, however, they all agreed that COVID-19 lockdown changed air quality worldwide, acting as a global air quality intervention. Such global interventions are very uncommon in recent history.

Several processes affect particle number counts and size such as nucleation, evaporation, condensation, deposition, and coagulation (Harrison et al., 2018). As freshly emitted particles move away from the emissions source their particle number and size distribution change due to these processes. Therefore, primary particles normally affect air quality near the emission source, however, as they travel away from the emission source secondary particles are formed, which affect air quality at the urban background and rural sites (Morawska et al., 2008). This is probably the main reason that both particle numbers and their composition are different at urban traffic, background and rural sites and they demonstrated different change during the lockdown period. Rivas et al. (2020) have provided a detailed analysis on how particle numbers in different size range are affected by local, city scale and regional scale emission sources and how the effect varies at different monitoring sites with different environment types. They have particularly analysed the effect of emissions from the Heathrow Airport on urban background monitoring sites in London.

Here it should be noted that this study has only considered the first lockdown for three reasons: (1) The data of the pollutants considered in this study was only available for the first lockdown period; (2) The first lockdown had a much greater impact on the mobility and air quality than the second and third lockdowns; and (3) the first lockdown was implemented simultaneously in all cities in the UK, whereas the later lockdowns were implemented at different times. Mohajeri et al. (2021) analysed the effect of COVID-19 lockdown on air quality in Greater London, Cardiff and Belfast and reported that the effect of the first lockdown on mobility was more abrupt and much stronger than the second lockdown. Quinio and Enenkel (2020) reported that the improvement in air quality was short lived and pollution levels increased again after the lockdown was relaxed. The recovery in pollution level was of three types: (a) V-shaped recovery, when the pollution levels returned back to their previous levels; (b) Plateau-shaped recovery, when the pollution increased but it didn’t reach the previous levels observed before the lockdown period; and (c) Tick-shaped recovery, when pollution levels increased even more than those observed before the lockdown period. This shows that the effect of lockdown was not sustainable and hence the implementation of Clean Air Zones in large cities in the UK should go ahead as planned.

5. Conclusions

The novelty of the study is that it focuses on particle numbers considering both total particle and nanoparticle numbers. This study uses more meteorological parameters than previous studies, which include wind speed, wind direction, temperature, relative humidity, atmospheric pressure, dew point, visibility, and ceiling height. Furthermore, the study considers both raw data and weather corrected data to quantify the effect of the lockdown on air quality. In this paper, the effect of COVID-19 lockdown on the levels of PM$_{10}$, PM$_{2.5}$, TPN and NPN is analysed using measured data from a rural, an urban background and an urban traffic site during the first lockdown in the UK. It is shown that although COVID-19 lockdown was implemented to curtail person-to-person transmissions of the virus, it acted as an air quality intervention and improved air quality in urban areas, particularly at urban traffic sites. Two approaches are employed to extract the effect of lockdown: (1) Comparing the measured concentrations for the lockdown equivalent months in the year 2019 and 2020; (2) Comparing the prediction of machine learning with the measured concentration for the lockdown period of 2020. Overall, according to measured concentrations particle numbers including both nanoparticles and total particles increased at Chilbolton Observatory (a rural site) and decreased at both London Honor Oak Park (urban background site) and London Marylebone Road.

![Fig. 4. Comparing predicted and measured PM$_{10}$, PM$_{2.5}$ and TPN concentrations for the lockdown period at Marylebone Road.](image_url)
(urban traffic site). Likewise, the mass concentrations of PM\(_{10}\) and PM\(_{2.5}\) demonstrated reductions at London Honor Oak Park (18\% and 10\%) and London Marylebone Road (30\% and 50\%) and increase at Chilbolton Observatory (8\% and 4\%), respectively. Using measured data, the average for all three sites demonstrated increase in P\(_{100}\) and reductions for all other metrics i.e. PM\(_{10}\), PM\(_{2.5}\), TPN, P\(_{200}\) and P\(_{605}\). However, quantitatively the amount of change was significantly different for each species. This shows that different metrics used for the expression of particles pollution are affected differently by their emission sources, meteorological parameters and policy interventions. The machine learning techniques results, however, showed that the concentrations of PM\(_{10}\), PM\(_{2.5}\) and TPN decreased at all three sites, but the amount of change varied from site to site. London Marylebone Road showed a significantly greater reduction than the other two sites.
Different changes in pollutant levels at different environment types demonstrate the complexity of the atmospheric system. On average, road traffic flow decreased by about 70% during the lockdown period in the UK, however, reductions in pollutant concentrations are relatively much milder. This probably shows the nonlinear association between the emissions and atmospheric concentrations of various pollutants. It is shown by several studies that after the COVID-19 pandemic air pollution levels increased back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lockdown period, shown by several studies that after the COVID-19 pandemic air pollution much milder. This probably shows the nonlinear association between demonstrate the complexity of the atmospheric system. On average, back to the levels observed before the lock...
NPL, 2021. National physical laboratory, airborne particulate concentrations and numbers in the United Kingdom, annual report 2019. NPL Rep. Env. 39 https://doi.org/10.47120/npl.ENV39.

Shen, X., Sun, J., Yu, F., Zhang, X., Zhong, J., Zhang, Y., Hu, X., Xia, C., Zhang, S., 2020. Enhancement of nanoparticle formation and growth during the COVID-19 lockdown period in urban Beijing. Atmos. Chem. Phys. 21 (9), 7039-7052.

Shen, J., Bigi, A., Marinoni, A., Lampilahi, J., Kontkanen, J., Ciarelli, G., Putaud, J.P., Nieminen, T., Kulmala, M., Lehtipalo, K., Bianchi, F., 2021. Emerging Investigator Series: COVID-19 lockdown effects on aerosol particle size distributions in northern Italy. Environ. Sci.: Atmos. 1, 214–227, 2021.

Shi, Z., Song, C., Liu, B., Li, G., Xu, J., Van Vu, T., Elliott, R.J.R., Li, W., Bloss, W.J., Harrison, R.M., 2021. Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns. Sci. Adv. 7 (3), eabd6696.

Solberg, S., Walker, S.E., Schneider, P., Guerreiro, C., 2021. Quantifying the impact of the Covid-19 lockdown measures on nitrogen dioxide levels throughout Europe. Atmosphere 12, 131.

Spinu, V., 2021. Make Dealing with Dates a Little Easier. An R Package ‘Lubridate’ version 1.7.10.

Tobías, A., Carnerero, C., Reche, C., Castaigné, J., Via, M., Minguillón, M.C., Alastuey, A., Querol, X., 2020. Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. Sci. Total Environ. 726, 138540.

Who, 2021. New WHO Global Air Quality Guidelines Aim to Save Millions of Lives from Air Pollution. World Health Organization, Geneva. Available online:https://www.who.int/news/item/22-09-2021-new-who-global-air-quality-guidelines-to-save-millions-of-lives-from-air-pollution. (Accessed 16 May 2022). accessed.

Wood, S.N., 2006. Generalized Additive Models: an Introduction with R. Chapman and Hall/CRC, Boca Raton, FL, USA.

Wood, S., 2020. The mgcv package: mixed GAM computation vehicle with automatic smoothness estimation. An R package ‘mgcv’ 8–33 version 1.