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A vulnerability-based approach to human-mobility reduction for countering COVID-19 transmission in London while considering local air quality

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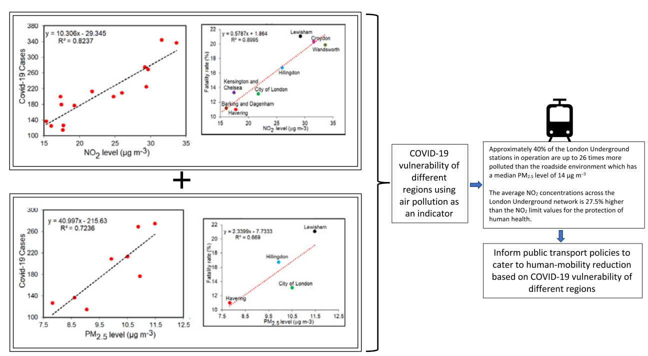
HIGHLIGHTS

- a strong correlation between increment in NO2 and PM2.5 levels and an increase in the risk of COVID-19 transmission
- a strong correlation between the risk of COVID-19 fatality and higher NO2 and PM2.5 levels
- Introduces a vulnerability-based approach to human-mobility reduction strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

An ecologic analysis was conducted to explore the correlation between air pollution, and COVID-19 cases and fatality rates in London. The analysis demonstrated a strong correlation ($R^2 > 0.7$) between increment in air pollution and an increase in the risk of COVID-19 transmission within London boroughs. Particularly, strong correlations ($R^2 > 0.72$) between the risk of COVID-19 fatality and nitrogen dioxide and particulate matter pollution concentrations were found. Although this study assumed the same level of air pollution across a particular London borough, it demonstrates the possibility to employ air pollution as an indicator to rapidly identify the city's vulnerable regions. Such an approach can inform the decisions to suspend or reduce the operation of different public transport modes within a city. The methodology and learnings from the study can thus aid in public transport's response to COVID-19 outbreak by adopting different levels of human-mobility reduction strategies based on the vulnerability of a given region.

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1. Introduction

The current outbreak of novel coronavirus COVID-19 or severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has resulted in the World Health Organization (WHO) declaring it as a global pandemic (World Health Organization, 2020). Reported first within the city of Wuhan, Hubei Province of China in December 2019, the COVID-19 exhibits high human-to-human transmissibility and has spread rapidly across the world (Qun et al., 2020). The human-to-human transmission of COVID-19 can occur from individuals in the incubation stage or showing symptoms, and also from asymptomatic individuals who remain contagious (Bai et al., 2020). The COVID-19 has been reported to transmit via the inhalation of exhaled respiratory droplets (Guangbo et al., 2020) that remain airborne for up to 3 h (Neeltje et al., 2020). The extent to which COVID-19 induces respiratory stress in infected individuals may also be influenced by underlying respiratory conditions (Wei et al., 2020) like acute respiratory inflammation, asthma and cardiorespiratory diseases (Centers for Disease Control and Prevention, 2020). Various studies have reported an association between air pollution levels and excess morbidity and mortality from respiratory diseases (Adamkiewicz et al., 2004; Dockery, 2001; Yan et al., 2003) with children and elderly people being at most risk (Department for Environment, Food, and Rural Affairs, 2017). 20% of England's population is at risk of mortality from COVID-19 due to underlying conditions and age (Amitava et al., 2020).

The simultaneous exposure to air pollutants such as particulate matter ($PM_{2.5}$) and Nitrogen dioxide (NO_2) alongside COVID-19 virus is also expected to exacerbate the level of COVID-19 infection and risk of fatality (Transport and Environment, 2020; European Public Health Alliance, 2020). Recent studies have also suggested that exposure to NO_2 and $PM_{2.5}$ may be one of the most important contributors to COVID-19 related fatalities (Xiao et al., 2020; Ogen, 2020; Travaglio et al., 2020). Moreover, the adsorption of the COVID-19 virus on PM could also contribute to the long-range transmission of the virus (Guangbo et al., 2020). For example, an ecologic analysis of the 2003 severe acute respiratory syndrome coronavirus 1 (SARS-CoV-1) reported that infected patients who lived in moderate air pollution levels were approximately 84% more likely to die than those in regions with lower air pollution (Yan et al., 2003). The aerosol and surface stability of the COVID-19 or SARS-CoV-2 is reported to be similar to that of SARS-CoV-1 (Neeltje et al., 2020). Given the limited understanding of the epidemiology of COVID-19, social-distancing and human-mobility reduction measures can contribute greatly to tailoring public health interventions (Shengjie et al., 2020).

2. Human-mobility reduction

Countries across the world have enforced lockdowns and other coordinated efforts to reduce human-mobility (European Commission, 2020; Anderson et al., 2020; Matteo et al., 2020; Edward et al., 2020). The UK's national framework for responding to a pandemic states that public transport should continue to operate normally during a pandemic, but users should adopt good hygiene measures, and stagger journeys where possible (Department of Health, 2007). Within the UK, London has recorded the highest COVID-19 related fatalities (i.e. 30.2% of UK's deaths as of 31 March 2020) (National Health Services, 2020). On 18 March 2020, further to the UK government's advice, Transport for London (TfL) closed 40 out of 270 London Underground (LU) stations that do not serve as interchanges with other lines and announced a reduced service across its network (Transport for London, 2020). This is also because 30% of TfL's drivers, station staff, controllers and maintenance teams were not able to come to work, including those self-isolating or ill with COVID-19 (Transport for London, 2020).

The UK's current human-mobility reduction response reflects the need to maintain business continuity, near-normal functioning of society and enable critical workers to make essential journeys (Department of Health, 2007; Joy et al., 2011). However, a statistically significant association exists between human-mobility through public transport and transmissions of acute respiratory infections (ARI) (Joy et al., 2011; Lara and Anders, 2018). It was found that using public transport in the UK during a pandemic outbreak has an approximately six-fold increased risk of contracting an ARI (Joy et al., 2011). Moreover, the pandemic case rates for London boroughs with access to interchange stations are higher (Lara and Anders, 2018), as individuals would interact with more people in comparison to through stations.

One of the most controversial debates in pandemic countermeasures is the potential benefit of human-mobility reduction and social-distancing attained by the closure of public transport systems. From a public policy perspective, there is a need to achieve a trade-off between the potential public health benefits of closing public transport during a pandemic thereby delaying the community spread, against the socio-economic impacts of curtailing/reducing human mobility. Determining the vulnerability of regions/locations to COVID-19 might help achieve such trade-offs. The proposed approach can be employed to rapidly identify regions that are highly vulnerable to COVID-19 and accordingly inform human-mobility reduction measures across the city's public transport network.

3. Materials and methods

An ecologic analysis was conducted to explore the correlation between short-term air pollution (of $PM_{2.5}$ and NO_2 levels) and COVID-19 cases and fatality rate in each London borough/region. To this end, a linear regression model was fitted to the data for regions with more than 100 reported cases and 10 COVID-19 related deaths as of 31 March 2020. Accordingly, the vulnerabilities of different boroughs in London to COVID-19 was measured.

3.1. Fatality data

As the COVID-19 is an evolving pandemic, the available data as of 31 March 2020 on COVID-19 morbidity and mortality for different boroughs in London was collected (Public Health England, 2020; National Health Services, 2020) The Office of National Statistics (A Baker, personal communication, 2020) confirmed that they are unable to provide COVID-19 related fatality data categorized by each London borough or local authority. To this end, the deaths reported by individual NHS Hospital Trusts in London were employed to inform the reported deaths for each London borough. The fatality rate across each London borough was estimated by dividing the number of reported deaths by the number of reported positive COVID-19 cases.

3.2. Air pollution data

The air pollution data associated with particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) for each London borough was collected from (King's College London, 2020). NO_2 data was available for 15 boroughs namely Barking and Dagenham, Bexley, Wandsworth, City of London, Croydon, Greenwich, Havering, Hillingdon, Kensington and Chelsea, Lewisham, Reading, Redbridge, Sutton, Tower Hamlets and Westminster. While, the $PM_{2.5}$ data was available only for 8 boroughs (Barking and Dagenham, Wandsworth, City of London, Croydon, Hillingdon, Kensington and Chelsea, Lewisham). Time series of available air pollution ($PM_{2.5}$ and NO_2) and COVID-19 cases could be seen in Fig. 1, which shows that COVID-19 cases increase with increasing air pollution at London boroughs.

The average NO_2 concentration within the LU network was reported to be 51 $\mu g\ m^{-3}$ (James David et al., 2016). The $PM_{2.5}$ concentration within different LU stations was recorded by Smith et al. (2020) with an average concentration of was 88 $\mu g\ m^{-3}$.

4. Results

A strong correlation between short-term NO2 and PM2.5 pollution concentrations and COVID- 19 cases with R^2 values of 0.82 (COVID-19

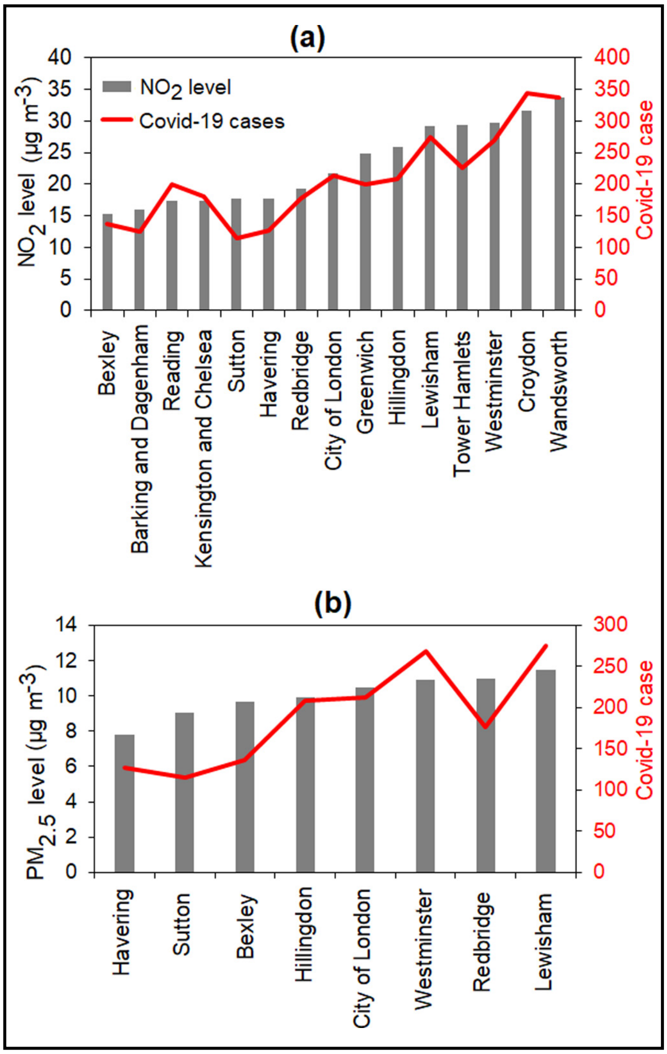

Fig. 1. The average **a**) NO_2 and **b**) $PM_{2.5}$ pollution concentrations and reported COVID-19 cases for different boroughs in London for March 2020. The grey bars show the monthly average of NO_2 and $PM_{2.5}$ concentrations and the line represent the cumulative number of reported COVID-19 cases in each London borough.

cases = −29.345 + 10.306*NO2 concentration) and 0.72 (COVID-19 cases = −215.63 + 40.997*PM2.5 level) were observed respectively (see.

Fig. 2). In particular, COVID-19 fatality rate increased with increase in short-term air pollution, where a significant correlation between COVID-19 fatality and NO2 and PM2.5 pollution concentrations with R^2 of 0.90 (fatality rate = 1.864+ 0.5787*NO2 level) and 0.67 (fatality rate = −7.733+ 2.3399*PM2.5 level) were found (see.

Fig. **3**).

The median $PM_{2.5}$ levels recorded for 27 of 40 closed LU stations range from 0 to 50 µg m^{-3} (5 stations), 50–100 µg m^{-3} (9 stations), 100–200 µg m^{-3} (5 stations), 200–300 µg m^{-3}(6 stations) and greater than 300 µg m^{-3} (2 stations) (see Table A1). Of the 230 operating stations, the median $PM_{2.5}$ levels recorded for 219 stations range from 0 to 50 µg m^{-3} (56 stations), 50–100 µg m^{-3} (15 stations), 100–200 µg m^{-3} (15 stations), 200–300 µg m^{-3} (18 stations) and greater than 300 µg m^{-3} (7 stations) (Smith et al., 2020) (see Table A1). This suggests that approximately 40% of the stations in operation during the current COVID-19 outbreak in London are up to 26 times more polluted than the ambient background locations and the roadside environment which has a median $PM_{2.5}$ level of 14 µg m^{-3} (Smith et al., 2020). Moreover, the average NO_2 concentrations across the LU network is 27.5% higher than the NO_2 limit values for the protection of human health (European Environment Agency, 2014).

5. Concluding discussion

Our analysis shows that short-term exposure to air pollution (both NO_2 and $PM_{2.5}$) is significantly correlated with an increased risk of contracting and dying from COVID-19, expanding on previous evidence linking high mortality rates in England (Travaglio et al., 2020), Northern Italy (Ogen, 2020) and USA (Xiao et al., 2020). Biologically, either long-term or short-term exposure to air pollutants such as $PM_{2.5}$ and NO_2 can compromise lung function and therefore increase the risk of dying from COVID-19 (Wei et al., 2020). Given that the immunity to the 2003 SARS-CoV-1 was reported to be relatively short-lived (around 2 years) (Li-Ping et al., 2007), achieving herd immunity for diseases like COVID-19 or SARS-CoV-2 would be unlikely without overwhelming the healthcare system (Edward et al., 2020). Human-mobility reduction measures provide the greatest benefit to COVID-19 mitigation (Matteo et al., 2020; Anderson et al., 2020) as prevention is potentially cost-effective than cure (Lara and Anders, 2018) or death.

The results from this study demonstrate that the air pollution levels can serve as one of the indicators to assess a region's vulnerability to COVID-19 and accordingly adopting human-mobility reduction strategies. For instance, the London Borough of Kensington and Chelsea is seen to be highly vulnerable to COVID-19 fatality from our analysis (see Fig. 3a). Table A1 shows that all the through stations and 3 out of 4 interchange stations (South Kensington, Sloane Square, Earl's Court, Notting Hill gate) in this borough are currently operational. Such a vulnerability-based assessment might aid decision-makers in selecting appropriate human-mobility reduction measures to COVID-19 in London's different local authorities/boroughs (such as apportion of transport staff across railway stations, arranging dedicated shuttling services for key workers, scheduling bus operations etc.) while adhering to the UK's national framework for response to pandemic outbreaks (Department of Health, 2007) of not isolating towns or even cities (Department of Health and Social Care, 2020).

We support the UK government's existing COVID-19 guidance (Department of Health and Social Care, 2020) to exercise good hygiene and to avoid unnecessary travel. While considering the evidence that COVID-19 can be transmitted from an asymptomatic individual (Bai et al., 2020), the currently implemented countermeasure of suspending operations only on the stations that do not serve as interchanges is not effective. This is because of the statistically significant risk of contracting ARI's on UK's public transport and higher pandemic case rates within London boroughs that have comparatively easier access to interchange stations. Moreover, the $PM_{2.5}$ and NO_2 levels, potential contributors to COVID-19 transmission and fatalities, are relatively higher in LU stations than other transport environments. E.g. the median level of airborne $PM_{2.5}$ in LU stations is several times higher than cycling (35 µg m^{-3}), bus (30.9 µg m^{-3}), cars (23.7 µg m^{-3}) (Vania et al., 2015; Smith et al., 2020).

It has to be noted that the number of positive COVID-19 cases considered within this study are only those reported at the hospitals and does not include the growing number of people who are self-isolating at home due to mild COVID-19. While the individual risk of contracting and dying from COVID-19 is dependent on various factors (including age, underlying conditions, availability of health care, population density etc.), these results are informative for both scientists and decision-makers in their efforts to reduce the transmission and socio-economic impact of the ongoing COVID-19 outbreak through appropriate human-mobility reduction strategies. It is also recommended to expand the study further to understand the effect (if any) of other air quality parameters such as volatile organic compounds (VOCs) and nitrogen oxides (NOx), on COVID-19 transmission and fatality rate.

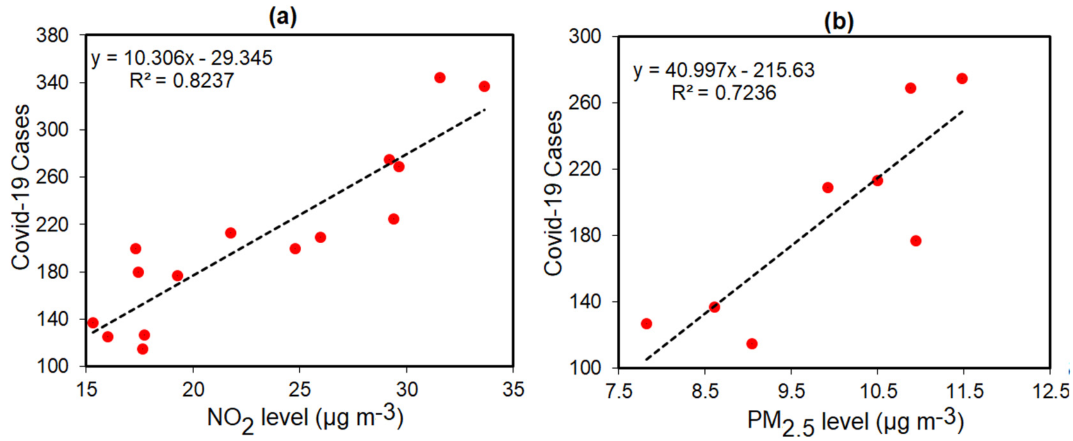

Fig. 2. Relationship between **a)** NO_2 and **b)** $PM_{2.5}$ pollution concentrations and reported COVID-19 cases at London boroughs using data during March 2020.

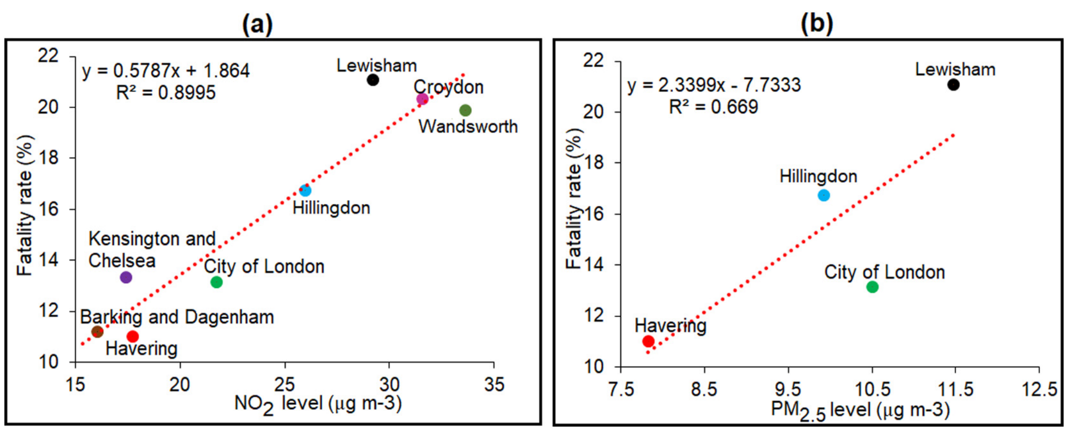

Fig. 3. Relationship between **a)** NO_2 and **b)** $PM_{2.5}$ pollution concentrations and the COVID-19 fatality rate for each London borough. The fatality rate was calculated by dividing the number of reported deaths by the number of reported positive COVID-19 cases.

CRediT authorship contribution statement

Manu Sasidharan: Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing.**Ajit Singh:**Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Mehran Eskandari Torbaghan:**Conceptualization, Writing - original draft, Writing - review & editing.**Ajith Kumar Parlikad:**Conceptualization, Writing - review & editing.

Declaration of competing interest

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

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Appendix A

Table A1
Status of LU stations (as of 31 March 2020) and their mean PM2.5 levels adapted from (Smith et al., 2020; Transport for London, 2020a, 2020b, 2020c).

Borough	Line	Station	Mean $PM_{2.5}$ level in the station ($\mu g\ m^{-3}$)	Status (as of 31/03/2020)
Barking and Dagenham	District	Becontree tube station	6	Open
Barking and Dagenham	District	Dagenham Heathway tube station	4	Open
Barking and Dagenham	District	Upney tube station	3	Open

Table A1 (*continued*)

Borough	Line	Station	Mean $PM_{2.5}$ level in the station (μg m^{-3})	Status (as of 31/03/2020)
City of Westminster	Central	Bond Street tube station	367	Open
City of Westminster	Central	Oxford Circus tube station	338	Open
City of Westminster	Northern	Embankment tube station	316	Open
City of Westminster	Bakerloo	Edgware Road tube station (Bakerloo line)	311	Open
City of Westminster	Victoria	Green Park tube station	308	Open
City of Westminster	Central	Marble Arch tube station	307	Open
City of Westminster	Central	Tottenham Court Road tube station	298	Open
City of Westminster	Victoria	Oxford Circus tube station	296	Open
City of Westminster	Northern	Leicester Square tube station	287	Open
City of Westminster	Bakerloo	Baker Street tube station	273	Open
City of Westminster	Bakerloo	Maida Vale tube station	268	Open
City of Westminster	Bakerloo	Oxford Circus tube station	263	Open
City of Westminster	Victoria	London Victoria station	253	Open
City of Westminster	Jubilee	Bond Street tube station	245	Open
City of Westminster	Bakerloo	Piccadilly Circus tube station	244	Open
City of Westminster	Jubilee	Westminster tube station	242	Open
City of Westminster	Northern	Tottenham Court Road tube station	239	Open
City of Westminster	Jubilee	Green Park tube station	236	Open
City of Westminster	Bakerloo	Embankment tube station	227	Open
City of Westminster	Piccadilly	Piccadilly Circus tube station	176	Open
City of Westminster	Jubilee	Baker Street tube station	174	Open
City of Westminster	Piccadilly	Leicester Square tube station	148	Open
City of Westminster	Piccadilly	Green Park tube station	144	Open
City of Westminster	Jubilee	St. John's Wood tube station	131	Open
City of Westminster	District	Embankment tube station	104	Open
City of Westminster	District	Westminster tube station	104	Open
City of Westminster	Circle	Westminster tube station	89	Open
City of Westminster	District	London Victoria station	75	Open
City of Westminster	Circle	Embankment tube station	61	Open
City of Westminster	Hammersmith & City	Baker Street tube station	57	Open
City of Westminster	Circle	Baker Street tube station	50	Open
City of Westminster	Metropolitan	Baker Street tube station	42	Open
City of Westminster	Circle	London Victoria station	42	Open
City of Westminster	Hammersmith & City	Edgware Road tube station (Hammersmith & City lines)	39	Open
City of Westminster	Hammersmith & City	Paddington tube station (Hammersmith & City lines)	19	Open
City of Westminster	Circle	Edgware Road tube station (Circle, District and Hammersmith & City lines)	10	Open
City of Westminster	Hammersmith & City	Royal Oak tube station	9	Open
City of Westminster	Circle	Paddington tube station (Circle)	6	Open
City of Westminster	Circle	Royal Oak tube station	4	Open
City of Westminster	Hammersmith & City	Westbourne Park tube station	4	Open
City of Westminster	Circle	Westbourne Park tube station	3	Open
City of Westminster	Circle	Bayswater tube station	3	Closed
City of Westminster	Piccadilly	Covent Garden tube station	132	Closed
City of Westminster	Circle	Great Portland Street tube station	91	Closed
City of Westminster	Metropolitan	Great Portland Street tube station	48	Closed
City of Westminster	Hammersmith & City	Great Portland Street tube station	99	Closed
City of Westminster	Piccadilly	Hyde Park Corner tube station	148	Closed
City of Westminster	Central	Lancaster Gate tube station	260	Closed
City of Westminster	Victoria	Pimlico tube station	460	Closed
City of Westminster	Central	Queensway tube station	277	Closed
City of Westminster	Bakerloo	Regent's Park tube station	243	Closed
City of Westminster	Circle	St. James's Park tube station	53	Closed
City of Westminster	District	St. James's Park tube station	94	Closed
City of Westminster	District	Temple tube station	82	Closed
City of Westminster	Circle	Temple tube station	14	Closed
City of Westminster	Bakerloo	Warwick Avenue tube station	277	Closed
Greenwich	Jubilee	North Greenwich tube station	103	Open
Hammersmith & City	Circle	Ladbroke Grove tube station	5	Open
Havering	District	Elm Park tube station	5	Open
Havering	District	Hornchurch tube station	3	Open
Havering	District	Upminster Bridge tube station	2	Open
Hillingdon	Piccadilly	Heathrow Terminals 2 & 3 tube station	50	Open
Hillingdon	Piccadilly	Heathrow Terminal 4 tube station	47	Open
Hillingdon	Piccadilly	Hatton Cross tube station	44	Open
Hillingdon	Metropolitan	Uxbridge tube station	31	Open
Hillingdon	Metropolitan	Ruislip Manor tube station	30	Open
Hillingdon	Metropolitan	Eastcote tube station	29	Open
Hillingdon	Metropolitan	Ruislip tube station	29	Open
Hillingdon	Metropolitan	Hillingdon tube station	28	Open
Hillingdon	Metropolitan	Ickenham tube station	28	Open
Hillingdon	Metropolitan	Northwood Hills tube station	23	Open

(*continued on next page*)

Table A1 (*continued*)

Borough	Line	Station	Mean $PM_{2.5}$ level in the station (μg m^{-3})	Status (as of 31/03/2020)
Hillingdon	Metropolitan	Northwood tube station	23	Open
Hillingdon	Central	Ruislip Gardens tube station	19	Open
Kensington and Chelsea	Piccadilly	Gloucester Road tube station	147	Closed
Kensington and Chelsea	Circle	Gloucester Road tube station	5	Closed
Kensington and Chelsea	District	Gloucester Road tube station	24	Closed
Kensington and Chelsea	Central	Holland Park tube station	123	Closed
Kensington and Chelsea	Central	Notting Hill Gate tube station	200	Open
Kensington and Chelsea	Piccadilly	South Kensington tube station	178	Open
Kensington and Chelsea	Piccadilly	Knightsbridge tube station	137	Open
Kensington and Chelsea	Piccadilly	Earl's Court tube station	105	Open
Kensington and Chelsea	District	Sloane Square tube station	57	Open
Kensington and Chelsea	District	South Kensington tube station	45	Open
Kensington and Chelsea	Circle	Sloane Square tube station	33	Open
Kensington and Chelsea	District	Earl's Court tube station	21	Open
Kensington and Chelsea	Circle	South Kensington tube station	18	Open
Kensington and Chelsea	Circle	High Street Kensington tube station	4	Open
Kensington and Chelsea	Hammersmith & City	Latimer Road tube station	4	Open
Kensington and Chelsea	Circle	Notting Hill Gate tube station	3	Open
Kensington and Chelsea	Circle	Ladbroke Grove tube station	2	Open
Kensington and Chelsea	Circle	Latimer Road tube station	2	Open
Redbridge	Central	Newbury Park tube station	56	Open
Redbridge	Central	Gants Hill tube station	55	Open
Redbridge	Central	Redbridge tube station	75	Closed
Redbridge	Central	Wanstead tube station	35	Open
Redbridge	Central	Barkingside tube station	31	Open
Redbridge	Central	Fairlop tube station	12	Open
Redbridge	Central	Hainault tube station	9	Open
Redbridge		Snaresbrook tube station		Open
Redbridge		South Woodford tube station		Open
Redbridge		Woodford tube station		Open
Tower Hamlets	Central	Mile End tube station	186	Open
Tower Hamlets	District	Tower Hill tube station	91	Open
Tower Hamlets	District	Mile End tube station	82	Open
Tower Hamlets	District	Aldgate East tube station	64	Open
Tower Hamlets	Circle	Tower Hill tube station	59	Open
Tower Hamlets	District	Bromley-by-Bow tube station	56	Open
Tower Hamlets	Hammersmith & City	Mile End tube station	45	Open
Tower Hamlets	Hammersmith & City	Aldgate East tube station	42	Open
Tower Hamlets	Hammersmith & City	Bromley-by-Bow tube station	40	Open
Tower Hamlets	Hammersmith & City	Bow Road tube station	76	Closed
Tower Hamlets	District	Bow Road tube station	80	Closed
Tower Hamlets	District	Stepney Green tube station	127	Closed
Tower Hamlets	Hammersmith & City	Stepney Green tube station	74	Closed
Tower Hamlets		Millwall tube station		Open
Tower Hamlets		St Katharine Docks tube station		Open
Wandsworth	Northern	Tooting Broadway tube station	284	Open
Wandsworth	Northern	Tooting Bec tube station	234	Open
Wandsworth	Northern	Clapham South tube station	203	Closed
Wandsworth		East Putney tube station		Open
Wandsworth		Southfields tube station		Open

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