# A vulnerability-based approach to human-mobility reduction for countering

# COVID-19 transmission in London while considering local air quality

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20      **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

25      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

30      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

40   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

45   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, Xiangdong, Ligang, & Guibin, 2020) that remain airborne for up to 3 hours (Neeltje, Trenton, & Dylan, 2020). The extent to which COVID-19 induces respiratory stress in infected

50   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

55   (Department for Environment, Food & 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 & Environment, 2020; European Public Health Alliance,

60   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, Rachel C, Benjamin M, Danielle, & Francesca, 2020; Ogen, 2020; Travaglio, Popovic, Yu, Leal, & Martins, 2020). Moreover, the adsorption of the COVID-19 virus on PM could also contribute to the long-range transmission of the virus (Guangbo, Xiangdong, Ligang, & Guibin, 2020). For example, an ecologic analysis of the 65   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, Trenton, & Dylan, 2020). Given the limited understanding of the epidemiology of COVID-19, social- 70   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, Heesterbeek, Klinkenberg, & 75   Hollingsworth, 2020; Matteo, et al., 2020; Edward, Daniele, & Yves, 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 80   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 & 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 & 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

105 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.

110 #### 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

115 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

120 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

125 (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 Figure 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 µg m$^{-3}$ (James

130 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 µg m$^{-3}$.
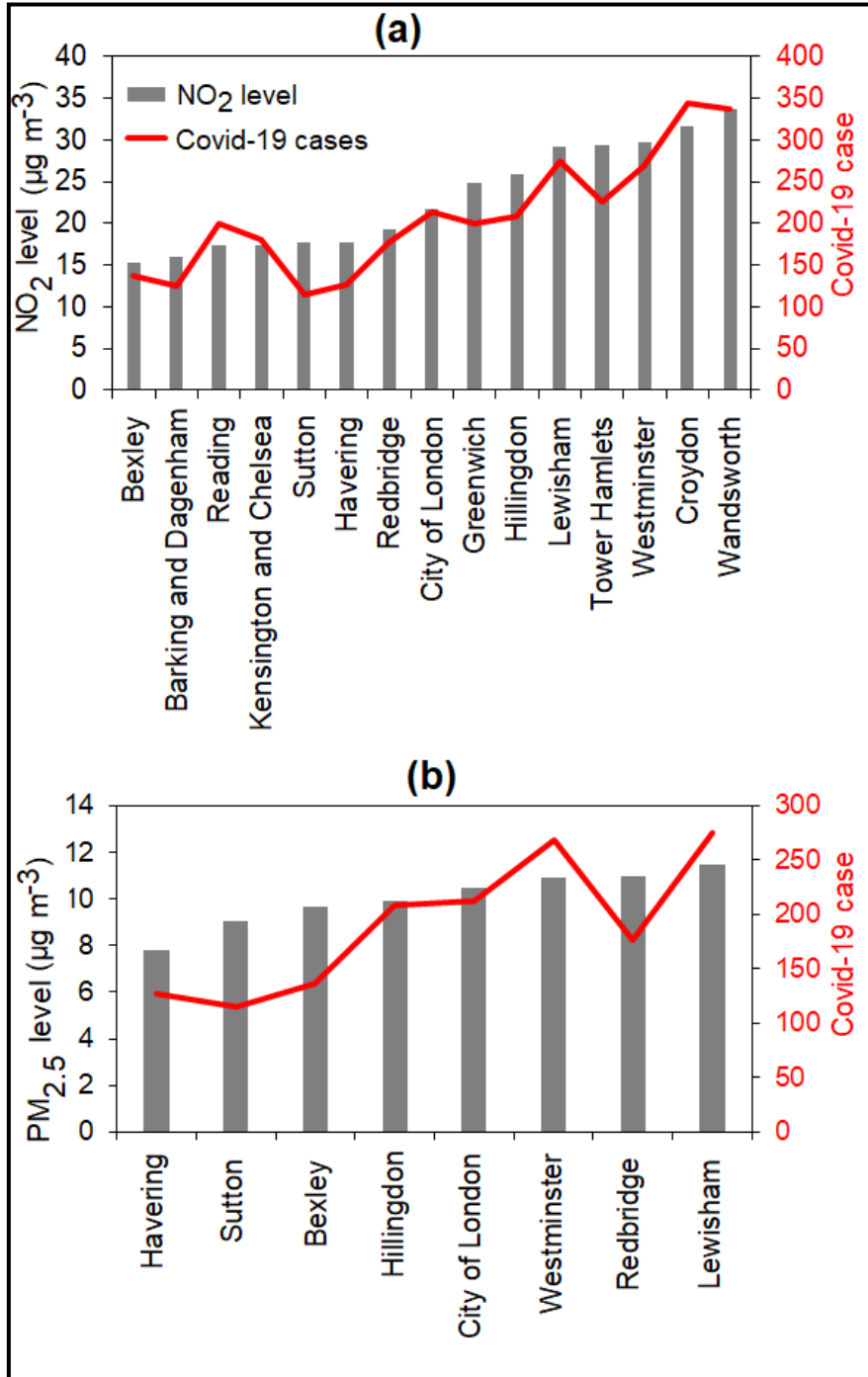
**Figure 1** The average **a)** NO$_2$ and **b)** PM$_{2.5}$ pollution concentrations and reported COVID-19 cases for different boroughs in London for March 2020. The grey bars show the monthly average of NO$_2$ and PM$_{2.5}$ concentrations and the line represent the cumulative number of reported COVID-19 cases in each London borough.

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

Figure 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
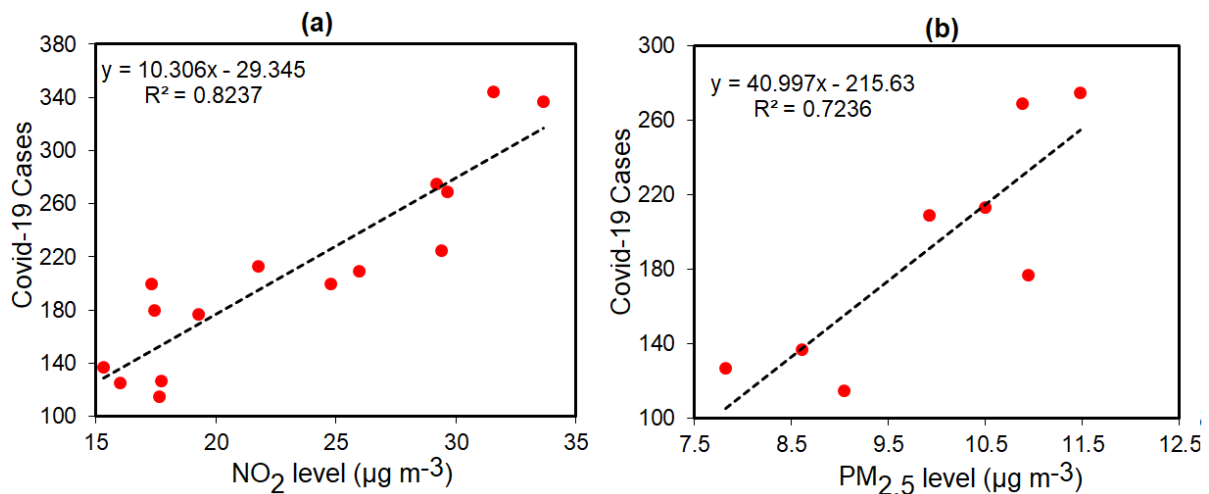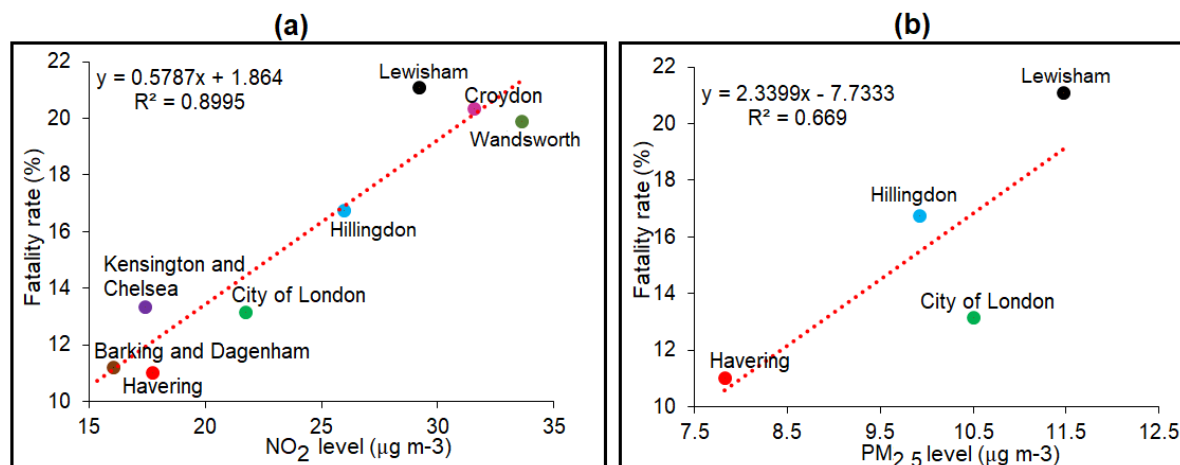
Figure **3**).



**Figure 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

**Figure 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

The median $PM_{2.5}$ levels recorded for 27 of 40 closed LU stations range from 0-50 $\mu g\ m^{-3}$ (5 stations), 50-100 $\mu g\ m^{-3}$ (9 stations), 100-200 $\mu g\ m^{-3}$ (5 stations), 200-300 $\mu g\ m^{-3}$ (6 stations) and greater than 300 $\mu g\ m^{-3}$ (2 stations) (see Table A1). Of the 230 operating stations, the median $PM_{2.5}$ levels recorded for 219 stations range from 0-50 $\mu g\ m^{-3}$ (56 stations), 50-100 $\mu g\ m^{-3}$ (15 stations), 100-200 $\mu g\ m^{-3}$ (15 stations), 200-300 $\mu g\ m^{-3}$ (18 stations) and greater than 300 $\mu g\ m^{-3}$ (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 $\mu g\ m^{-3}$ (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
170    evidence linking high mortality rates in England (Travaglio, Popovic, Yu, Leal, & Martins, 2020), Northern Italy (Ogen, 2020) and USA (Xiao, Rachel C, Benjamin M, Danielle, & Francesca, 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
175    (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, Daniele, & Yves, 2020). Human-mobility reduction measures provide the greatest benefit to COVID-19 mitigation (Matteo, et al., 2020; Anderson, Heesterbeek, Klinkenberg, & Hollingsworth, 2020) as prevention is potentially cost-effective than cure (Lara & Anders, 2018) or death.

180    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 Figure 3a). Table A1 shows that all the through stations and 3 out of 4 interchange stations (South Kensington, Sloane
185    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 & Social Care, 2020).

We support the UK government's existing COVID-19 guidance (Department of Health & 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 $\mu g\ m^{-3}$), bus (30.9 $\mu g\ m^{-3}$), cars (23.7 $\mu g\ m^{-3}$) (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.

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345     **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, 2020)

| 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 |
| 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 |

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|---|---|---|---|---|
| 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 |

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|---|---|---|---|---|
| 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 |
| 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 |

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| 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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