Breathe London Technical Report

Pilot Phase (2018 – 2020)

January 2021

BREATHE LONDON PARTNERS

Acknowledgements

The pilot phase of Breathe London was delivered by a consortium led by Environmental Defense Fund Europe and funded by the Children's Investment Fund Foundation, with continued funding from Clean Air Fund and additional funding support provided by Valhalla Charitable Foundation.

The project was convened by C40 Cities, the leading global alliance of cities committed to addressing climate change, and the Greater London Authority. The project consortium included ACOEM Air Monitors, Cambridge Environmental Research Consultants, Google Earth Outreach, the National Physical Laboratory and the University of Cambridge. The Wearables study was commissioned by the Environmental Research Group at Imperial College London (formerly at King's College London). The pilot phase ran from July 2018 to November 2020.

Breathe London partners would like to thank the many hosts of Breathe London air quality monitors including local councils, schools and residents, as well as the scientific and project advisors, technical partners and other non-governmental organisation partners for their contributions. The lessons and insights gained from Breathe London draw from these collective efforts.

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PART 1 THE BREATHE LONDON PROJECT

PART 1

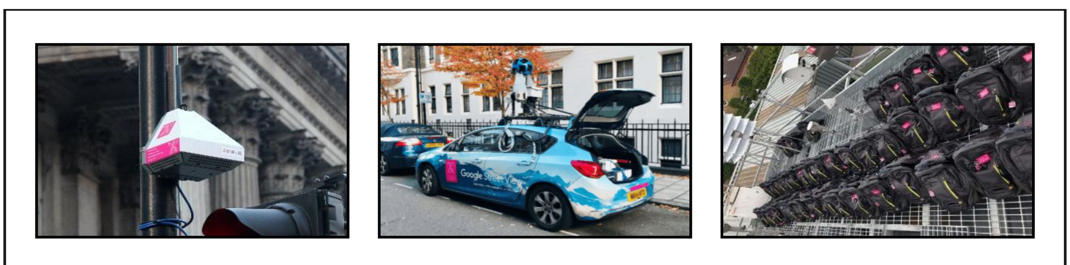
The Breathe London project

1.1 Overview

Millions of Londoners face health threats every day from air pollution. To better understand Londoners' exposure, the Breathe London project combined state-of-the-art monitoring technology with new methods of data analysis. By measuring harmful pollution across London and at thousands of locations, especially at a local level, the project informed data-driven solutions to clean London's air and foster healthier, stronger communities.

Breathe London was convened by C40 Cities and the Greater London Authority (GLA). Project planning began in July 2018 and the pilot phase ran through November 2020. The project was funded by the Children's Investment Fund Foundation (CIFF), with continued funding from Clean Air Fund (CAF) to extend the project to November 2020. The project consortium was led by Environmental Defense Fund Europe (EDF Europe) and included ACOEM Air Monitors, Cambridge Environmental Research Consultants (CERC), the Environmental Research Group (ERG) at Imperial College London (formerly at King's College London), Google Earth Outreach, the National Physical Laboratory (NPL) and the University of Cambridge (see Appendix 1 for more details on the roles of each partner).

With cutting-edge sensor technology and research, Breathe London comprised three projects that brought new understanding of air pollution levels where people live, work and play:

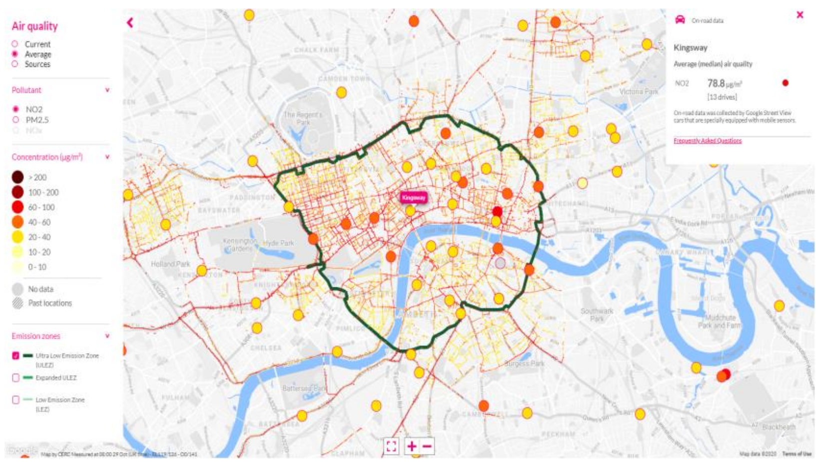


Stationary Network	Mobile Mapping	Wearables
100 sensor pods installed on lamp columns and buildings across the city that continuously transmitted air quality measurements.	Specially equipped Google Street View cars used mobile sensors to measure air pollution on a variety of roadways, taking readings approximately every second.	Specially designed back packs with air quality sensors inside that allowed children and teachers to monitor air quality during their journey to and from school.

FIGURE 1. Breathe London projects: stationary sensor network, mobile mapping and wearables

In its first year, Breathe London monitoring spanned the months leading up to and immediately following the implementation of the world's first Ultra Low Emission Zone (ULEZ) in Central London and in its second year, the extended operation of the stationary network captured the unprecedented times of COVID-19 and the air quality effects of restrictions that ensued.

Breathe London developed openly shared quality assurance and quality control (QA/QC) procedures and analysis algorithms and demonstrated how to effectively leverage lower-cost and new monitoring techniques. It enabled the assessment of pollution hotspots and the evaluation of policy interventions through a network of 100 stationary sensors, combined with repeated mobile monitoring on nearly 600 kilometres (km) of varied roads, to measure and map air pollution across Greater London. Policymakers and community groups were able to use Breathe London data to hold polluters accountable and to develop local clean air solutions.



Breathe London map displaying average NO_2 pollution levels at pods (29 Oct 20) and mobile measurements along roads in Central London; ULEZ boundary in green.

Breathe London also created a robust, open-access, hyperlocal dataset that generated an unprecedented level of detail about air quality in London and made it available to the public on the Breathe London platform (right). The city has a well-established regulatory network of high performing and high cost, stationary, continuous air quality monitors used to assess compliance with legal standards. This network served as an excellent reference to study the reliability and accuracy of the lower-cost sensors deployed as part of Breathe London. Validating lower-cost methods of measurements against such a network was an important goal of Breathe London in order to support replication in other cities interested in using lower-cost air quality sensors.

This report presents findings from the Breathe London pilot project to provide technical advice to cities on how lower-cost monitoring networks can be used to inform air quality solutions. It is intended for environmental health bodies including air quality officers and air quality network managers, as well as, academic and research institutions. Secondary users may include transport planners, other health and policy officials and civil society groups and community organisations.

1.2 Aims, goals and data objectives

Breathe London was created to accelerate air quality improvements in London and share lessons for other global cities through three overarching project aims:

1. Test the reliability and accuracy of a lower-cost stationary sensor network
2. Characterise the spatial patterns of air pollution, identify hotspots and assess the impact of policy interventions
3. Provide hyperlocal air pollution data to the public

To achieve these project aims, six monitoring goals and corresponding data objectives were established (see **Table 1**). The monitoring goals informed which pollutants to measure and the type of monitoring that was required and the data objectives focussed on the learning outcomes.

TABLE 1. Monitoring goals and data objectives

Monitoring Goals	Data Objectives
1. Provide unprecedented levels of air pollution data	• Quantify air pollution at a fine spatial and temporal resolution, to better understand variation across the city. • Identify pollution hotspots.
2. Advance the use of lower-cost sensors and mobile monitoring technology	• Compare performance with the existing reference network to better understand the reliability, accuracy and limitations. • Advance QA/QC procedures to derive a cost-effective, robust means of maintaining reliable network performance. • Provide key considerations for designing an effective monitoring network and data collection campaign.
3. Raise public awareness	• Share Breathe London's data and methodologies through innovative and open-source platforms.
4. Assess air quality before and after a policy intervention*	• Use collected data to evaluate local policies that aim to directly address sources of pollution and improve air quality. • Quantify changes in pollution levels over time.
5. Improve emission inventories and air quality model	• Use model-measurement comparisons to identify pollution hotspots and determine local inaccuracies in London's Atmospheric Emissions Inventory. • Produce updated high-resolution annual average pollution maps. • Provide the framework for the development of inversion modelling techniques that combine modelled and measured pollution data to understand emissions changes, while accounting for meteorological impacts. • Use measured CO_2 data at all sites to derive emission indices.
6. Enhance source apportionment	• Create a high-resolution dataset of hourly pollution at all stationary monitoring sites and sensitive receptors that showed the contribution of air pollution from different activity sectors.**

*The second year of monitoring took place in part during the COVID-19 pandemic and although the resulting local and national policies and actions put in place were not targeted at reducing air pollution, several had a direct impact on pollution and were assessed by the Breathe London project.

**Sensitive receptors include locations with vulnerable populations such as schools and hospitals.

PART 2 SETTING UP THE NETWORK AND COLLECTING DATA

PART 2

Setting up the network and collecting data

2.1 Stationary sensor network

Deployment overview


AQMesh pods were deployed across the city on lampposts and buildings.

Credit: ACOEM Air Monitors

The Breathe London stationary air pollution monitoring network was made up of [AQMesh pods](#) installed at 100 locations across London.[1] The stationary network collected data from 1 November 2018 to 30 November 2020. Each pod contained several air quality sensors that provided near real-time (available on-line within one hour of measurement) local air quality information and measured CO_2 (see **Table 2**). The pods also measured temperature, humidity and air pressure to correct for environmental conditions. Sensors measuring gaseous pollutants were set to collect data continuously for 10-second intervals, while particulate matter (PM) sensors operated 30-seconds in each minute, and create an overall average every 1-15 minutes. Data was presented on the Breathe London website as current, hourly averages and averages over the entire deployment period for each pod.

TABLE 2. Pollutants measured by the Breathe London stationary network and sensor types

Pollutant	Sensor Type
Nitrogen dioxide (NO_2)	Electrochemical sensor
Nitric oxide (NO)	Electrochemical sensor
Particulate matter (including $PM_{2.5}$ and PM_{10})	Light-scattering optical particle counter
Carbon dioxide (CO_2)	Non-dispersive infrared absorbance sensor
Ozone (O_3)*	Electrochemical sensor

*Only 10 pods were equipped with electrochemical sensors to measure ozone.

[1]AQMesh pods were manufactured by Environmental Instruments Ltd.

Site selection
Locations for the Breathe London pods were identified based on the following criteria developed in consultation with the Greater London Authority (GLA).[2]

- Establishing coverage across Greater London in all 32 boroughs plus the City of London.
- Filling gaps in the existing network of regulatory air quality monitors.
- Prioritising sensitive locations, such as primary schools and medical facilities.
- Supporting assessments of the impact of new policies designed to reduce air pollution, such as the Ultra Low Emission Zone (ULEZ), the Expanded ULEZ and the Low Emission Bus Zones (LEBZ).
- Distributing pods across a range of traffic environments and at varying distances from major roads and intersections, parks, residential areas, high-traffic streets and other commercial areas.
- Reserving three pods (termed "gold pods") for calibrating other pods throughout the network using periodic co-location studies (six additional gold pods were later loaned to the project by the University of Cambridge).

Stationary sensor network data QA/QC

The AQMesh sensors were not intended to provide equivalent accuracy to the existing reference network, but rather to provide information across a wide area and in many locations at a much lower cost. As such, the sensors were not calibrated like reference monitors using known standard materials. Their accuracy was quantified by periodic co-location with reference monitors and comparisons with each other. QA/QC checks were carried out on data produced by the AQMesh pods before initial field placement, after they were installed and periodically throughout their deployment. Data was evaluated in stages, with each stage adding one or more quality assurance steps. This was done using the process outlined in the *AQMesh Fixed Sensor Network Data QA/QC Procedures* in Appendix 2A and summarised below (see **Table 3**).

TABLE 3. Summary of stationary sensor network data QA/QC process

Stage	Description of QA/QC Process
0	Factory QA/QC settings applied
1	Field derived scaling factors, for the range of environmental conditions at intended field location, determined through one of three methods (described in Section 2.2).
2	Manual QA/QC review to flag suspect data
3	Automated QA/QC for data removal and correction based on flags
4	Special issues (NO_2 data drift, regulatory data ratification)

[2]The GLA also provided additional funding in the second year to increase the number of hospital sites included in the network, bringing the total to 10.

Post-deployment and periodic QA/QC checks were further supported by the online platform that hosted all the Breathe London data (see Section 3.1 for more details). The platform performed continuous QA/QC on the AQMesh data in accordance with the process outlined in Appendix 2A.

The overall QA/QC process was audited by the National Physical Laboratory (NPL) at the end of the pilot phase who confirmed adherence to the QA/QC requirements (see Appendix 2B for the full audit report). Provisional data from the stationary sensors were published on the Breathe London website in near real-time while QA/QC checks were undertaken. A final dataset was produced by applying the full QA/QC process as outlined in Appendix 2A and made publicly available at the end of the project.

2.2 Stationary sensor network calibration methods

To ensure that the AQMesh pods were correctly calibrated for the range of environmental conditions present at their field location, Stage 0 data was adjusted with scaling factors determined through one of three methods (Stage 1 in **Table 3**). Breathe London developed these methods to verify, and where necessary improve, the accuracy of sensor measurements during the QA/QC process (see **Table 4** and the sub-sections below). This is because conventional calibration procedures using certified gases were not practicable or indeed desirable for field-deployed, lower-cost sensor networks.

TABLE 4. Summary of stationary sensor network calibration methods

Calibration method	Description of method
1. Reference site co-location	AQMesh pods co-located with a reference monitor to determine slopes and offsets (calibration factors) between reference site and pod data.
2. Transfer standard	AQMesh pods calibrated against a designated subset of AQMesh pods that were periodically co-located with a reference monitor to become qualified as transfer standards, also known as “gold” pods.
3. Network calibration	Cloud-based method that remotely calculated calibration factors for each sensor within the network.

Reference site co-location

Prior to initial field placement approximately one-third of the AQMesh pods were co-located with reference monitors in Greater London for 3 - 7 days. This amount of time typically enabled sufficient variability in pollution concentrations to produce a valid test that met co-location criteria. After each calibration period, linear regressions were performed to derive calibration parameters for the co-located pod.

AQMesh gold pods co-located at a reference site. Credit ACOEM Air Monitors.

Transfer standard method (gold pod co-location)

Nine AQMesh pods were co-located periodically with one or more reference monitors to become qualified as designated transfer standards, also known as gold pods. After characterisation, gold pods were moved adjacent to "candidate" pods across the network for individual co-locations. Candidate pods were the 100 stationary AQMesh pods that made up the Breathe London stationary sensor network. After a reference or gold pod co-location, calibration adjustments (slope and/or offset) were applied to the candidate's pre-scaled data when regressions indicated good correlation.

Network calibration method

Since physical co-locations for a large network are resource intensive, alternative methods like the remote network calibration became advantageous. Developed by the University of Cambridge, this method dramatically reduced the level of effort needed to operate the stationary sensor network by enabling calibration without extensive co-location studies. Based on earlier work reported in Heimann et al. (2015) and Popoola et al. (2018), the method separates three signals: local, near-field and far-field/background. The local contributions are due to emissions near the receptor (1 – 10 m), the near-field contributions vary on scale of 10 – 1000 m and represent the contribution from dispersed sources local to the environment, while the far-field/background contribution is uniform over 1-100 km. By selecting periods when non-local pollutant levels are likely to be relatively homogeneous over the study area the method can be used to determine relative pod calibration parameters. The entire network can be scaled relative to a single AQMesh pod co-located with a reference monitor.

Breathe London used the network calibration method to determine NO_2 scaling factors for sensors without a valid gold pod co-location and for all $PM_{2.5}$ data. For NO the network calibration was used as a basis for deriving offsets, which were applied to regressions used to determine the sensor sensitivities from gold pod co-locations. Breathe London provided an extensive testbed for quantifying the performance of the method due to the density of the existing reference network, which enabled the widespread use of physical co-locations for validation purposes. The network calibration methodology and an evaluation of this method's performance to that of gold pod co-locations can both be found in Appendix 2.

Statistical methods for performance characterisation of lower-cost sensors
The team from NPL leveraged Breathe London monitoring data, together with reference measurements from London's existing regulatory network, to investigate the application of statistical and machine learning tools for performance characterisation of the lower-cost sensors. Results showed promise for certain applications such as quantifying measurement uncertainty, identifying malfunctioning devices and determining regional background levels, which is complementary to the network calibration method of the University of Cambridge. Additional detail on this work is provided in Appendix 2.

2.3 Key considerations for future projects from the stationary network

Installing a new dense network of lower-cost monitors can be challenging because there are numerous site-specific logistical issues and permissions which need to be resolved before full deployment can take place. Lower-cost sensors have some inherent technology limitations that can vary by system and by sensor, and it is only possible to identify and address these by implementation of networks in long-term monitoring studies like Breathe London.

It is important to select suitable low-cost sensor systems which can make rapid one-minute measurements in order to support new network calibration approaches that could transform air quality monitoring methods of the future. In addition, the species selected for measurement should not be restricted to just regulated compounds which are monitored at reference instrument sites. The new technology may be exploited further by incorporating sensors which can detect tracer molecules such as CO_2 thereby delivering vital new information on pollution source apportionment.

Below is a summary of key issues and considerations found during deployment, which should be accounted for when planning similar hyperlocal stationary monitoring at other locations.

Sensors and equipment

Installation

The time and resources to obtain permissions to install monitors should not be underestimated. Local knowledge and political buy-in, as well as access to ideal siting locations such as lampposts with mains power supply (including the correct sockets), can streamline this process. Depending on location, installation may require outside contractors, increasing the budget and creating time constraints.

AQMesh pod installed on a lamppost with mains power supply. Credit: ACOEM Air Monitors.

Sensor technology

Lower-cost sensor technology is rapidly evolving, and both sensor manufacturers and sensor system manufacturers frequently upgrade their products sometimes without making this process completely transparent. This is very common in the present market but can create complications such as when a manufacturer's firmware algorithm is updated, which can impact on the data quality, or when sensor models are discontinued and replaced with upgrades during the lifetime of the project. It is recommended that projects proactively ask manufacturers about planned product updates during the procurement process and keep stocks of suitable replacement sensors.

Network performance

Overall, the Breathe London network performance maintained a high operational rate between March 2019 and June 2020 with more than 80 pods in the network reporting at least 75% valid hourly data (see **Figure 2**). The increase in number of active pods with valid data in early 2019 reflects correcting power supply and other performance issues in the early months of deployment. This demonstrated how vital it is to get as much information as possible on sensor performance ahead of procurement, as well as incorporating time to test and validate instrumentation. Sensor replacement and pod maintenance costs are also key considerations for understanding the overall project budget.

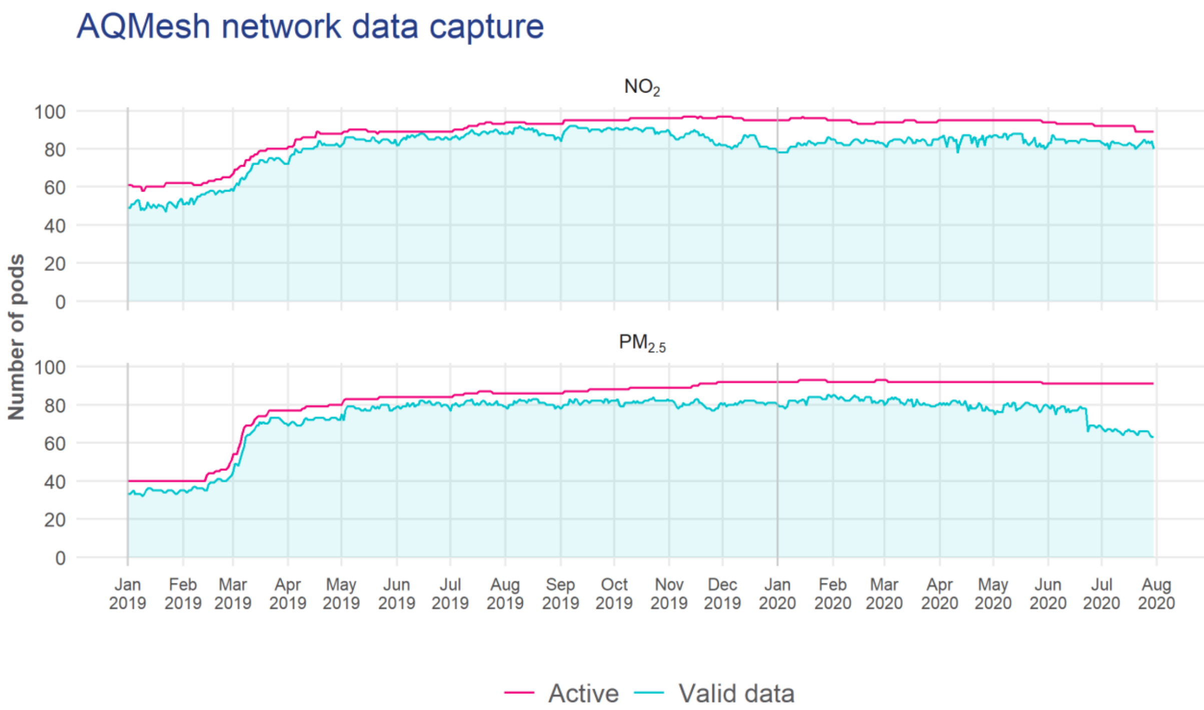


FIGURE 2. Number of AQMesh pods with > 75% valid hours of NO_2 or $PM_{2.5}$ data each day (blue line) and maximum number of operating or active pods in the network (red line). Coverage criterion is met for generally over 80% of the instruments deployed although some degradation is seen later in the project in June 2020 for $PM_{2.5}$

Monitoring plan

Siting logistics

Logistical needs are a vital consideration when choosing the location of monitors. Requirements such as pod power, weight, and height should be clearly documented to streamline communication between the project and potential hosts when determining the suitability of sites. For example, the pods used in Breathe London needed sufficient power, so potential sites either required adequate sunlight for installing solar panels or the ability to plug into mains, both of which have cost and logistical implications.

Microscale siting

Positioning of the pods can potentially impact the representativeness of the measurements. Due to the limited options for mounting pods on buildings or street furniture, large networks may have to compromise on locations. To assess possible sampling issues at sites that did not follow siting guidelines set out in the European Union (EU) directives for reference instruments, a microscale siting study was conducted at three sites to better understand the potential effect of pod siting (see Appendix 2F). This showed the effects to be minimal, at least for the sites tested, so that an important point of lower-cost, small sensors is that they can in fact be sited in places that are impossible for traditional reference instruments, generally outweighing potential disadvantages associated with microscale siting.

Data quality assurance and quality control

Pre-deployment co-location at reference monitoring sites

Ideally, adequate time should be built-in prior to deployment to ensure that all sensors can be co-located at reference sites representative of their ultimate placement location and that as many pollutants are measured by the system as possible. However, a key output from the Breathe London project was the network-based calibration methodology (Appendix 2C) which yielded results comparable to physical co-location. It is highly recommended that future projects test the performance of at least a subset of the sensors to be deployed in order to address any unexpected compatibility or suitability issues.

Designated gold pods and spare pods

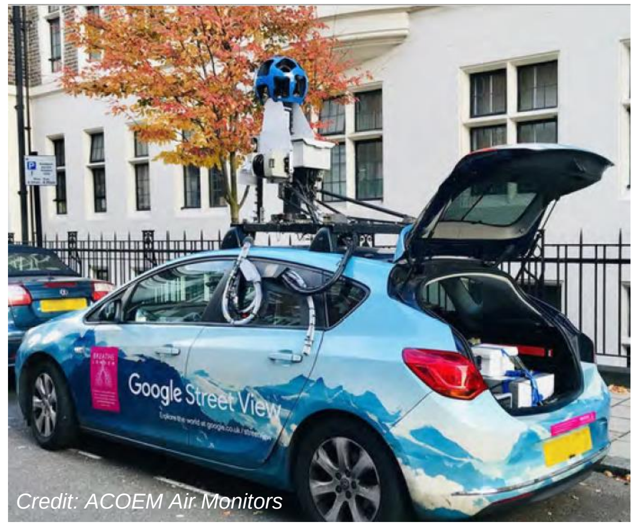
A valuable capability is the ability to move a subset of pods within the network based on project needs. Designating a subset of pods for gold pod calibrations or as transfer standards will help maintain network performance and for testing and validating any cloud-based calibration methodology. It is recommended that future projects consider maintaining several calibrated, spare pods to allow anomalous sites to be investigated or to replace the pods in the network that have been otherwise rendered inoperable to ensure continuity. The ability to move spare pods within the network can determine whether atypical results are a data/measurement issue or local air pollution issue (i.e. potential hotspot).

Long-term co-location at reference monitoring sites

Although the network-based calibration method is an important basis for maintaining the calibration and QA/QC of the lower cost network, co-locating one or more pods with a reference monitor for an extended period (i.e. many months), or repeated co-locations, can provide insights into the performance of the lower-cost sensor network. For example, such co-locations during Breathe London enabled evaluation of performance issues, including identification and correction of a gradual upward drift of NO_2 measurements associated with an ozone (O_3) cross interference. In this context, access to multiple reference sites spanning different site types could be of value.

2.4 Mobile mapping deployment

Deployment overview



The mobile mapping campaign was conducted by two Google Street View cars equipped with reference-grade air quality sensors, that measured air pollution over approximately 40,000 km of driving between August 2018 and October 2019. The fast-response, reference-grade instruments measured pollution concentrations approximately every 1-10 seconds. Pollutants were measured on a variety of London roads (see **Table 5**). Mobile monitoring is unique because measurements occur so close to the vehicle sources that emissions can be practically measured directly. This enables characterisation of vehicle emissions performance as well as ambient pollution on streets.

The National Physical Laboratory (NPL) conducted the necessary regular checks of instrument performance and periodic calibrations. Frequent calibrations and daily instrument and data checks were necessary to ensure the highest possible valid data capture. The *Google Street View Cars Instrumentation Operating Procedure* document provides further details about the instrumentation, checks and calibrations conducted during the project (see Appendix 3A). The cars collected data from early morning to late evening, Monday to Saturday, with most of the driving occurring on weekdays.

TABLE 5. Pollutants measured by the Google Street View cars and instruments

Pollutant	Instrument
Black carbon (BC)	Magee AE33 Black Carbon Monitor
Carbon dioxide (CO_2)	LiCor Model 7200RS CO_2/H_2O Monitor
Lung Deposited Surface Area (LDSA)	Naneos Partector - nano PM monitor
Nitric oxide (NO)	Serinus 40 NO_x Monitor
Nitrogen dioxide (NO_2)	Aerodyne CAPS Direct NO_2 Monitor
Ozone (O_3)	2B Tech 211G Ozone Monitor
Particulate matter (primarily $PM_{2.5}$)	FIDAS 100 PM Monitor and Thermo PDR - 1500 $PM_{2.5}$ Nephelometer

Daily sampling plans were designed to distribute repeat passes of each target area as evenly as possible across times of day, day of the week and month of year. The initial sampling plan included full coverage of the Ultra Low Emission Zone (ULEZ) and targeted driving routes in select areas outside of the ULEZ. The project team selected these routes based on predicted high and low NO_2 concentrations, using Cambridge Environmental Research Consultants' (CERC's) ADMS-Urban model, as well as randomly selected areas of high and low deprivation. The full *Mobile Deployment Strategy Overview* can be found in Appendix 3B. **Figure 3** and **Figure 4** show the drive coverage achieved between August 2018 and October 2019 across Greater London and within the ULEZ boundary.

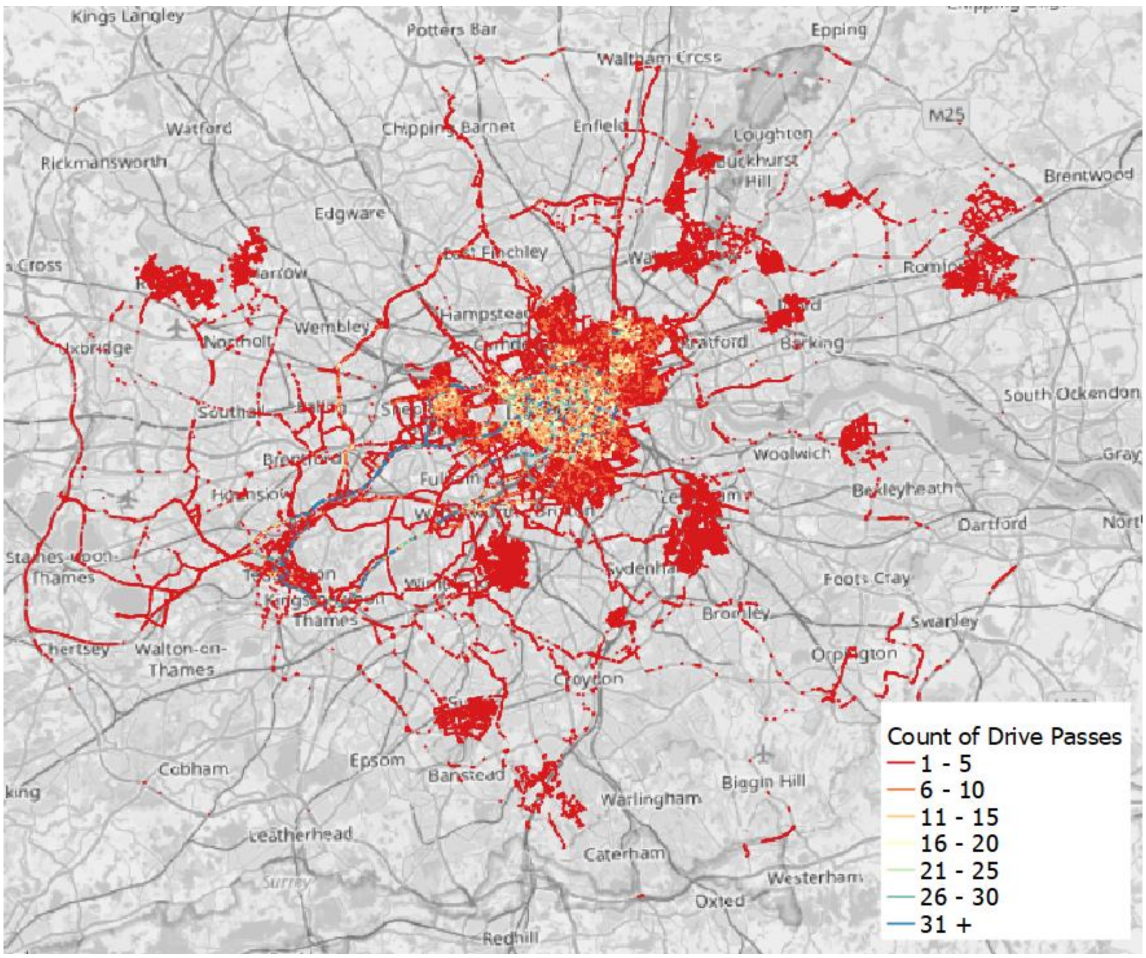


FIGURE 3. Map of mobile drive coverage on all roads across Greater London showing count of valid drive passes for the $PM_{2.5}$ instrument between August 2018 and October 2019

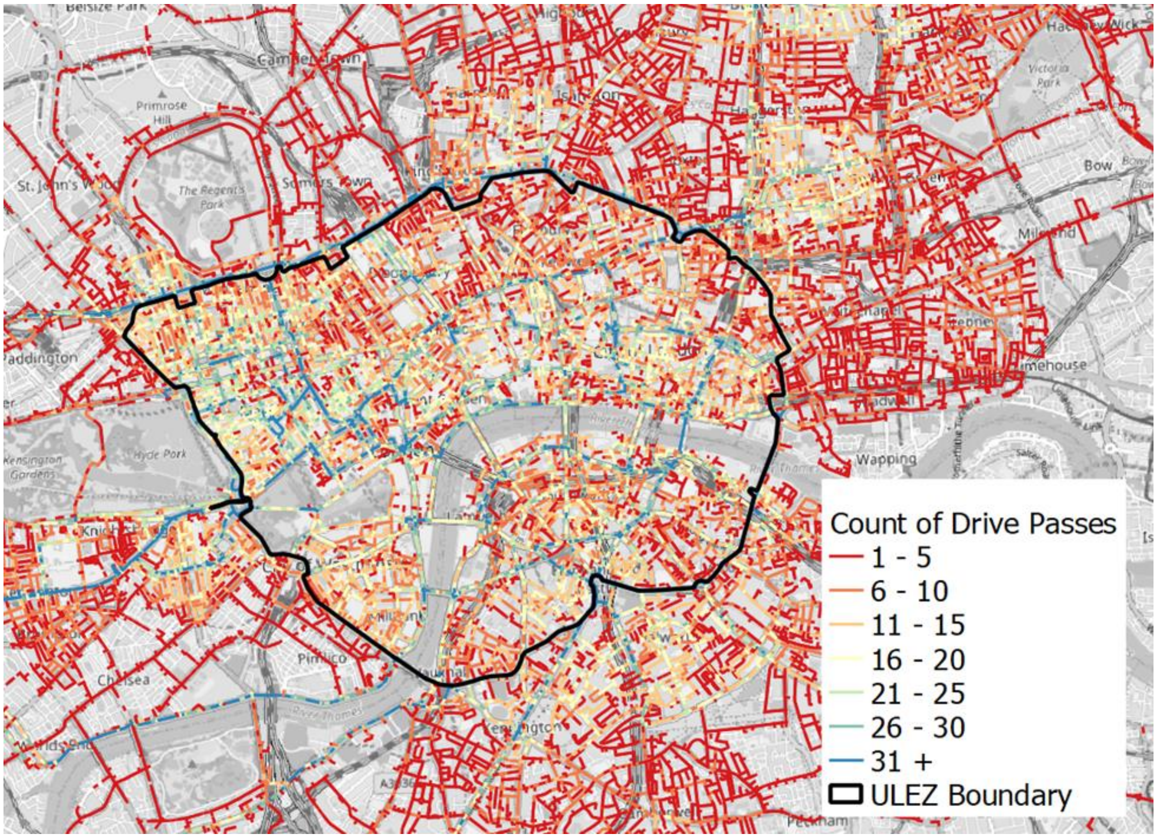


FIGURE 4. Mobile drive coverage in the ULEZ showing count of valid drive passes for the $PM_{2.5}$ instrument mounted on Google Street View cars between August 2018 and October 2019

Mobile data QA/QC

The data collected from the mobile mapping campaign followed the QA/QC process outlined in Appendix 3C and is summarised below in **Table 6**. Instrument uncertainties for each pollutant measured are also presented in the *Mobile Uncertainty Documentation* in Appendix 3E. The code is available to the public in a GitHub repository for use in other projects.

TABLE 6. Summary of QA/QC Stages for Breathe London Mobile Data

Stage	Description of QA/QC Process
0	Raw data entry into BigQuery and duplicate removal[3]
1	Time alignment
2	Flag assignments (instrument status, exceptional events, operating limits)
3	Data removal/correction based on flags (replacement with null or correction factor applied); measurement mode codes added
4	Minimum detection limit calculation

[3] BigQuery is a serverless data warehouse that enabled analysis of vast quantities of raw mobile measurements.

2.5 Key considerations for future projects from the mobile mapping campaign

Monitoring plan

Sampling plan design

Clear objectives and local knowledge of air pollution concerns are key to tailoring sampling strategies. Plans need to be adaptive and flexible because, as experienced in Breathe London, real world traffic conditions impact repeat drive coverage. Optimising drive routes as well as journeys between sampling areas can improve sampling efficiency that could otherwise be impacted by transit time and local congestion.

It is also important for future project teams to understand the trade-off between spatial and temporal coverage with mobile platforms and that a single visit to a location provides little utility in analyses. As a minimum, Breathe London required at least five drive passes over monitoring sites of interest for hyperlocal mobile analysis. An understanding of sampling uncertainty as a function of number of visits and acceptable levels of sampling uncertainty for desired analyses can help guide the monitoring plan.

Vehicles, sensors and equipment

Vehicle space and power

These two factors influence what is possible in terms of monitoring instrumentation and need to be addressed in detail during planning. Instrument choices and operating modes were modified in Breathe London to reduce power draw, and custom installation was arranged to fit all the equipment safely and securely. The amount of power available on the mobile platform limited the data collection shifts and coverage so it is important to consider equipment with lower power requirements, smaller size, and less weight.

Parking

Finding a suitable, secure site for the cars to park is a key consideration. Due to the daily equipment checks and calibration needs, it was important that the parking location be easily accessible by the staff conducting those tasks. Additionally, there is value in parking the cars in proximity to reference monitoring sites to enable long-term evaluation of instrument performance, which can eliminate the need for intentional co-locations to be scheduled.

Driver training and manuals

While drivers need to conduct only basic operational procedures (e.g. turning on instruments), these can impact data collection and other parts of operations. Therefore, it is important to provide effective training and a user-friendly instruction manual for drivers, including basic troubleshooting procedures.

Instrumentation needs

Instruments utilised equipment like pumps more intensively on mobile platforms compared to laboratory settings and are therefore more prone to wear and tear. It is helpful to have backup items of specialist parts on hand. Instruments also need to be cooled for safe operation. Putting in place adequate cooling systems, both on the mobile platform and where the vehicles park overnight, is critical. We also recommended a thermal cut-off to power down instruments in the event of a cooling system failure as occurred during the Breathe London deployment.

Data quality assurance and quality control

Data logging

Logging data correctly is vital to the overall data quality and the ability of the dataset to be used for intended analyses. Critical considerations include synchronising instruments and GPS time stamps, testing instrument response time, automating alerts for data flags, uploading data daily and ensuring consistent instrument settings throughout the campaign.

Sampling systems

The configuration and design of sampling systems affects the results obtained. In future designs, the use of metallic tubing instead of plastic, avoiding sharp bends in the tubing, and utilising shorter tubing lengths can help overcome some of these effects. Characterization of uncertainty of the data, including $PM_{2.5}$ sampling losses can be found in Appendix 3E.

2.6 Wearables study

In order to understand how children are exposed to the risk of air pollution, and where and when the risks are highest, the Environmental Research Group (ERG) at Imperial College London (formerly at King's College London) worked with five London primary schools in spring 2019 to conduct the Breathe London 'Wearables' study. The study characterised school children's exposure to air pollution and presented the information in a way that the school community could understand and act on. The five participating schools were part of the 2017 Mayor's school air quality audit programme, carried out in 50 primary schools located in the most polluted areas of London.

On average, children were shown to be exposed to higher levels of air pollution travelling to and from school (especially in the morning) when compared to being at school. Children that travelled to and from school using busy main roads were exposed to higher levels of air pollution than those that chose to walk, scoot, or cycle to school using quieter streets. The full report is presented in Appendix 4 and more information about the project, including details of the sensor evaluation reports can be found here.

PART 3 DATA PRESENTATION AND PUBLIC AWARENESS

PART 3

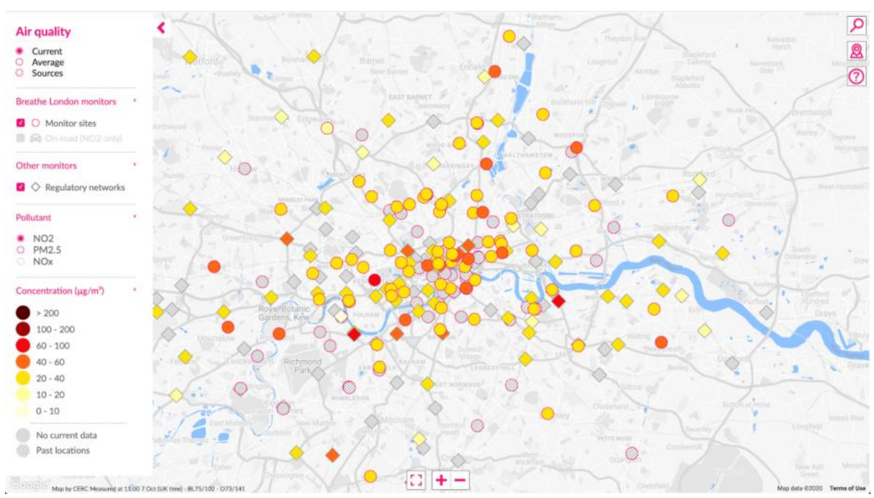
Data presentation and public awareness

One objective of the project was to share Breathe London's data and methodology through innovative and open-source platforms, with a goal to increase public awareness and support efforts to reduce pollution and improve the health of Londoners. This section of the report describes the Breathe London platform, including the project's interactive map that displayed current levels of air pollution, and the activities carried out to increase public awareness of local air pollution.

3.1 The Breathe London platform

Breathe London created a dynamic, unique online platform for sharing and visualising air pollution data with the public.[4] A number of important steps were taken to promote public access and to ease the ability for others to access the data and replicate the platform.

The interactive map was the centrepiece of the site and available in desktop and mobile versions. It was the first time all of London's air pollution readings were presented in one place – London's regulatory network, consisting of the London Air Quality Network (LAQN) and Air Quality England Network (AQE), alongside Breathe London (right).



Breathe London map showing 'current' NO_2 levels at Breathe London pods (circles) and regulatory monitors (diamonds) on 7 October 2020

The map was powered by an open-source data platform developed for the Breathe London project by Cambridge Environmental Research Consultants (CERC), with design assistance from Punk my Pixel, in close collaboration with Environmental Defense Fund (EDF), and with consultation with other partners and stakeholders, including the Project Advisory Committee ([Appendix 1](#)).

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[4]The www.breathelondon.org website domain has been passed to the new operators of the Breathe London project and may no longer contain the information described in this section. To view an archived version of the website from the pilot phase please visit https://breathelondon.edf.org/.

The Breathe London map displayed the features described in **Table 7** below; supplementary images and descriptions are provided in Appendix 11. The data were presented this way to address the variability of pollution levels throughout the day at individual sites, as well as the variability of pollution at sites across London, and to meet the needs of different types of users from the general public to citizen scientists and academics.

TABLE 7. Features of the Breathe London interactive map

Map Features	Description
Monitoring Sites	• Different icons representing each type of monitoring network (Breathe London, Regulatory and School Streets) and located at each site. • Site characteristics including location and type (kerbside, roadside, urban background and industrial). • Air quality alerts that show forecasts of expected pollution levels for tomorrow and the day after. The forecasts are taken from the free airTEXT service.
Monitoring Data	• A seven-toned heat-palette colour scale, darkening as pollution levels increase. • Breathe London pods ○ Current levels of NO_2 and $PM_{2.5}$ are presented as a point on a graph showing individual pollutant levels over the past 24 hours. ○ Average levels of NO_2 and $PM_{2.5}$. ○ The date monitoring began and, if applicable, ended at each location for each pollutant. ○ Full historic data via a time-series graph with a customisable date range. ○ A link to the Air Quality Data Commons (AQDC) for further data. • Regulatory monitors ○ Current levels of NO_2 and $PM_{2.5}$ for each regulatory monitor. ○ Links to the third-party websites where the historic data is stored. • On-road mobile data ○ Average NO_2 levels from Google Street View drives, providing average data in 30 m segments along nearly 600 km of road. • A disclaimer stating the data was provisional as the project consortium worked to refine and apply the data QA/QC procedures.
Pollution Sources	• A source apportionment tool showing the contribution of 15 source categories of NO_x pollution modelled by CERC's ADMS-Urban software. • A bar chart to visually break down each category's contribution at that site, complemented by a further breakdown of each source within that category.
Special Functions	• Selectable map layers showing different policy-related boundaries, including the existing and proposed clean air zones. • A search function that automatically found users, identified their nearest air quality monitor or mobile drive segment, and presented its pollution data. • A search function that allowed users to look for a specific monitoring pod site, road, borough or landmark name.

Breathe London's open-source data platform design is available here to enable replication by project partners or other cities around the world. The platform automatically logged and stored 1-minute data from the AQMesh pods, as well as near real-time data from the reference network. By the end of the 2-year pilot project, the Breathe London platform had loaded over 160 GB of data on the Google Cloud Datastore, including the full historical 1-minute dataset from the AQMesh pods. The Google Cloud provided a user-friendly interface and allowed querying of large datasets to generate graphs and visualisations. Google Cloud hosting also ensures scalability of the platform to much larger volumes of data, and replicability to other cities around the world.

Standardised APIs allowed third-party users and other applications to connect to the platform. Several organisations were provided with API access during the project. The API documentation is available online. Downloadable Breathe London datasets for the stationary network measurements and modelled source apportionment were made available to the public on the Breathe London website. Air Quality Data Commons (AQDC), an open-access data platform where researchers, companies and cities could share and use data from low- and medium-cost air quality sensors further hosted the stationary network and mobile monitoring datasets for download.

EDF is now collaborating with OpenAQ, a non-profit organisation focused on open air quality data, in a joint effort to host lower-cost sensor data on an expanded platform. In early 2021, the OpenAQ platform will host the stationary and mobile datasets, with full QA/QC applied, from the Breathe London pilot project.

Information about the pilot phase, including downloadable datasets and a subset of archived data displayed on an interactive map, can also be found on EDF's Global Clean Air website.

3.2 Public awareness

In addition to advancing the understanding of spatial and temporal patterns of air pollution in London, the project sought to increase public awareness of the impacts of local air pollution and the need to improve air quality. One avenue was to make Breathe London data available so it could be leveraged by various stakeholders, like engaged citizen groups, academics and government officials. For the data to be useful, the public first needed to be aware of the project.

In January 2019, the Breathe London platform was publicly launched with a press event at a central London primary school with the Mayor of London, Sadiq Khan. EDF created an informational video to tell the story of the innovative project. The launch helped to highlight the importance of the project's communications resources and staff, as they were instrumental in engaging the public by sharing important stories, extensive data and new Breathe London insights.

To further increase public awareness of the project, Breathe London:

- Created a dynamic social media presence on Twitter.
- Created a MailChimp newsletter to provide followers with project updates.
- Hosted a webinar for schools, local air quality managers and monitoring pod hosts preceding the launch of the map to demonstrate the platform and answer questions.
- Launched the interactive map in July 2019 and made periodic enhancements.
- Provided school hosts a personalised fact sheet with average NO_2 pollution levels and information on how Breathe London planned to leverage the data (see Appendix 5).

The Mayor of London's support was a key component in increasing awareness; there was a clear uptick in website visits following a Breathe London mention in one of the Mayor's news releases. The Mayor also hosted the International Air Quality Conference in October 2019, at which EDF represented Breathe London at various events around London, including showcasing the map at a special exhibition at the Science Museum and sharing an overview of the Breathe London project at the conference. EDF, along with ACOEM Air Monitors and the University of Cambridge, also hosted C40 Cities air quality leaders from around the world, showing them the Google Street View car and its special monitoring equipment at a Breathe London site visit.

EDF actively promoted the Breathe London project and data findings to news outlets and received significant media coverage. The EDF-created video introducing the Breathe London project — featured on the "About" page of the website — was nominated for a Global Sustainability Film Award, and the project itself was a recipient of a Smart 50 award by Smart Cities Connect.

Breathe London data has been used to bolster community efforts to lower pollution near primary schools and a bus garage. It has also been used by cycling campaigners and politicians as evidence for the need for clean air action, such as expanding the Ultra Low Emission Zone (ULEZ). EDF analysis revealed the impact of diesel car pollution at different spots in the city comparing levels in and outside of the ULEZ. Local advocacy groups have used the results of this data analysis to support their work. For example, Global Action Plan incorporated data into a call to businesses to let employees work from home if possible to reduce air pollution, and Clean Air for Southall used the EDF diesel story based on Breathe London data to pressure their local councillor to accelerate clean air policy.

It is important to note, however, that data alone will not inspire action. In raising public awareness, data is a strong foundation, but marketing, communications and community outreach are crucial components of any campaign and require dedicated resources.

PART 4 USING DATA AND MODELS TO INFORM POLICY

PART 4

Using data and models to inform policy

Breathe London data was used to evaluate and inform public policies that directly address pollution sources. The project partners analysed Breathe London data to assess the implementation of the Ultra Low Emission Zone (ULEZ) and identify previously unrecognised pollution hotspots. The Cambridge Environmental Research Consultants (CERC) air quality model was further used to estimate the maximum expected impact of the ULEZ on pollution levels and determine the highest contributing sources to pollution in London. This section of the report presents the findings of these analyses, while detailed methodologies are provided in supporting appendices.

The COVID-19 global pandemic also presented a unique opportunity to analyse data from the stationary sensor network in relation to restriction measures in the city, which had a direct impact on levels of air pollution.

4.1 Ultra Low Emission Zone

Breathe London's dense, distributed stationary network and mobile monitoring was used to establish a more complete baseline of air quality before the introduction of the world's first ULEZ in central London on 8 April 2019. The combination of stationary and mobile monitoring ensured both temporal and spatial coverage of measurements to assess the changes in ambient air pollution concentrations. Monitoring started around seven months before the ULEZ came into force and continued more than a year after.

ULEZ sign posted near boundary in Central London

The ULEZ policy was established by local government in 2014 for implementation in 2020. In February 2017 it was announced that the effective date would be brought forward to 2019 and that a charge would be levied on older vehicles entering the zone from October 2017, initiating the pre-compliance period. The ULEZ took effect and was enforceable in April 2019. A gradual increase in ULEZ benefit rather than an abrupt change, as can be seen in **Figure 5**, results from pre-compliance: many drivers chose to replace non-compliant vehicles prior to the effective date.

The expected ULEZ benefit during the Breathe London project was modest in relation to a large NO_2 background. Benefits occurred concurrently with other reductions in NO_2 emissions (such as natural fleet turnover) and only gradually increase throughout the Breathe London project with a possible additional "step change" around the 8 April 2019 ULEZ implementation date (see **Figure 5**). Greater London Authority (GLA) data indicates that 40% of vehicles already complied in 2017, with a total of 61% complying the month before the effective date of the ULEZ, and 77% complying 10 months after implementation.[5]

EDF analysis of reference network data showed that NO_2 air quality in Greater London, after ULEZ implementation on 8 April 2019, improved compared to the same periods in the previous year by 13%, one of the largest year-over-year reductions in NO_2 concentrations in the last 20 years. Analysis of Breathe London mobile and stationary network NO_2 and NO_X measurements are consistent with the ULEZ-associated changes observed in reference networks and expanded the spatial coverage of insights.

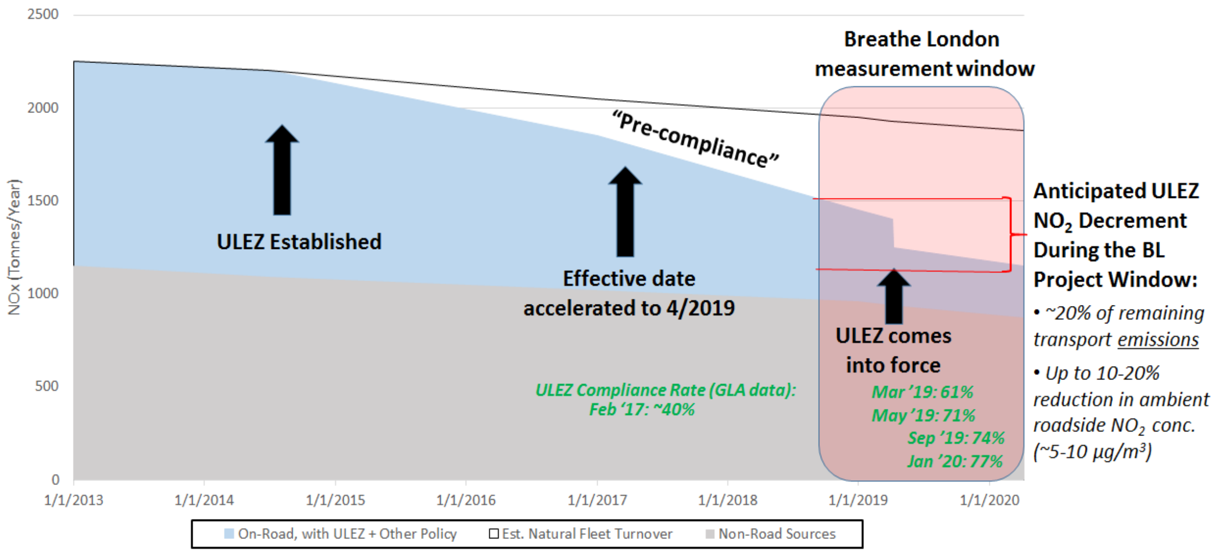


FIGURE 5. Estimated modelled changes in NO_X emissions in Central London due to the ULEZ and other policies in relation to the first year of the Breathe London project [6]

Breathe London partners analysed data to quantify the pollution reductions from the implementation of the ULEZ. However, determining the impact of policy interventions, like the ULEZ, on London's NO_2 levels is complex. Local NO_2 pollution, such as from vehicles in central London, gets mixed with pollutants that have travelled from elsewhere. Meteorological variability (e.g. wind speed, prevailing wind direction, temperature) can affect pollution levels in the atmosphere, enhancing or masking the expected ULEZ benefits. Traffic levels can also vary seasonally, further complicating simple before/after comparisons. Air quality models, like CERC's ADMS-Urban model, and detailed traffic data can help account for some of these variable factors.

[5] Central London ULEZ Ten Month Report

[6] Other policies include Low Emission Bus Zones and those that local authorities implemented as part of statutory duties to tackle air pollution, such as Low Emission Neighbourhoods. Sources of data for this figure from Central London ULEZ Ten Month Report and Proposed changes to the ULEZ, Consultation and information document, April 2017.

Mobile and stationary data assessments also found that the beneficial effects of the ULEZ likely extend beyond ULEZ borders. For example, NO_x pollution was similar or lower not only inside the ULEZ boundaries, but also in other places that were sampled in Greater London including around the ULEZ border and on main arteries into and out of Central London. This finding is consistent with the expectation that many trips that pass through the ULEZ originate or terminate outside of Central London and therefore ULEZ-compliant vehicles will also favourably impact air pollution outside of Central London. Projections of annual-average NO_2 concentrations, based on mobile observations, show the percentage of streets within the ULEZ (with sufficient mobile monitoring to analyse) that are likely to exceed the World Health Organization (WHO) annual guideline of 40 ug/m^3 has decreased from 77% pre-ULEZ to 53% post-ULEZ. NO_X and NO_2 concentrations have clearly improved and the spatial extent of concerning NO_2 pollution has decreased in places where Breathe London measured. However, without additional interventions, annual average NO_2 pollution will likely remain elevated above WHO health guidelines in many locations. Additional discussion of these findings and analysis methods are provided in Appendix 12.[7]

CERC also used innovative inversion techniques (Carruthers et al., 2020[8]) developed during the course of this project to assimilate measurements with modelled data to improve model predictions; these have been applied to assess the impact of the ULEZ on road traffic emissions (see Appendix 6), and also to estimate the impact of COVID-19 restrictions on road traffic emissions (Appendix 8A). This is an exciting area of research that is likely to be highly valuable results in future, particularly in a post-COVID world of changing traffic patterns.

4.2 CO_2 emission indices

The Breathe London consortium used the relationship of CO_2 to NO_x and other health-impacting pollutants to improve both our understanding of London air quality, and the modelling tools used to assess it. Primary pollutant emissions (NO_2, NO_x, $PM_{2.5}$) are associated with combustion sources and therefore with CO_2 emissions. The ratio of pollutant to CO_2 from an emissions source is termed the "emission index" and is generally distinct for each vehicle type or combustion source. Knowledge of the emission index is thus a key additional test of an emission inventory, which is critical information required for policy intervention decisions.

Analysis of stationary sensor network data

The inclusion of CO_2 measurements as part of each Breathe London AQMesh pod enables the estimation of emission ratios at each AQMesh location. With the method deployed, this is only possible if the network has high time resolution measurements, as is the case with Breath London, which allows local emissions to be separated from the non-local component due to long range transport (i.e. CO_2 signals of 10-50 parts per million [ppm] against a background of 400

[7] This report is currently being adapted for publication in a scientific journal and will be available in due course. An embargoed version of the report can be shared with interested researchers upon request globalcleanair@edf.org.
[8] Carruthers D, Stidworthy A, Clarke D, Dicks J, Jones R, Leslie I, Popoola OAM and Seaton M, 2019: *Urban emission inventory optimisation using sensor data, an urban air quality model and inversion techniques*. International Journal of Environment and Pollution, vol. 66, issue 4, pp. 252-266, DOI: 10.1504/IJEP.2019.104878.

ppm, and the equivalent local component for other pollutants being used for the determination of emission ratios). This method has been used extensively with low-cost sensors by the University of Cambridge group, for example for a study at Heathrow Airport for deriving emission ratios and to remove the effects of meteorology (see Appendix 7B). A description of this study is provided in the peer reviewed literature (Popoola et al., 2018[9]).

This analysis approach will also be used in evaluating the impact of the ULEZ in Central London. It will also play a key role in the analysis of the various COVID-19 related lock-down restrictions in the UK in 2020, where significant road traffic reductions have taken place.

Analysis of mobile data

The high time resolution (1-second frequency) mobile measurements made by the Google Street View cars offered the opportunity to distinguish recently, locally emitted components of the total concentration of a pollutant at measurement locations. The value of the ratio of recent local NO_X and recent, local $PM_{2.5}$ to recent, local CO_2 gives an indication of the types of engine and exhaust systems that produced the emissions. These emission ratios were compared with equivalent ratios in the emissions inventory typically used for modelling air quality in London, to provide insight into the accuracy of both the emission factors and the relative numbers of different vehicle types used in compiling the inventory. An assessment of the ULEZ and the insights gained by applying this methodology to both pre- and post-implementation periods, as well as inside and outside the ULEZ boundary, can be found in Appendix 7A.

4.3 COVID-19 impact analysis

Following COVID-19 confinement measures, Breathe London analysis shed new light on NO_2 pollution levels in the city (**Figure 6**). EDF analyses revealed substantial NO_2 pollution reductions after the measures went into place, particularly after social distancing was strongly encouraged on 16 March 2020. The greatest changes were between 6 am and 10 pm – from 17 March to 13 April 2020, monitors registered a 9-17% drop in NO_2 pollution across the network, with monitors in central London showing a greater reduction with an average of 20-24% drop in NO_2 pollution.

Based on data from the Waze For Cities Program, EDF also found an apparent association between the reduced pollution levels and lower traffic congestion, or traffic jams, on London roads. Specifically, traffic congestion was reduced to such an extent that traffic was approaching free flow in most Greater London roads after the stay-at-home order. Analysis of the daily patterns of traffic congestion, showed that the biggest drops in pollution and the biggest drops in congestion occurred during the same time period — in the late afternoon from around 3:00 pm to 7:00 pm. Details of the analysis undertaken to understand the impact of confinement measures due to COVID-19 on air pollution can be found in Appendix 8.

[9] Popoola, O. A., Carruthers, D., Lad, C., Bright, V. B., Mead, I.M., Stettler, M., Saffell, J. and Jones, R.L. (2018). *The use of networks of low cost air quality sensors to quantify air quality in urban settings*. Atmospheric Environment 194, 58-70. https://doi.org/10.1016/j.atmosenv.2018.09.030.

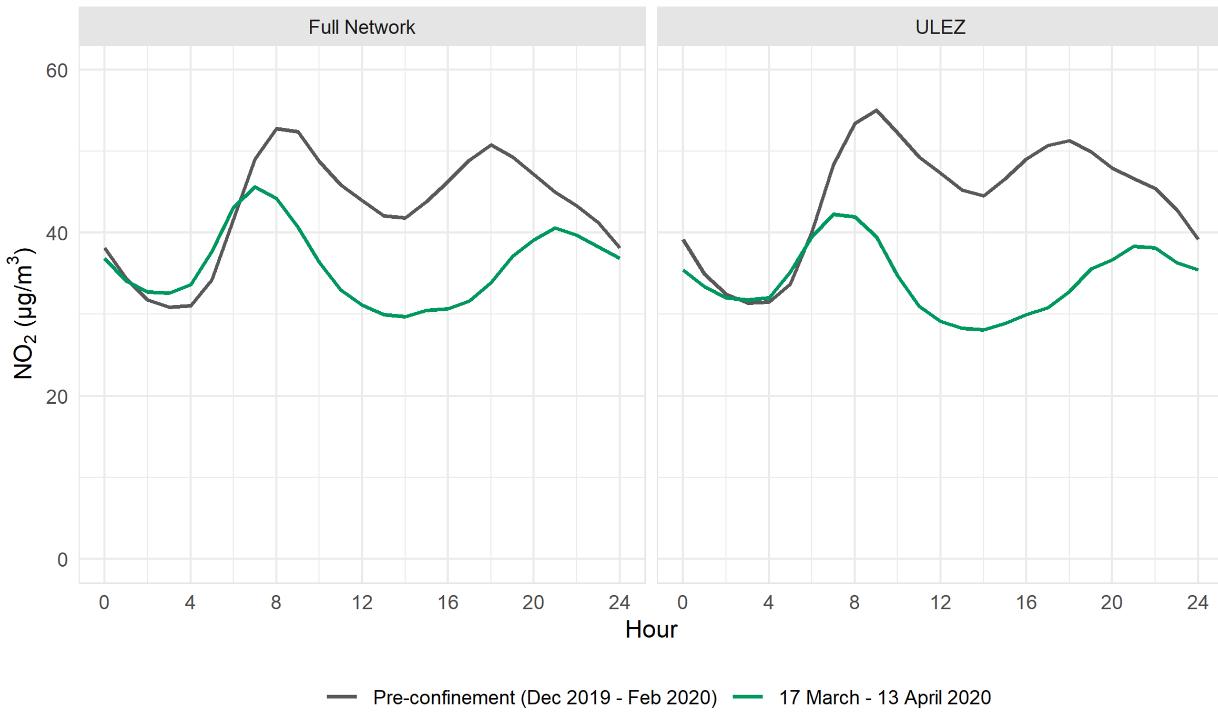


FIGURE 6. Observed changes in NO_2 pollution levels (µg/m³) measured across the full Breathe London network (left) and Breathe London monitors inside the ULEZ (right) during the first four weeks of the UK's national lockdown in March-April 2020

4.4 Source apportionment modelling

In the second year of the project the modelling was updated from 2018 emissions to 2019 emissions, and then further updated to incorporate the findings of the 'Hotspot analysis' (Appendix 9). CERC used the ADMS-Urban air quality model to conduct a source apportionment study to determine the highest contributing sources to concentrations of NO_x and $PM_{2.5}$ at specific locations in London. The modelling was carried out at all locations of Breathe London AQMesh sensors and regulatory network monitors and an additional 3623 discrete receptors representing schools, care homes and hospitals across London for 2019 (see Appendix 6 for more details).

Source apportionment analysis was carried out for 23 categories for NO_X and 25 categories for $PM_{2.5}$, including 10 traffic exhaust categories, traffic non-exhaust emissions, 4 fuel usage categories and 11 other non-traffic categories. Traffic sources dominate the NO_X concentrations, with the concentrations at all sites from traffic sources attributable to at least 32% of the total concentrations and reaching a maximum of 73% at Kerbside monitoring sites outside the ULEZ. Of the traffic sources, Diesel Cars, Diesel LGVs and TfL Buses are the highest contributors. Inside the ULEZ, concentrations are higher across all site types, with a marked increase of 40 µg/m³ from Hospital sites outside the ULEZ compared to inside. The percentage of commercial and domestic fuel usage approximately doubles inside the ULEZ, which is largely dominated by gas combustion.

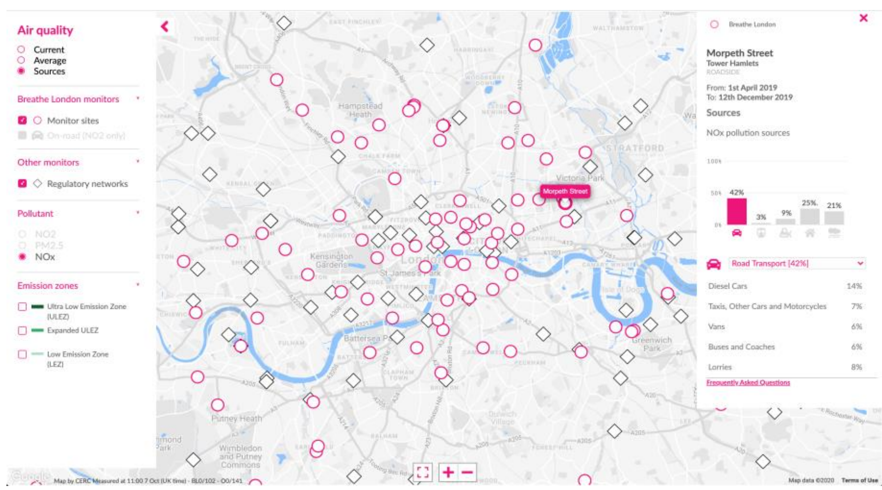
For $PM_{2.5}$, the concentrations are dominated by background pollution that originates outside London. The Kerbside, Roadside sites inside and outside the ULEZ, and Hospital sites within the ULEZ have the highest traffic components with 30% and 29%, for the sites that are nearby roads in the ULEZ, 31% and 25% for the sites located near the roads outside the ULEZ and 22% for the ULEZ Hospital sites. Traffic sources are almost entirely dominated by Brake, Tyre and Road wear.

Using the results from the source apportionment analysis, three policy scenarios were assessed to estimate the impact of:

- replacing all Transport for London (TfL) buses with zero emission buses;
- making all taxis zero emission taxis; and
- implementing (a) and (b) together.

The largest NO_X reductions are at kerbside sites within the ULEZ when both TfL Buses and Taxis have zero exhaust emissions, with a reduction of 27.3 µg/m³ (23%) in NO_X concentrations, and a reduction of 9.1 µg/m³ (18%) in NO_2. A larger proportion of the reduction is attributable to the zero emission TfL Buses. There is minimal (<1 µg/m³) reduction in $PM_{2.5}$ annual average concentrations, because the policy action only targets exhaust emissions, and the bulk of road traffic $PM_{2.5}$ emissions are associated with the non-exhaust component of emissions.

Additionally, modelling results from the year 1 source apportionment analysis using a 'pre-ULEZ' emissions scenario – standard emissions from London's Atmospheric Emissions Inventory (LAEI) for 2019, representing 67% compliance with ULEZ criteria – were added to the Breathe London map. The feature enabled anyone interested in learning more about sources of NO_X pollution to select a monitoring location and view the breakdown of sources contributing to concentrations experienced at that location, such as diesel cars and heating of commercial buildings (more details on the features of the Breathe London map are provided in Appendix 11).



Breathe London platform showing the pollution sources layer. The interactive bar chart provided a breakdown of NO_x contribution from different pollution sources, such as road transport, at Breathe London and regulatory monitoring sites.

4.5 Improvements to London's air quality model

CERC's ADMS-Urban modelling software was used throughout the Breathe London project to simulate pollution measured by the Breathe London stationary sites, the Breathe London mobile instruments and the reference networks. Comparisons between modelled and measured data provided new insights into areas, or pollution hotspots, where London emissions data need to be improved and areas where model refinements were needed (see Appendix 9). Comparisons also played an important part in the QA/QC of the Breathe London measurements themselves. This work produced recommendations for improvements to London's air quality model, including updated baseline maps of air quality and source attribution data by activity sector (see Appendix 6 for more details).

4.6 Hyperlocal mobile insights

EDF made novel use of the unprecedented spatial coverage and hyperlocal resolution of on-road pollution data from the mobile monitoring campaign to extract valuable insights, despite low temporal coverage with just two Google cars driving largely during the daytime and on weekdays. Results of these analyses provide both policy-relevant findings and replicable methods for accounting for uncertainty associated with low-frequency sampling that may be useful to organizations with a use case for mobile monitoring but limited time or resources.

The EDF analyses included: a hyperlocal (street-level) assessment of pollution central tendencies, an analysis mapping vulnerable streets that are likely to exceed annual-average reference limits on pollution along with less vulnerable locations, and characterization of mobile pollutant:CO_2 emission ratios spatial patterns and temporal trends as well as demonstration of their usefulness in the case of evaluating ULEZ policy. These analyses are described in detail in Appendix 13.[10]

4.7 Hotspot analysis

The unprecedented levels of air pollution data collected in this project allowed for the identification of pollution hotspots not registered by the regulatory monitoring network or present in London's air quality model. Several months into monitoring, it was noticed that one Breathe London pod was consistently measuring higher NO_2 levels than the rest of the network (see **Figure 7**). The monitor was located near the entrance of the Holloway Bus Garage, at the end of a residential street. Interestingly, the pod was often registering significantly higher NO_2 levels than the regulatory monitor down the road. The diurnal trend of NO_2 levels observed at the Bus Garage compared to the network average revealed elevated concentrations.

[10] The Appendix 13 report is currently being adapted for publication in a scientific journal and will be available in due course. An embargoed version of the report can be shared with interested researchers upon request globalcleanair@edf.org.

As a result of these findings that were highlighted on the Breathe London platform, Transport for London, the government entity responsible for Greater London's transport system, worked with the bus operator to find ways to reduce pollution and improve air quality, including working on eliminating engine idling. This is an excellent example of the way hyperlocal data can be used to pinpoint local sources of elevated pollution that are missed by pollution models.

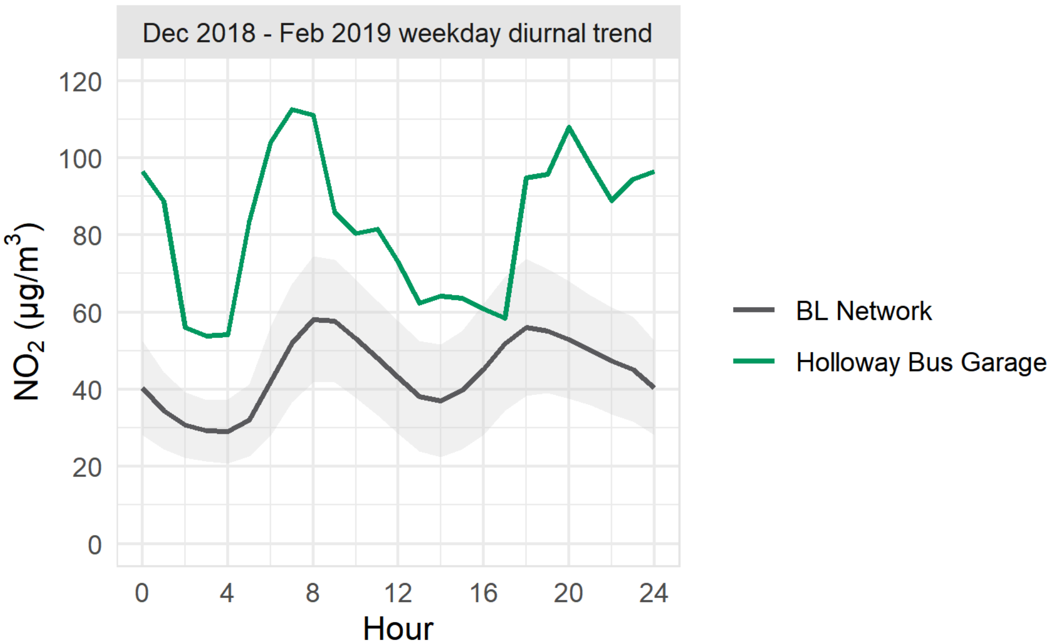


FIGURE 7. Diurnal weekday trends of NO2 hourly average concentrations (µg/m3) at the Holloway Bus Garage monitoring site (green line) compared to the Breathe London network average across the whole of London (black line, +/- one standard deviation in grey) from 1 Dec 2018 to 28 Feb 2019

Detailed hotspot analysis was also carried out by CERC at 12 locations across Greater London, including Holloway Bus Garage, by comparing measured concentrations with simulated concentrations from the ADMS-Urban air quality model. This process helped to identify potential refinements in the modelling approach, issues with monitoring data and areas were London's Atmospheric Emissions Inventory (LAEI) used in London's air quality model could be improved. Recommendations for model improvements and details of the analysis are included in Appendix 9.

PART 5 REPLICABILITY, LEARNINGS AND RECOMMENDATIONS

PART 5

Replicability, learnings and recommendations

As one of the first pilot projects of this scale, Breathe London successfully deployed an extensive network of lower-cost sensors and conducted mobile monitoring across a major global city. This experience has yielded a number of important reproducible tools, models and methodologies for use by cities and other interested individuals and groups in designing, maintaining and using data from lower-cost air sensors and mobile monitoring. Learnings and recommendations related to project resourcing, monitoring design and data analysis have also been produced that can advise and guide other global cities looking to undertake efficient and effective hyperlocal monitoring campaigns.

5.1 Reproducible project components

The data collection processes, quality assurance and control procedures and open-access data platforms developed through Breathe London provide a blueprint for others to implement and scale similar lower-cost networks of stationary and mobile, hyperlocal air quality monitors. A summary of these reproducible components and the appendices to this report where further details and resources may be found are provided below in **Table 8**.

TABLE 8. Summary of reproducible project components from Breathe London

Project component	Resources	Description of reproducible elements
1. Data collection, QA/QC and analysis	Appendix 2 Appendix 3 Appendix 6 Appendix 8 Appendix 9	• Stationary and mobile data collection standard operating procedures, monitoring plans and QA/QC protocols that serve as prototypes for other cities to adapt and use, including calibration via the gold pod co-location technique for cities that do not have a full "network" to use the network calibration method. • Modelling techniques including assimilation of air quality observations into a model to modify pollution emission rates based on local measurements.
2. Network calibration method	Appendix 2	• Methodology described in detail; a scientific publication to enable replication of the method is forthcoming. • Remotely calibrates pods across a stationary sensor network without the need for extensive physical co-location, reducing cost and effort.
3. Data sharing platform	Section 3.1 The Breathe London Platform	• Allowed the public to interact with project data and is open-source and based on the Google Cloud. • Using cloud technologies makes the platform more reproducible because it uses common architecture available from many different cloud providers and does not require sophisticated computing resources on premises.
4. Emission ratios analyses[11]	Appendix 7 Appendix 12 Appendix 13	• Demonstrated the value of monitoring CO_2 alongside air pollutants to derive insights into pollution sources. • Methods and tools used to manage and assess both pollution and policy using mobile data.

5.2 Key learnings and recommendations

The learnings accumulated through all aspects of the Breathe London pilot project highlight the success of the project and reflect the challenges that the partners faced and largely overcame in implementing a large-scale monitoring campaign. The knowledge gained through implementing the project has also informed valuable recommendations for anyone aiming to utilise similar hyperlocal monitoring techniques to assess air pollution. Learnings from year one of the project informed EDF's how-to guide for mapping hyperlocal air pollution, which provides considerations for cities to design effective monitoring networks or data collection campaigns. Following an additional year of monitoring and data analysis, Breathe London can provide even further resources and advice. Learnings and recommendations from the full 2-year pilot project are given below and a more comprehensive list is included in Appendix 10.

[11] Appendix 12 and 13 reports are currently being adapted for publication in a scientific journal and will be available in due course. An embargoed version of the reports can be shared with interested researchers upon request globalcleanair@edf.org.

Sensor-based networks and mobile monitoring are valid monitoring approaches

Breathe London data produced insights that were broadly comparable to findings from London's reference network, suggesting that cities can use lower-cost, sensor-based networks and mobile monitoring to identify and characterise pollution levels and to assess and evaluate policy interventions (see Appendix 12 and 13). By extending the network and mobile measurements to include CO_2, it also showed how important additional information could be obtained.

The project deployed lower-cost sensors and mobile monitoring to understand whether cities are able to these approaches to learn about specific pollution challenges and opportunities. Breathe London demonstrated that – with rigorous QA/QC procedures – lower-cost sensor systems and mobile monitoring can yield reasonably accurate, precise, stable and informative data when used in real-world conditions.

To get the best results from a monitoring project, the Breathe London team suggests four key recommendations based on learnings throughout the project:

1. **Build in adequate resources from the outset**

   Breathe London required considerable resources to build, test, deploy and maintain both the stationary sensor network and the mobile data collection platforms – substantially more resources than the project consortium initially anticipated. However, it is important to recognise that future projects could benefit from many of the advances made within this project, leading to significant efficiency and cost savings in the future.

   All project partners provided additional resources and support to ensure that both the stationary and mobile data collection remained on schedule. Ideally, a project of similar scale to Breathe London should have multiple team members dedicated full-time to maintenance and operation of the data collection platforms, with regular assessments of whether more resources are needed to maintain high data quality. **Table 9** below provides a description of the roles of those involved in Breathe London and the number of full-time staff needed for each the stationary and mobile monitoring campaigns as well as a summary of their duties. These estimates provide a guide for other global cities to scale their resources according to the spatial coverage, duration and type of monitoring campaign.

TABLE 9. Estimated staff needs for stationary and mobile monitoring campaigns

Roles	Number of staff		Duties
	Stationary	Mobile	
Senior Manager	1		Overseeing all aspects of the project including relevant reporting.
Project Manager	1	1	Project management of each monitoring scheme.
Operations Manager	1	1	Logistics for all aspects of the procurement, installation, maintenance and co-location of instruments.
Communications Manager	1		Addressing and producing all communications (i.e. print, social media) for monitoring campaigns.
Communications and Project Coordinator	1		Addressing and coordinating responses to all correspondence. Coordinating meetings and assisting managers.
Air Quality Scientists	2 - 4		Designing monitoring scheme, developing QA/QC to data, assessing pollution and performance of monitoring network, and ratifying data. This includes at least one Senior Scientist.
Data Analysts	3		Applying QA/QC to data, assessing pollution data, and producing datasets. This includes at least one Data Scientist.
Maintenance Technician	1	0.25	Conducting installations, maintenance and repairs.
Drivers	-	2 - 4	For two cars on mainly weekday, daytime shifts only (approximately 8-hour shifts).
Website Designer	0.5 - 1		Designing and building website including visualisation of data. Ensuring platform and relevant data-feeds are functioning and up to date.

TABLE NOTES:

- This list does not include staff management and resources (Finances, Human Resources, Payroll, Line Management, etc) nor does it account for other overheads.
- This is a list for running networks of similar scale to Breathe London, communicating results, and undertaking policy and pollution assessments, not to develop methods such as the cloud-based network calibration or undertake modelling activities.
- Costs will depend on the rates for these specialists in the cities that the project is deployed.

2. Build in sufficient time to test and prepare prior to deployment

The project was originally designed to obtain a sufficient baseline of data before the implementation of the Ultra Low Emission Zone (ULEZ) in April 2019. As a result, the timeline between securing contractual agreements with technical partners and sensor deployment was extremely tight. More time to calibrate and perform additional quality control on the evolving sensor technology would have been beneficial. The team also encountered delays in obtaining permissions to install equipment at suitable sites and had to make compromises in the choice of monitoring locations.

Future projects require careful planning and enough lead-times for optimising the sampling strategy and preparing and testing equipment. Accelerated timelines could compromise the quality and utility of data gathered, especially with newer technology. The simultaneous deployment of the stationary and mobile monitoring components created additional pressures, and one way to lessen strain on a project's capacity would be to phase these deployments.

3. **Align expectations around release of provisional data**

The desire to provide the public with data that was both near real-time and robustly validated was a key tension of the Breathe London project. Although it is common practice for regulatory networks to release provisional data, there are additional uncertainties associated with data from lower-cost monitors. Prior to the initial data release, Breathe London partners had not fully discussed the risks of providing provisional data that had undergone only minimal validation and were subject to change after further evaluation. The project consortium elected, in this case, to err on the side of caution by pursuing a more rigorous verification process prior to the initial data release, which led to a delay from the project's expected timeline. Project partners should clearly define levels of data quality at the outset and agree on what is acceptable for public release, and with what caveats, at different stages of the project.

4. **Recognise the challenge of successfully assessing policy interventions**

Assessing policy interventions with air pollution data takes time, expertise and suitable data quality, so it is essential to factor these into the timeline and resources. When designing a monitoring network, consider policy aims from the outset to ensure the most appropriate method of stationary or mobile data collection. However, using lower-cost technology brings greater instrument uncertainty, compared to traditional reference-grade air quality monitors, which needs to be taken into consideration when determining the type of monitoring necessary to achieve the objectives and when analysing the data. The counterpoint is that innovations such as the inclusion of CO_2 for emission ratio determination and assessment of the impacts of interventions can reduce uncertainties caused by meteorological variability.

Finally, the setup of the air quality model needs to be aligned to ensure that the output is optimal in determining the impacts on air quality of specific policy interventions which may be difficult to distinguish from other trends in pollutant concentrations. Model limitations should be understood, both in input data and in the model descriptions of the complex physics and chemistry in urban areas, as these may impact the ability to answer policy questions or test scenarios. Projects should carefully consider the resolution/number of receptors for modelling, source categories that can be modelled based on existing emissions inventories, the time it takes to run simulations (i.e. days or weeks), the time needed to analyse, interpret results, and present to the public or other relevant stakeholders.

5.3 Conclusion

The Breathe London pilot project has achieved the overarching aims, goals and objectives it set out to accomplish. Notably, the project found that lower-cost sensors and mobile monitoring may be used by global cities to identify and characterise pollution levels and to assess and evaluate policy interventions, yielding results that are broadly comparable to those based on reference network data. Breathe London data was used to characterise spatial patterns of air pollution across the city, to find a significant hotspot at a bus garage that had not been picked up by local monitoring and state-of-the-art modelling, and to assess pollution reductions resulting from the city's world-renowned Ultra Low Emission Zone. The project also showed how air pollution data may be displayed in new, open-source, dynamic, and innovative ways, providing a single location to view current pollution levels at monitors across London along with easy-to-understand visual aids to revealing how pollution rises and falls throughout the day – in order to catch the public's eye and raise awareness of air pollution.

The project has advanced the science and practice of collecting and analysing data with lower-cost sensor systems and mobile monitoring. The findings in this report provide a roadmap for global cities on how they too may use these technologies to complement a city's regulatory grade monitors to assess and target air pollution. This includes practical guidance to inform the design and implementation of a monitoring campaign, including an innovative network calibration technique that reduces manual activities. It also provides insights on how to use other novel tools, like measuring CO_2 alongside other air pollutants to better understand local emissions. Taken together, the outcomes of Breathe London reveal that these networks can be reliable and provide valuable insights to the public and to policy makers for improving air quality and, in turn, people's health.

PART 6 APPENDICES

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Appendices

Appendix 12 and 13 reports are currently being adapted for publication in a scientific journal and will be available in due course. An embargoed version of the reports can be shared with interested researchers upon request globalcleanair@edf.org.