OxAir Air Quality Sensor Pilot

Trialling of low-cost air quality sensor technologies as part of the wider future air quality evidence programme for Oxford, to inform policy decisions, raise public awareness and support personal behaviours.

Prepared by OxAir, April 2021 for Oxford City Council

Executive summary

OxAir is a local urban air quality project led by Oxford City Council and delivered by local stakeholders. The project was born out of a community action initiative in partnership with Oxford City Council. Its current implementation seeks to evaluate the role and place of low-cost sensors within the context of:

- Delivering air quality policy geared towards the City of Oxford e.g. Local Air Quality Management (LAQM) type activities
- Cultivating an active, bidirectional dialogue with residents on the need and opportunities for improving AQ
- Supporting the information needs of residents that might encourage decisions to reduce personal contributions and exposures to air pollution

The partnership submitted a successful bid for funding through the Defra Grant aid programme to deploy low-cost sensors within Oxford to evaluate their performance and determine their suitability for these purposes.

Over the period of summer 2019 to autumn 2020, OxAir established a temporary network of low-cost air quality (AQ) sensors. The network and its ancillary activities were designed to test and trial the technology(s) chosen as a source of high spatio-temporal resolution evidence to support the goals outlined above. Key components of the OxAir work programme responded to sensor performance relative to local reference measurements, data handling needs, ease of use / application within both air pollution mapping and citizen science context and the information needs and attitudes of local communities towards AQ. Qualitative data was recorded throughout the Competency Group (CG) social research exercise which contextualise circumstances surrounding air pollution exposures and attitudes to AQ.

The sensor technologies chosen for OxAir included the Alphasense Electronic Diffusion Tube (EDT - version 1), and a prototype Praxis Handheld device (PHH) supplied by South Coast Science Ltd. These sensors were chosen based on price, reputation, and the ubiquity / reliability of sensor components within mainstream UK sensor systems.

Key findings from the study on these themes are outlined below.

1. Raw, unprocessed data from the two low-cost sensors tested showed uncertainty estimates outside of the data quality objectives set by the European Directive on ambient AQ (2008/50/EC).
2. As such, the raw, unprocessed low-cost sensor data was not viewed as fit for purpose for LAQM type activities, which inherits rules and guidance on uncertainty from the AQ Directive
3. Validation of raw sensor data was demonstrated using manual methods (a human AQ expert) and automated methods (a computer).
4. Validation delivered up to a factor of 5 improvement uncertainty to levels that approached or exceeded the levels required for European Directive on ambient AQ and therefore LAQM.
5. The high spatio-temporal resolutions achievable with both fixed and mobile sensor observations and the flexibility of the techniques offer potential e.g. short-term hotspots identification / characterisation, exposure assessment and progress the monitoring of measures to improve AQ.

6 Potentials for short-term hotspots identification / characterisation, exposure assessment and progress the monitoring of measures to improve AQ are limited by the uncertainty of raw observational data.
7 The evidence base from mobile sensor observations as a tool for LAQM requires further research. Although successful as a data collection technique, insufficient data were collected to robustly assess the method. Anecdotal evidence also pointed towards additional interferences previously not consider e.g. sensitivity to vibration and air velocity.
8 Sensor reliability was an issue commonly experienced by AQ experts and lay AQ practitioners alike and resulted in low data capture and frequent maintenance.
9 The sensor systems used within OxAir were targeted at experienced AQ professionals and not suited for use by the general public. Although this was a deliberate decision to maximise quality of measurements – the sensors were expected to deliver better data quality - there was a steep learning curve for inexperienced users which could be off-putting.
10 Using sensor systems in controlled, fixed locations gave good spatial distribution information about pollutant concentrations.
11 The OxAir competency group presented a useful engagement vehicle - providing valuable insight into public perception of air quality, local knowledge of hot spots, pinch points, ideas for improvements and operating equipment to evaluate their typical exposure. The consultation showed that local engagement is a key component in the process of understanding, measuring and implementing air quality action plans.

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1 Introduction

OxAir is an Oxford City Council lead urban air quality project trialling low-cost sensors for ambient air quality (AQ) assessments. The project aims to generate an improved local evidence base to support decision making in AQ policy and engage with the public to promote positive actions to reduce poor AQ and exposure to it.

As a Local Authority committed to Local Air Quality Management (LAQM), Oxford City Council is acutely aware of the need to act and manage air quality at a local level. Well informed local policies and measures are essential to deliver changes to AQ in the shortest time possible and for the protection of our residents from exposure to air pollution. Our need for local evidence in Oxford is reinforced by the high level of engagement we experience with residents on the subject. Within this context an improved local AQ information landscape would enable residents and visitors to Oxford to make informed personal choices which can have a positive impact their health and that of the city in general. Furthermore, the trade-offs between a compliance based AQ management approach (e.g. the limit values for NO2 / particles), and one structured around achieving the greatest net public health and economic benefit per unit area remains a critical issue requiring more data to support research.

As a city, Oxford measures AQ in over 75 locations and conducts air emissions and AQ modelling research which contributes to our local policies to reduce and manage air pollution. Even so, a more responsive local understanding of when, why, and where pollution levels are worst would greatly support in making and taking localised action on poor AQ and support a shift in personal behaviours to reduce exposure.

In November 2019, OxAir submitted a bid to Defra for grant funding to assess low-cost sensors to supplement the monitoring already undertaken in Oxford, to specifically address these gaps in knowledge.

1.1 Aims & objectives

With the overarching goals and drivers set out above in mind, a summary of project specific objectives and benefits thereof are set out in the Table 1 below.

Table 1 Proposed OxAir objectives and anticipated AQ benefits

OxAir objective	AQ benefits
Higher spatial and temporal resolutions in the evidence base.	Improved monitoring of the effectiveness of policy measures / interventions.
Improved data to support cost benefit analysis of major policy interventions.	Effective LAQM via access to information on performance of measures.
Improved information and engagement with the public on sources, effects of air pollution and behaviours and travel choices to limit it.	Improving understanding of local AQ cause and effect, fostering a sense of ownership and empowering choice(s) to minimise adverse health outcomes (behavioural transformation).
Progress towards improved estimates of personal exposure to air pollution.	Better evidence for understanding the health effects of real world AQ exposures and development of relevant

OxAir objective	AQ benefits
	policies.
Simple, replicable standard operating procedures for AQ sensors (SOPs) that scale to other locations.	More reliable and replicable methods for AQ sensors, promoting data quality and reducing barriers to sensor data as part of the day-to-day AQ evidence base.
An easy access, impartial platform to share information on the performance of sensors.	Improved choice of technologies to promote data quality and reducing barriers to sensor uptake in the evidence package.

1.2 Structure of this report

This report is structured around the key project outputs which respond to our project objectives as outlined below. Where appropriate, key outputs from each section are summarise in a 'key notes' breakout box at the start of the section.

Section	Content
2	Introduces the project team
3	A summary of OxAir's AQ sensor technology and key observations arising from operational use
4	Sets out OxAir's sensor network configuration and sampling strategy
5	Details work undertaken to evaluate sensor performance and correct for common issues
7	Presents results of sensor measurements undertaken
8	Summarises social research and public engagement activities undertaken
9	Presents conclusions and recommendations from the project

1.3 External influences on the project delivery

Oxford City Council and the project team acknowledges that there was, inevitably, variance in the programme outlined within this document and that of our proposed study. This variance has largely been due to unanticipated external influences including.

- The Coronavirus pandemic and its emergency measures
- Delays in the delivery of sensor hardware (of up to 5 months) which necessitated the cancellation of the initial order(s), procurement of replacement devices, and reorganisation of the project timeline, budgets, and scope - within the context of the original project brief and proposal.

  Recasting of the project around these factors was conducted internally by the project team, its steering group and communicated with Defra throughout the quarterly reports.

2 OxAir project team

In assembling the project team, Oxford City Council recognised the urgent need for this work, its obligations to the delivery of core public services and internal resource constraints. In response to these, Oxford City Council proposed a hybrid project team and delivery model. The team structure is presented in Figure 1 below.

Figure 1 OxAir project team and delivery model

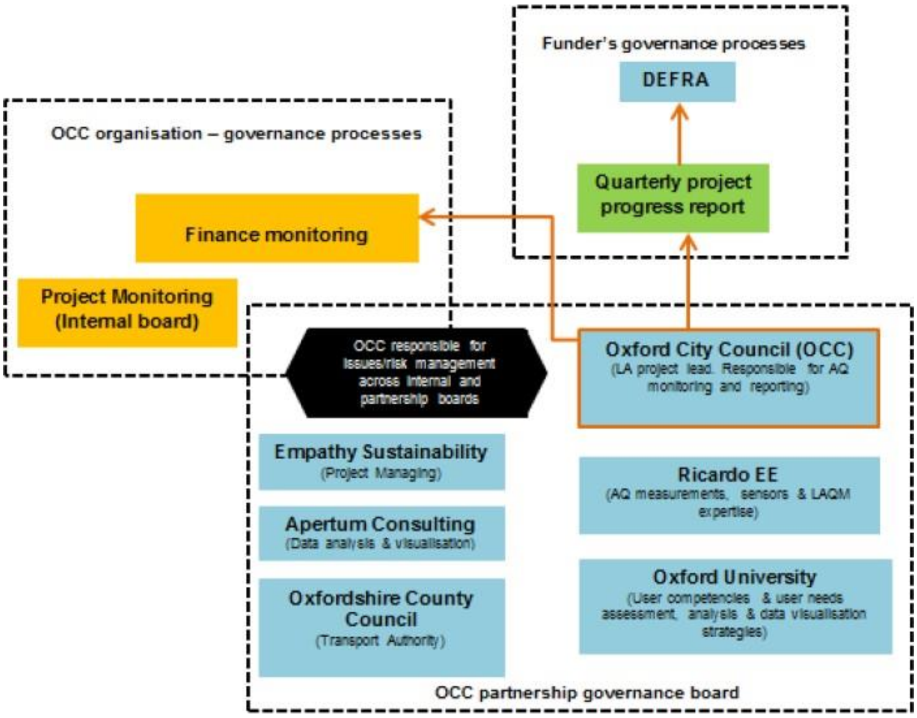


Figure 1 illustrates Oxford City Council's high-level project directorial role within OxAir, being responsible for overall project monitoring and acting as a single point of contact with Defra for reporting. Day-to-day project management and reporting was outsourced to a designated team within the OxAir partnership. With this relationship in place, Oxford City Council were confident in delivering the project without compromising obligations to its core public services. More on the project team can be found in Appendix A.

3 OxAir air quality sensor technology

The low-cost AQ sensor marketplace is diverse, with suppliers and technologies to suit every price point. Bearing in mind OxAir's aims and objectives, it was important to source sensors that delivered value-for-money, reliability, and data credibility. With the experience of our project team' we identified suitable candidates guided by the themes below.

Pricing. Delivery at scale was a long-term aspiration that would support overall project aims. Unit pricing in the low £100s was highly attractive.

Transparency. OxAir recognised that a significant barrier to the acceptance of sensor technology as part of the LAQM tool kit was the lack of transparency in the typical sensor data pipeline – the journey from sensed observation to an AQ concentration data point is frequently closed, proprietary information. Technology which supported an open ethos, or at least a less closed approach to data processing would be beneficial. This would help AQ communities to understand how data were produced and the idiosyncrasies of sensor performance under some environmental conditions.

Reliability. Low-cost sensor systems in general, have a reputation for not transferring the accuracy and precision demonstrated in the laboratory to the field environment. In the absence of open field trials demonstrating sensor performance, either relative to a reference method or otherwise, anecdotal evidence on the reliability and performance was important. The OxAir team benefited from contacts within the AQ standards community who provided guidance on those sensors that were well regarded within the broader European sensor communities.

Key notes

- OxAir's used the Alphasense electronic Diffusion tube (EDT) and South Coast Science Praxis Handheld (PHH) device
- The devices offered valuable flexibility in deployment as both static and mobile units
- Both devices were low footprint and offered battery power
- The EDT device was more environmentally robust, being weather proof and designed with fixed measurement in mind
- The PHH device was primarily aimed at portable monitoring being both GPS and Wi-Fi enabled but had fixed measurement applications with suitable sheltering and power
- The application of the EDT was more limited - finest time resolution of the version available to OxAir being 1-minute and constrained to 1 gas (NO_2) at a time
- The PHH device delivered data down to 10-second resolution for NO_2 and particles
- The data download workflow for the EDT was clunky
- The PHH GPS capability was an excellent feature but not as reliable as hoped for
- The PHH sensor was thought by some to be a little too big for portable sensing
- The data download workflow and dashboard of the PHH sensor were excellent
- Sensed data from the PHH device display less noise
- It was difficult to identify correct operation of either device in the field

3.1 Low-cost sensor technologies

The sensor technologies / systems chosen for use within OxAir were the Alphasense Electronic Diffusion Tube (EDT), and a prototype Praxis Handheld (PHH) device supplied by South Coast Science.

3.1.1 The Electronic Diffusion Tube sensor (EDT)

- Alphasense Electronic Diffusion Tube sensor (version 1)
- Species measured - nitrogen dioxide, (others available), temperature and relative humidity.
- Battery powered, Lithium AA cells. Lifetime - several months.
- Low form factor - length ~19 cm, diameter (max) ~4 cm.
- Highest time resolution available 30 seconds to 1 minute.
- Alphasense NO2-A43F electro-chemical NO_2 sensor.
- Solid state internal memory offering several weeks to month storage space.
- Free street furniture mount / weather shield
- Android App for device connectivity, troubleshooting and data processing / download.

Picture 1 Alphasense Electronic Diffusion Tube sensor

3.1.2 The Praxis Handheld sensor (PHH)

- Species measured - NO_2, PM_{10}, $PM_{2.5}$, PM_1, particle counts, temperature, relative humidity. location.
- Power - rechargeable internal LiPo battery, 8-9-hour lifetime & 5-volt DC mains power & charging unit (supplied).
- Low-medium form factor - ~23 x 12 x 4.5 cm (max.)
- Highest time resolution - 10 seconds.
- GPS enabled.
- Alphasense NO2-A43F electro-chemical NO_2 sensor.
- Alphasense R1 Optical Particle Counter (OPC) - PM_{10}, $PM_{2.5}$, PM_1, particle counts.
- Solid state internal memory offering several months storage space.
- Configurable Wi-Fi.
- Remote data acquisition via MQTT (whilst on Wi-Fi).

- Cloud based data storage on AWS & dashboard

Picture 2 South Coast Science Praxis Handheld NO_2 and particles sensor

3.1.3 Data acquisition

The EDT and PHH sensors implement different data acquisition methods, outlined below.

EDT data acquisition

The Alphasense EDT logs sensor observations internally to solid state disk at 1-minute intervals. Data may be downloaded from the device using a vendor supplied Android smartphone app (iOS was not available at time of writing). The app connects securely to the sensor via Bluetooth and handles download and some data pre-processing tasks to convert raw (encrypted) data to readable text files. Download is effective at distances of up to several metres thanks to the Bluetooth communications, although this distance can be variable. After initial processing on a smartphone, data may be transferred from the smartphone to a laptop or network storage device via a range of options e.g. email, upload to Google Drive (or similar), directtransfer via SD card etc. Screenshots of this Android App based download workflow are presented in Picture3.

Picture 3 Screenshots of EDT Android App based data download and processing workflow

PHH data acquisition

The PHH sensors also log observations internally on an SD card, although in contrast to the EDT a higher temporal resolution was achievable (down to 10 second intervals). In addition, the PHH devices are equipped with a Wi-Fi adapter which is configurable for wireless network access to the device for configuration / maintenance and for data download. When in range of and connected to, a wireless network the PHH sensor can automatically uploaded sensed observations in near real-time to a vendor hosted cloud database. In situations where connectivity is not possible, sensed observations are also logged internally as a CSV file on the SD-card. On reconnection to a known wireless network, any accrued backlog of sensor observations is automatically uploaded to the cloud environment. The internally logged CSV files are persistent and act as an impromptu backup should the device backlog not clear automatically.

An extra feature of the South Coast Science sensor bundle is the provision of an online data dashboard environment, (see Figure 2 overleaf). This facility presents sensed data in the form of time series graphs. It was well received by experts and lay users alike. It also acts as a front-end data access and download layer for the South Coast Science AWS cloud database for desktop users. Command line data APIs and python utilities are also available.

3.1.4 Capturing sensor usability indicators

From an end-user perspective, the ease-of-use, deployment and data access of the systems was also important. Lower cost sensor systems appeal to a broad audience, with a wide range of technical capability. The usability of the systems needs to reflect the ability of the target audiences and be developed and enhanced where necessary.

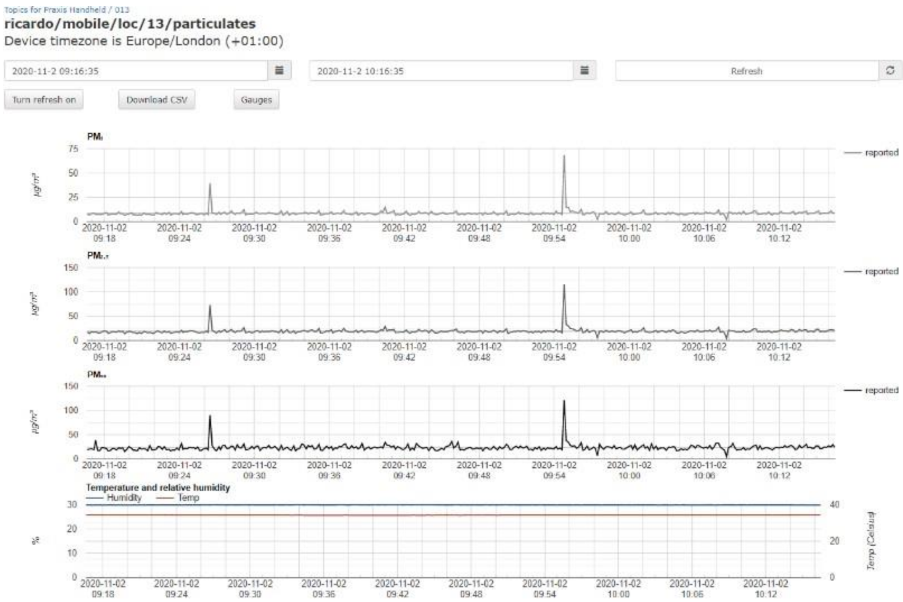
The usability of EDT and PHH sensors is closely coupled with the maturity of the devices as products. Both are in active development, although the EDT is a marketed product, the PHH sensor is a research instrument. As a result, the OxAir team, Competency Group (CG) users and sensor hosts experienced challenges over the course of the project.

Sensor usability feedback was captured from three groups:

- Low Carbon North Oxford O2 group
- Feedback from participating professional drivers & cyclists, and a volunteer cyclist
- OxAir CG participants - detailed feedback from participant interaction with the sensors was captured as part of the CG exercise and social research process.

Feedback, both positive and negative, was fed back to the manufacturers for product development.

Figure 2 South Coast Science online data dashboard time series representation of sensor particle observations



EDT sensor usability

The EDT sensors are cylindrical in shape about 19cm in length by 4cm in diameter. An NO_2 sensor is located at one end behind a gas permeable membrane. They are extremely portable and light, lending themselves to being carried in the hand, fixed to a bicycle or placed in a housing and attached in a fixed location outside. It is necessary to keep the gas permeable membrane clean and dry so some experimentation on bicycles is necessary to determine a good location.

The EDT version acquired by OxAir needed older Bluetooth enabled mobile phones in order to collect the data (Android <9). The workflow for data download was initially found to be problematic but improved with practice and experience. Download times could be significant if data were downloaded at frequencies longer than at two-week intervals.

The project had a number of issues with EDTs, particularly in cold weather, when it was found to be harder to connect with some of the EDTs, data process was unreliable and battery drainage was much higher. In experienced hands, however, they worked well in static locations in their housing, since they do not have GPS data, they become harder for the general public to use as a portable sensor, and it creates a significant extra workload to analyse and marry-up alternatively acquired GPS data.

Additionally, OxAir's EDTs had a maximum time resolution for observations of 1-minute. For a pedestrian based mobile sensing this resolution was acceptable however, for faster transport modes – car, cycle etc. it was sub-optimal, as considerable distance can be covered in this time.

PHH sensor usability

The PHH sensor became available mid-project. Since it came integrated with GPS, sensing capability for PM_{10}, $PM_{2.5}$, PM_1 and NO_2 (plus temperature and humidity), and measured time resolutions down to 10 seconds it was well suited for mobile sensing.

In addition, it came with the benefits of (i) automatic download of data over Wi-Fi, (ii) a web-based data viewing and download portal. The latter was a significant benefit for public participants, who are keen to get quick feedback on their data collection.

Over the course of the project, the team gathered input and experiences from residents who tested this equipment. Generally, the PHH was described as 'bulky' and awkward to carry. The unit was more noticeably susceptible to knocks and shakes which could result in device failure and required a specific reset protocol whilst connected to a known Wi-Fi. As a result, the PHH sensor could not be fixed permanently to a bicycle, and instead had to be carried by the cyclist. There were no carry fixings on the device, so we adopted the use of mesh shoulder bags (see image below). See Appendix B for sensor issues / improvement log and usability feedback.

Picture 4 PHH sensor carried in a mesh shoulder bag.

4 Sampling strategy and sensor network

OxAir's objectives necessitated a complex sampling strategy, capable of responding to the challenges of evaluating sensor technologies for their ability to contribute to LAQM assessments, and also generating a new evidence base to informed upon day-to-day human exposures to poor AQ.

The chosen sampling strategy involved hybrid approach, incorporating sensor observations from:

- Fixed, non-mobile sensor locations, e.g. street furniture, building facades
- Mobile sensor platforms, / hosts e.g. pedestrians, cycle couriers, cycle commuters, taxis and local buses

Key notes

- A mixture of fixed and mobile sampling was used to assess local scale AQ and test the sensor within the context of LAQM
- Fixed samplers location was lead by demographic analysis of candidate locations to promote diversity and equity
- Schools featured highly as enthusiastic fixed measurement sensor hosts
- Bicyclists (commuter & commercial), taxis and bus operators proved the most reliable mobile sensor hosts
- The mixed sampling modes and platforms presented a novel approach to capturing local AQ evidence on major and minor roads and at sensitive receptor locations based on a common sampling protocol

4.1 Fixed sensing locations

Fixed sensing locations were chosen at a range of traditional AQ assessment location types, although schools were targeted and prioritised as important sensitive receptors, not least willing participants. Oxford has been the recipient of a range of schools related AQ studies in recent years and OxAir recognised the co-benefits of utilising schools already familiar or geared up for AQ projects and furthering AQ as an educational topic within schools.

A socio-economic assessment of City of Oxford wards and the schools within these, was used to identify candidate schools, sensor locations and guide upon uniform coverage of Oxford's demographics. Schools participating in existing research with the County and City Council's were cross-referenced in order to established which schools received support for behaviour change - 40% were in receipt of support, 60% were not[1]. In addition, OxAir took guidance from local residents on candidate locations based on inputs arising from its social research and public engagement work package.

During periods of COVID-19 lock-down, mobile sensors were redeployed to a number of additional locations on key city routes, because restrictions made it difficult to undertake mobile measurement exercises (See also Appendix C: Sensor Placement Strategy).

[1] https://inews.co.uk/news/education/air-pollution-schools-children-learning-683391

Picture 5 Example of static EDT outside a school

Picture 6 Example of static use of PHH sensor (bike shop)

4.2 Mobile sensing

The small form factor and battery power of both the EDT and PHH sensors make them good candidates for personal monitoring and mobile sensing applications. These characteristics were appealing within the context of generating a new evidence base for AQ exposure during day-to-day life and a high resolution AQ map of the City of Oxford.

OxAir's mobile AQ sensing strategy centred on using volunteers to act as hosts for the sensors which would then be carried around in the outdoor environment during their normal, day-to-day activities. The CG exercise also fed into the mobile AQ sensing strategy, as resident members had the opportunity to collect data along their daily commutes and journeys of personal importance. The protocol for this is addressed in greater detail throughout the social research & public engagement section of the report.

In order to recruit non-CG mobile sensor hosts, OxAir engaged with stakeholder groups with high frequency journeys covering much of the city centre. As a result, the Oxford Bus Company, the bicycle delivery team of a local laundry company (OxWash) and a private hire taxi service (Royal Cars) were recruited as commercial road user sensor hosts. Where possible, sensors were deployed upon multiple vehicles within these organisations. Non-commercial road user communities were represented by commuter cyclists regularly using Oxford's north-south, east-west arterial roads, and recreational cyclists. Regular pedestrian sensor hosts proved difficult to recruit.

Picture 7 Example of mobile EDT use (volunteer cyclist)

Picture 8 Example of mobile PHH use (OxWash courier)

4.3 Sampling strategy observations

- Most value was realised from the EDT sensors when dedicated to fixed sampling. Despite its small and rugged form factor which was attractive for mobile applications, the EDT version acquired by the project supported a maximum measurement time resolution to 1-minute. This was in general, too coarse a resolution for most mobile sampling modes other than walking.
- GPS information for EDT observations could be supported via third party GPS applications (Smart phone apps or sports trackers). The additional complexity and technical burden frequently resulted in the failure of the host to capture GPS information and or sensor data, resulting in unreliable datasets.
- EDT data acquisition was best performed by core team members rather than a volunteer which is illustrative of the reliability issues experienced with the Bluetooth app supplied by the vendor for data download.

4.4 Standard operating procedures (SOPs)

The OxAir team brought recent experience of working with community groups and sensors and in turn a knowledge of the pitch and type of guidance that the general public required to successfully operate low-cost sensors. It also helped expedite compilation of standard operating procedures (SOPs) for the project and informed the technical team considerably on the difficulties experienced by sensor users and the guidance needed.

OxAir's SOPs remain a live document, reflecting the level of training or understanding required to get reliable results and the level of maturity in the sensors themselves. A high-level summary is presented below.

4.4.1 Detailed fixed AQ sensor SOPs

In order to promote homogeneity in sensor location types, observations and thereby comparisons between similarly exposed sensors across Oxford, micro-scale siting of fixed sensor locations followed the rules set out for LAQM[2].

Regular movement of the sensor was discouraged; a particular problem for the EDT which, being battery powered, was easy to relocate. Relocation of sensors by volunteer groups increases the risk of (i) reduced homogeneity in measurements (they are less comparable) and (ii) comparisons with LAQM and European standards being invalid.

4.4.2 Detailed mobile AQ sensor SOPs

Mobile sensor placement / location does not benefit from the published rule sets similar to those available for fixed measurement. Even so, similar philosophies and concepts apply. Sensor hosts were encouraged to:

- Place the sensor in the same location on each journey
- Avoid moving / jostling or exposing the sensor to vibration during exposure
- Keep a log / diary of their movements with the sensors including dates and times
- Keep the sensor in a well-ventilated location close to breathing zone
- Avoid exposure to microclimates
- Avoid getting the sensor wet
- Carry the sensor in a way that exposes it as far as possible to the same air that the host breathed
- Keep the display panel of the PHH sensor pointing upward as far as possible – the GPS receiver faced in this direction
- When sampling inside a vehicle cabin, to keep the windows open
- Use the sensor holster where provided

See also Appendix D for Standard Operating Procedures.

4.5 The OxAir sensor network

Figures 3-5 below present maps of fixed sensor locations and mobile sensor observations deployed by the OxAir project. The extent of the Oxford City Council administrative boundary is shown in Figure 3 as a blue shaded polygon. Locations of fixed EDT sensors are shown by red markers, fixed PHH sensors in green. Figure 3 illustrates the level of coverage achieved by OxAir fixed sensor locations within the context of the main arterial roads and residential communities across Oxford.

Similarly Figure 4 and Figure 5 provide an indication of the coverage the City's road network achieved by OxAir's mobile PHH sensor fleet. These maps show that the majority of arterial and main roads were regularly traversed by sensors and to a lesser extent minor road also. There is evidence also for mobile sensors travelling and sampling on main roads outside of Oxford. These are associated with bus journeys

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[2] https://uk-air.defra.gov.uk/assets/documents/reports/cat13/0604061218_Diffusion_Tube_GN_approved.pdf

to northern Oxfordshire market towns e.g. Woodstock and Kidlington, taxi journeys (to the east and London) and residential areas to west and south of Oxford.

Despite the seemingly good coverage of Oxford’s road network shown, it is perhaps worth recognising that the PHH sensor returned a valid GPS fix for only a small fraction (10-20%) of the total number of mobile sensor observations. This is likely to have arisen from limitations to both the GPS units fitted to the sensors and mounting location upon the mobile host which may have restricted line of sight. Irrespective of the cause this feature was a serious limiting factor preventing detailed analysis of sensor observation from mobile sensors upon the Oxford road network including the spatial and statistical distribution of measure concentrations and hence population exposures on or adjacent to busy roads.

Further work to geo-reference mobile sensor measurements without valid GPS data is on-going but goes beyond the scope of the current project.

Figure 3 Fixed OxAir AQ sensor locations

Praxis Handheld

Electronic Diffusion Tube

City of Oxford boundary

Figure 4 OxAir mobile sensor observations Jan to Sept 2020, Oxford & surrounds

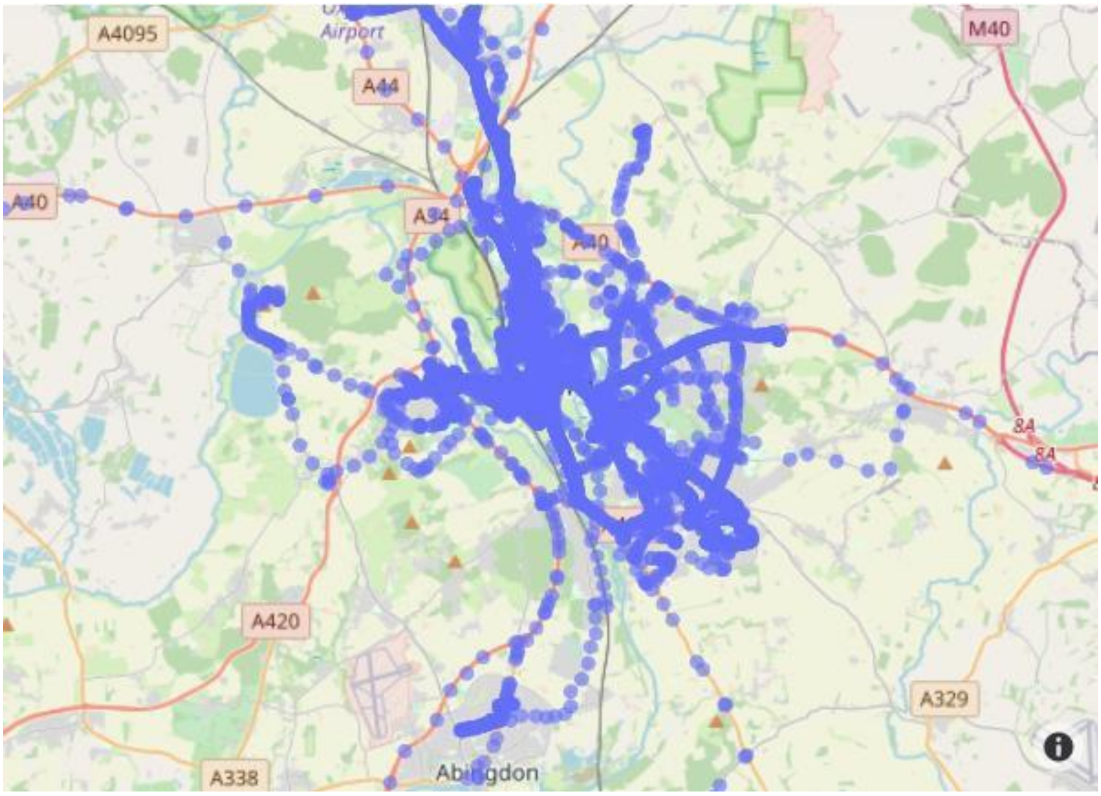


Figure 5 OxAir mobile sensor observations Jan to Sept 2020, Oxford & further afield

5 Sensor performance evaluation

There is clear understanding, at least within regulatory communities (e.g. LAQM), that sensor data can only be useful for real world applications if data quality is high enough to draw robust conclusions - whether these be indicative of otherwise. Despite this position, there is also relatively little information in the public domain on what users can expect in terms of sensor data quality or signal characteristics, a position which is exacerbated by the fast-moving nature of the sensor market.

In response, OxAir's evaluation of its chosen sensor systems performance and signal characteristics, independently of sensor manufacturers, was an important component of the work programme, developing transferable knowledge for Local Authorities, Defra and Oxford residents alike.

The following sections outline the proposed activities to investigate the performance characteristics of the EDT and PHH sensors. The results, observations and recommendations arising from the work are also presented. It should be noted that the intended rollout of these activities was adversely affected by delays in sensor delivery, pandemic restrictions and trade-offs with planned sensor deployment; the project viewed that some components of the sensor evaluation were not required in advance of the deployment in the field.

Key notes

- The expanded uncertainty of raw and validated sensor data have been calculated based on a method set out by the European standards organisation (CEN)
- Raw data presented by the PHH and EDT devices were not of sufficient standard for application within LAQM type activities and struggle to each the levels expected of even indicative measurement techniques e.g. diffusion tubes
- The performance of both sensors and variability in datasets in their raw form was such that the valuable application for information raising and citizen science are questionable
- The EDT devices displayed greater noise observation than the PHH sensor
- Dataset from both EDT and PHH sensors could be validated by an AQ measurements expert to impressive standards which met of surpassed the standards required for indicative monitoring set out by current legal frameworks in Europe and UK
- Both NO_2 and particles sensor technologies used are heavily influenced by temperature and relative humidity
- It is recommended that correct / reliable sensor performance is checked alongside an alternative reputable data source before acceptance from a product from a vendor
- You get what you pay for; sensor data quality seems to be proportional to sensor system complexity and market value, but this does not appear to be directly proportional nor a linear relationship
- Data validation is essential for informative applications or above
- Pandemics will affect field work no matter how carefully one plans

5.1 Sensor acceptance testing

Upon receipt of sensors from the manufacturer(s), the units were turned on and operated in a controlled environment (lab / workshop) for 1-2 weeks. This was intended to confirm correct functioning of devices, telemetry and realistic measurements. This task ensured systems were working properly before entering field use. Those units not working satisfactorily were exchanged with the manufacturer for replacement units under warranty before reiterating acceptance checks.

Acceptance testing is a core recommendation of the OxAir project. In our view, we consider the low-cost AQ sensor market to be too immature to rely on manufacturer quality assurance checks as an appropriate marker for satisfactory off the shelf sensor performance.

5.2 General sensor characteristics

Sensors that passed acceptance tests were to be deployed in batches at the same location (an urban environment) to test the relative performance of sensors in terms of signal noise, baseline offset etc. This was a preparatory step in identifying provisional correction methods for the sensor signal (s) and as a result a "*calibrated*" network of sensors. OxAir's intended trials were adversely affected by the actors outline in Section 1.3. As a result, the project drew upon comparable recent work performed by the consortium and time series from actively deployed sensors. In conjunction, these data sources provide sufficient information to characterise the raw, unprocessed sensor performance characteristics.

5.3 EDT sensor characterisation trials

OxAir re-analysed recent EDT datasets from community outreach projects within Oxford. As part of this project 10 EDT sensors were co-located at the AURN monitoring station at St Ebbes' School in the centre of Oxford. The sensors were deployed for 6 weeks during the winter of 2018/19, to evaluate usability, intra-comparability and for characterisation relative to a reference instrumentation.

The initial evaluation yielded mixed results. Manual data downloads were slow (10 minutes to download 1-week of data from each sensor, which could only be done sequentially) and initial failure rates were high. In the end, 20 sensors were exchanged with the manufacturer to realise 10 working devices. Figure 6 below presents a time series of observations from seven of the 10 sensors with long running datasets over the period of the exercise. It illustrates one of the key outputs, showing that although sensor observations are temporally well aligned (the rise and fall in observations are well correlated), the spread in the baselines associated with each time series is broad (+3ppb to -40ppb) and does not correlate well with typical ambient concentrations nor the baseline from the St Ebbes monitoring location.

Expectation was for sensors performance to at least be internally consistent - follow similar trends and present a consistent baseline, as seen in the first part of Figure 6. However, for the majority of the exercise different baseline offsets were presented contributing to sizeable variance in even aggregations concentrations.

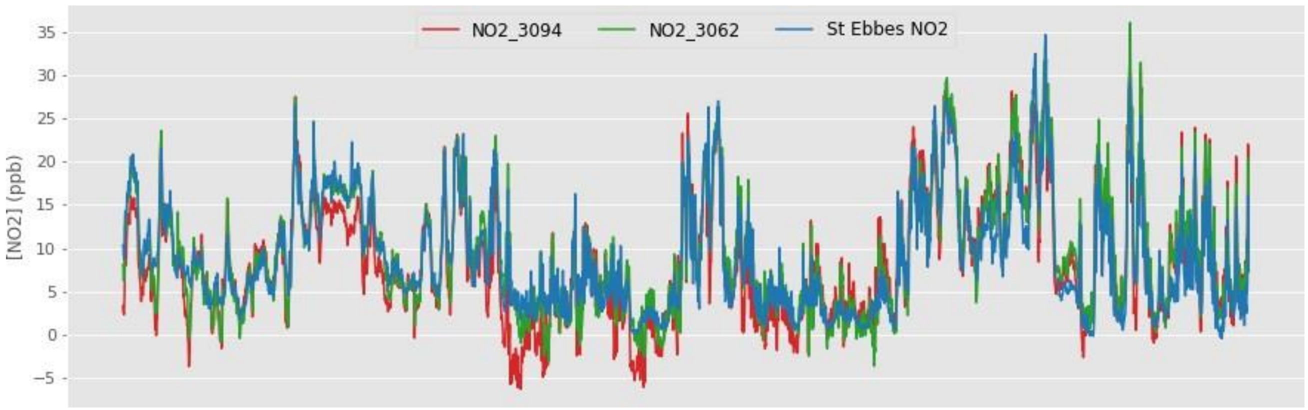
Figure 6 A comparison of raw co-located sensor outputs from seven NO_2 EDT sensors

A substantial amount of work was required by the study data presented in Figure 6 and prepare it for its intended AQ assessment task. The process is outlined below.

1 Use four weeks of "training" to characterise the performance of the sensors against the reference analyser.
2 Reject / replace any defective sensors, restart the training as required.
3 Use a simple scatter plot technique of the collected EDT vs. reference measure datasets to calculate slope/offset/r2 values for each EDT sensor.
4 Select the best performing sensors, based on r2 correlation with reference analyser.
5 Run these EDTs for a further four-week period, again co-located with reference instrumentation.
6 Perform a "normalisation" of the raw EDT data, using the factors derived earlier in (3) and any necessary baseline adjustments to calculate scaled measurements.
7 Compare these scaled measurements with the reference data in time series and scatter plots.

Applying this method to the 10 datasets presented in Figure 6 resulted in good data quality sensor observation, see Figure 7 plot below.

Figure 7 Validated sensor outputs from 2 well performing EDTs.



Subsequent to the validation trials, two measurement campaigns to assess micro-scale air pollution levels at St Nicholas and St Ebbes Primary Schools and within the St Clements area of Oxford a known AQ hotspot were undertaken. Sensor data from these studies, after applying the validation process outlined above, presented defensible concentrations profile from source receptor perspective. Even so, the amount of work required to derived usable data and the data handling needed was unsatisfactory.

Picture 9 Collocation trials of Praxis Handheld sensors at Oxford High St monitoring station

5.3.1 EDT NO2 sensor characteristics in the field

A time series of the raw, unvalidated sensor observations made in the field by all OxAir EDT sensors is presented in Appendix E. A subset of these data for three typical EDT sensors is presented in Figure 8 for illustrative purposes.

Figure 8 Illustrative characteristics of raw EDT NO_2 observations, OxAir Sept 2019 to Sept 2020

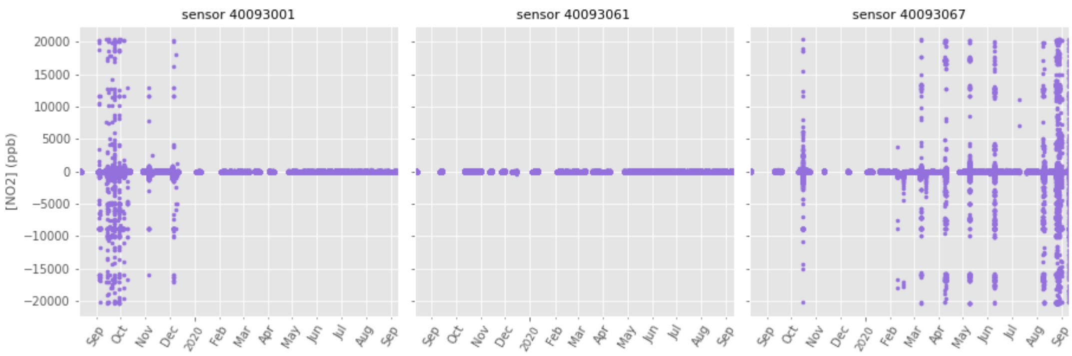


Figure 8 presents 1-minute NO_2 observations on the y-axis (in ppb) and time on the x-axis (Sept 2019 to Sep 2020). The y-axis has been constrained to +/- 20,000 ppb to illustrate the range in observations. The figure shows that raw sensor outputs from two out of the three sensors include large positive and negative spikes in sensed NO_2 concentration, to the order of ±20,000. The magnitude of spikes in the sensor signal masks the behaviour of the sensors normal ambient range in between these events. The remaining sensor does not present similar behaviour. The profile of observed spikes and the regularity in occurrence of some allude to a a number of potential interferences e.g. changes in relative humidity levels and systematic effect data handling events e.g. change in sensor system stability during a data download.

The prevalence of positive and negative spikes presented in the EDT sensors data, coupled with a lack of diagnostics regarding their cause, necessitated the application of broad brushed empirical filters on EDT sensor datasets to remove the instantaneous spikes in the time series. After processing in this way, the sensor time series and baseline offset were far more obvious and could be evaluated.

All three sensors presented show periods of data outage (gaps in the time series). These correlate well with interaction with the sensors via the App for data download and occur frequently across the OxAir EDT sensor stock, see Appendix E.

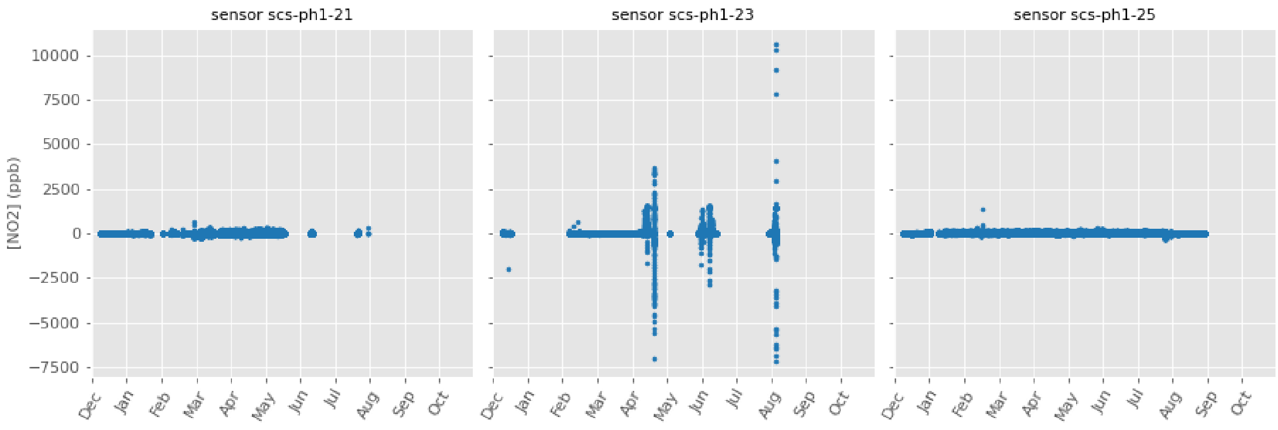
5.3.2 PHH NO2 sensor characteristics in the field

A comparable analysis is presented for OxAir's NO_2 sensor on board the PHH device within Figure 9 Illustrative characteristics of raw PHH NO_2 observations, OxAir Jan 2020 to Sept 2020, (also Appendix F). Once again, concentrations are presented in ppb, aggregated to 1-minute values. Time is presented on the x-axis in this case Jan to Sept 2020, the duration for which the project had access to PHH sensors. In this instance the y-axis has also been constrained to +/- 8,000 ppb.

The time series presented in Figure 9 are typical on the PHH NO_2 sensor performance and show some similarities that of the EDT – the sensor used is identical although peripherals are different. Discrete spike in concentrations are still obvious in the dataset although both the magnitude and frequency are much reduced. As a result, there is greater tendency towards sensor concentration response being in the normal ambient range .

Periods of data outage are obvious in the PHH sensor which coincide with periods when devices were operating offline (not connected to a Wi-Fi hotspot) i.e. in 'mobile monitoring mode'. PHH sensor initialisation for this state we found was critical and operator error frequently resulted in system failures and which prevent the logging of sensor observations. Diagnosing this state in real time also proved difficult.

Figure 9 Illustrative characteristics of raw PHH NO_2 observations, OxAir Jan 2020 to Sept 2020



Again, after initial processing the baseline offset in sensor time series were far more obvious and could be evaluated.

Comparing the performance of the two types of NO_2 sensor the following observations are raised (i) the PHH sensor delivers a less noisy signal than the EDT, (ii) both sensors require data screening / signal processing techniques to remove outliers and reduce signal noise for any LAQM type applications.

5.3.3 PHH particles sensor characteristics in the field

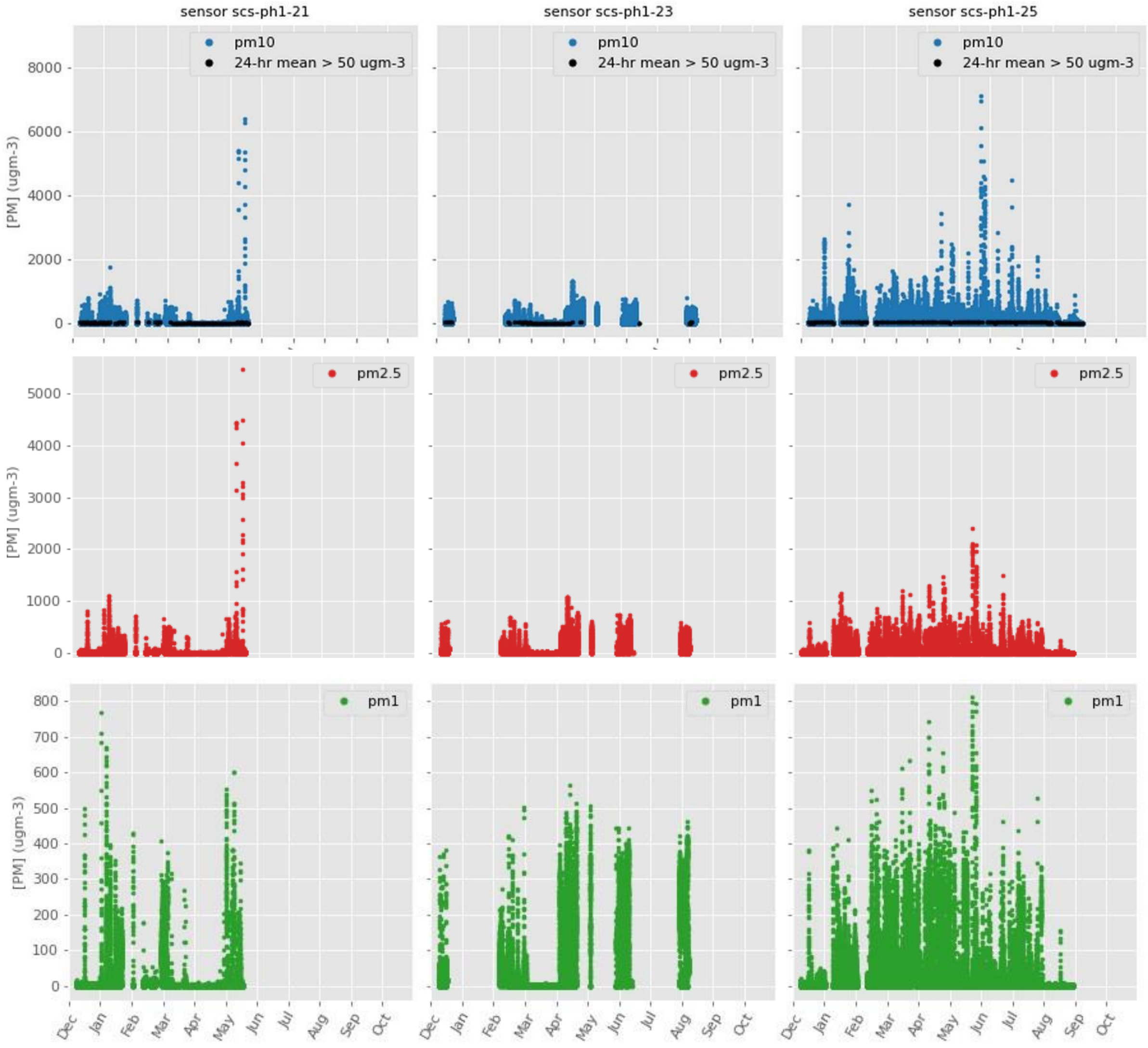
For the particle mass size fractions provided by the PHH sensor, similar illustrative time series are presented Figure 10, (and Appendix F) in which concentrations for each size fraction are shown in microgrammes per cubic metre (μgm^{-3}), aggregated to 1-minute values. Time is presented on the x-axis - Jan to Sept 2020. The y-axis has not been constrained and is not shared across the size fractions.

Figure 10 shows that whereas we see some positive markers for sensor performance;

- a consistent and stable baseline in the correct order of magnitude for ambient concentrations
- comparable concentrations for sensors 21 and 23
- the speciation profile / ratio conforms expected norms - PM_{10} mass > $PM_{2.5}$ mass > PM_1 mass
- the fluctuation in the PM profile over time for each sensor is consistent

There is evidence that the raw PM sensor data is erroneous. For example, peaks in the 1-minute average concentrations can be large and of sufficient magnitude to skew longer term average concentrations. This is illustrated in Figure 10 by the regularity with which the daily mean PM_{10} concentrations (calculated from raw sensor observations) exceeds 50 μgm^{-3} (shown in black). This metric represents the concentration threshold for the daily mean Limit Value / UK AQ objective, which ought not be exceeded on more than 35 occasions. Indeed, evidence from reference method instrumentation in Oxford indicates that exceedance of this threshold was a rare occurrence. Whereas, Figure 10 shows that the daily mean of raw sensor data was regularly above 50 μgm^{-3}, and certainly more than 35 times over the duration shown. The transient nature of the peaks observed is indicative of interferences from very short-term changes in relative humidity.

Figure 10 Illustrative characteristics of raw PHH particle observations, OxAir Jan 2020 to Sept 2020



As for NO_2 periods of data outage are clear and attributable device connectivity issues.

5.4 Comparisons with reference methods

Because individual sensors are differentially susceptible to interferences, as shown in section 6.2, sensor baselines can vary substantially from device to device, hindering comparability between sensors and contributing to the uncertainty of sensor observations relative to a reference method.

In order to evaluate sensor uncertainty, OxAir carried out co-located exposures of its sensor stock alongside reference monitoring. The duration of tests varied from several days to weeks, depending on the prevailing social distancing and travel restrictions.

The data generated from this exercise was used to evaluate the measurement uncertainty of the sensors, following a method proposed by the European Standards Committee [3, 4]. A prescribed equivalence demonstration spreadsheet calculation produced by CEN was used for this purpose[5] and allowed data quality to be determined within the context of the data quality objectives set by the European Directive legislation[6] (Annex I), and upon which LAQM guidance is based. This procedure calculates calibration factors and measurement uncertainties from the validated reference method and sensor devices.

For the purposes of this exercise the aim was for sensor observation to achieve at "indicative" status, equivalent to an uncertainty of ±25% for NO_2 and ±50% for PM_{10}.

5.4.1 Uncertainty estimates for EDT sensors

Data collected from the co-location studies was used to evaluate the measurement uncertainty of the EDTs, compared with the reference method at St Ebbes. This procedure utilised an Equivalence Calculation developed by a CEN standardisation Working Group, as outlined above. The figures below illustrate the outcomes of this work (i) for raw sensor data and (ii) for sensor data that has been validated manually by an AQ expert. The outputs from 2 months of 15-minute average data (to match the highest time resolution available for the reference method) are presented below in Figure 11 (raw data and Figure 12 (validated data).

Figure 11 CEN Standardisation WG equivalence spreadsheet outputs for unvalidated nitrogen dioxide EDT sensor observations in St Ebbes 2018

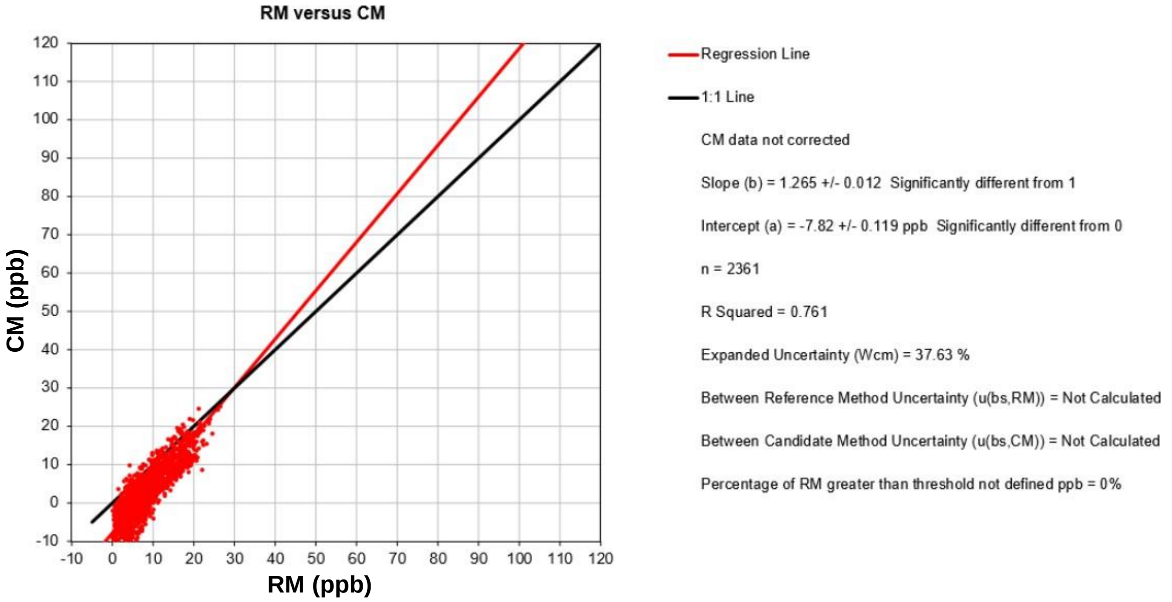


Figure 11 shows that the Expanded Uncertainty (the measurement uncertainty) for the raw NO_2 sensor dataset was approximately±38%. This value is around 13% outside of the accepted range for indicative

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[3] https://ec.europa.eu/environment/air/quality/legislation/assessment.htm

[4] https://ec.europa.eu/environment/air/quality/legislation/pdf/equivalence.pdf

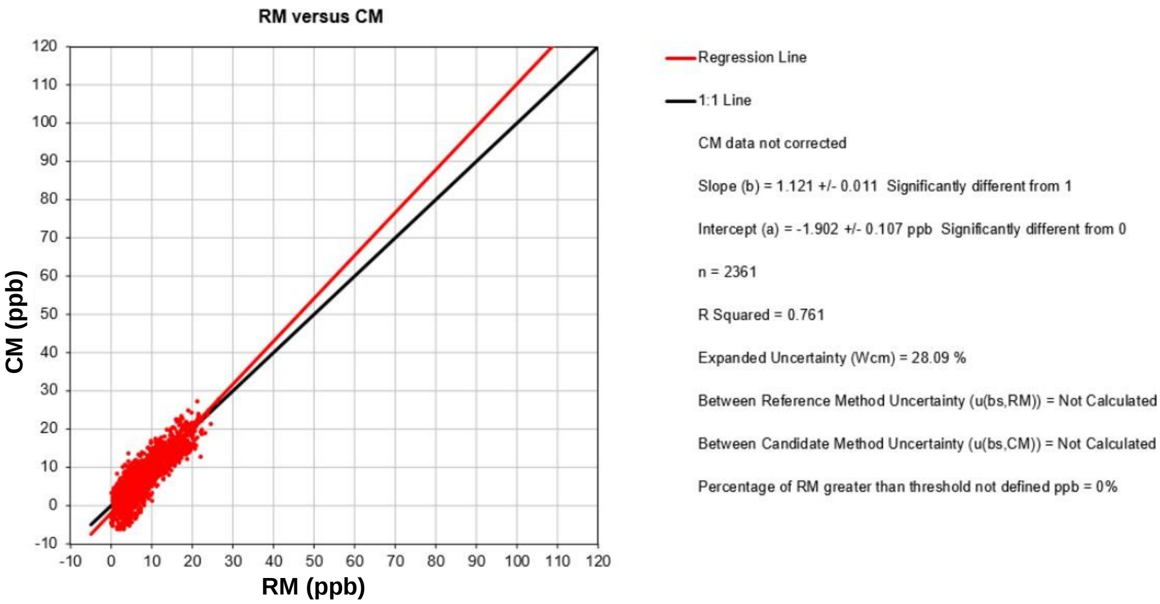
[5] https://ec.europa.eu/environment/air/quality/legislation/pdf/Equivalence_Tool_V3.1_020720.xlsx

[6] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0050-20150918&from=EN

measurement techniques (±25% for NO_2), a threshold that allows indicative measurement methods to be used for supplementary assessment under the European AQ Directive and de facto target for LAQM. From Figure 11 it is also clear the this particular sensor tended to under-read relative to the reference method although this is much reduced but still evident in the validated data presented in Figure 12.

Figure 12 presents the reciprocal plot and Expanded Uncertainty estimate for sensor observations after validation. It shows that the validation process has reduced the uncertainty estimate for the sensor by ~10% to approximately ±28%, very close to what might be considered acceptable standards status. Despite the level of expert knowledge and input into quality control required this is highly encouraging and demonstrates that it is possible to obtain good quality data from relatively cheap sensors.

Figure 12 CEN Standardisation WG equivalence spreadsheet outputs for validated nitrogen dioxide EDT sensor observations in St Ebbes 2018

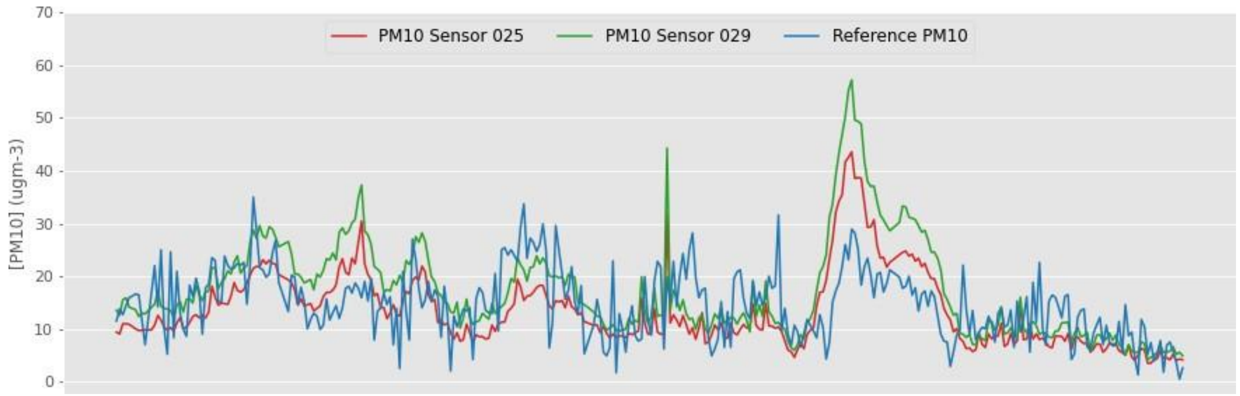


5.4.2 Uncertainty estimates for PHH particles sensors

Co-located uncertainty studies with the PHH sensor were hindered by lockdown travel restrictions, low ambient AQ levels and poor sensor reliability. Ambient concentrations at the time of the trials were very low resulting in a heightened signal-to-noise ratio and limit of detection of the sensors. This resulted in more scatter in the PHH data compared to the reference analysers, making a meaningful evaluation of measurement uncertainty difficult. As a result, co-location trials were moved from our preferred urban background location to a roadside location in the centre of Oxford.

Good quality PM_{10} measurements from the comparison are presented in the time series plot presented in Figure 13.

Figure 13 Time series of co-located PM_{10} measurements from co-located PHH sensors at Oxford High Street 2020



The raw data from the two sensors presented in Figure 13 show reasonable agreement, both with each other and the reference method (TEOM). To the eye, the scatter and variance in the raw sensor observations relative to the reference method is broadly acceptable, although during two events approximately ¼ and ¾ of the way through the time series sensor observations can be seen to depart from the reference method. The expanded uncertainty for measurements from sensor 025 is estimated to be ±70% (based on the CEN Standardisation WG on equivalence method) . This is slightly outside the European AQ Directive DQOs for the indicative monitoring (±50%), see Figure 14a below. Even so, an encouraging result for raw (unvalidated) sensor data in difficult conditions. Sensor 029, performed less well, its expanded uncertainty estimate is almost double that of sensor 025 at ±133% and clear differences in the slope of relationships. See Figure 14a &b below.

Figure 14a Expanded uncertainty estimates for raw NO_2 observations from a PHH sensor 025, Oxford High St 2020 (calculations based on CEN Standardisation WG on equivalence spreadsheet).

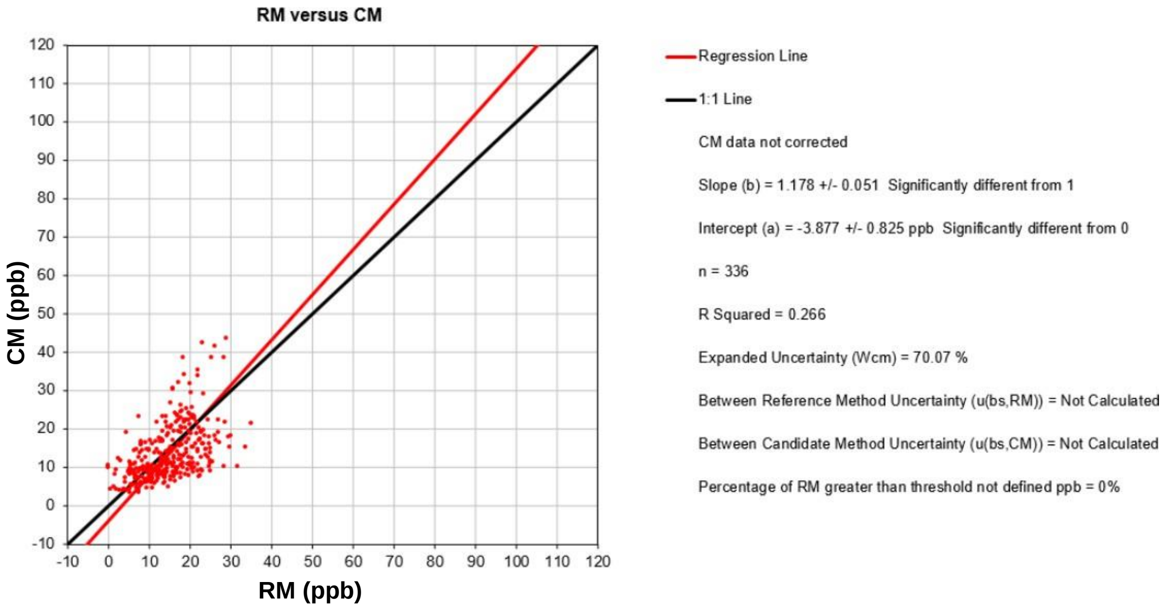
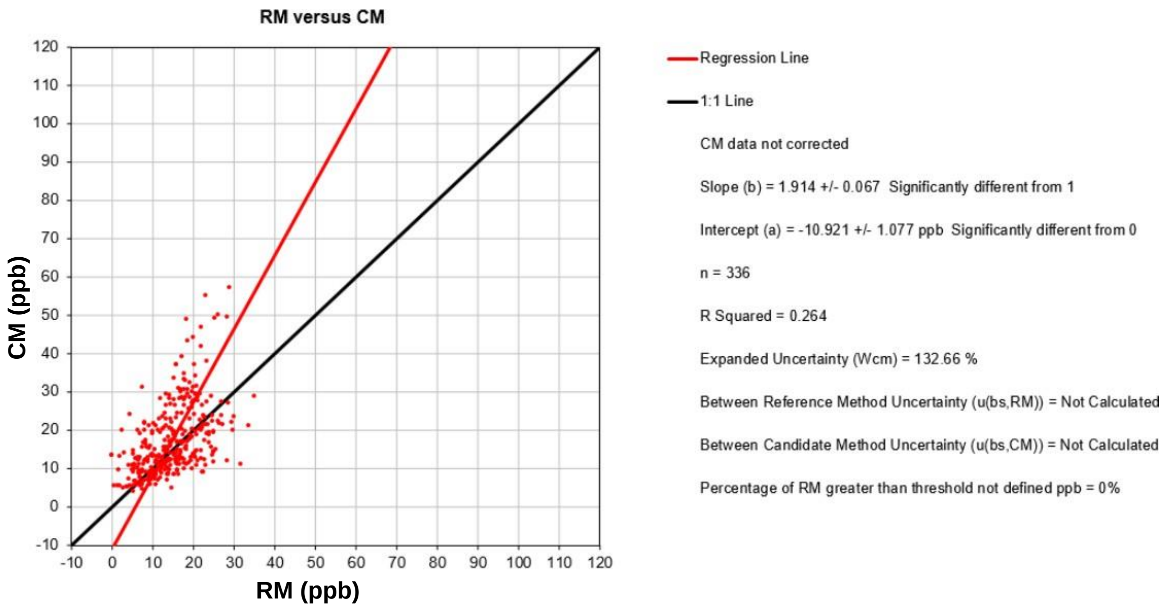


Figure 14b Expanded uncertainty estimates for raw PM_{10} observations from PHH sensor 029, Oxford High St 2020 (calculations based on CEN Standardisation WG on equivalence spreadsheet).



Based on these outputs from the equivalence tool and taking into account that concentrations for the trials were low and the data are in 'raw' state, the performance of the PM_{10} sensor is satisfactory. For further context the raw hourly measurements from the PM sensor are always within 20 μgm^{-3} of the reference analyser and mostly within 10 μgm^{-3}. Likewise, the similarity and shape of performance characteristics of the sensors in shown Figure(s) 14 is encouraging. It is also notable that the CEN Standardisation WG on equivalence method is highly sensitive to seemingly small changes in sensor performance.

5.4.3 Uncertainty estimates for PHH NO2 sensors

The caveats applicable to the PHH PM sensor analysis also apply to its NO_2 sensor regarding the impacts of lockdown etc. A time series of the good quality sensor measurements of NO_2 from the co-location study are presented in Figure 15.

Figure 15 Time series of co-located NO_2 measurements from co-located PHH sensors at Oxford High Street 2020

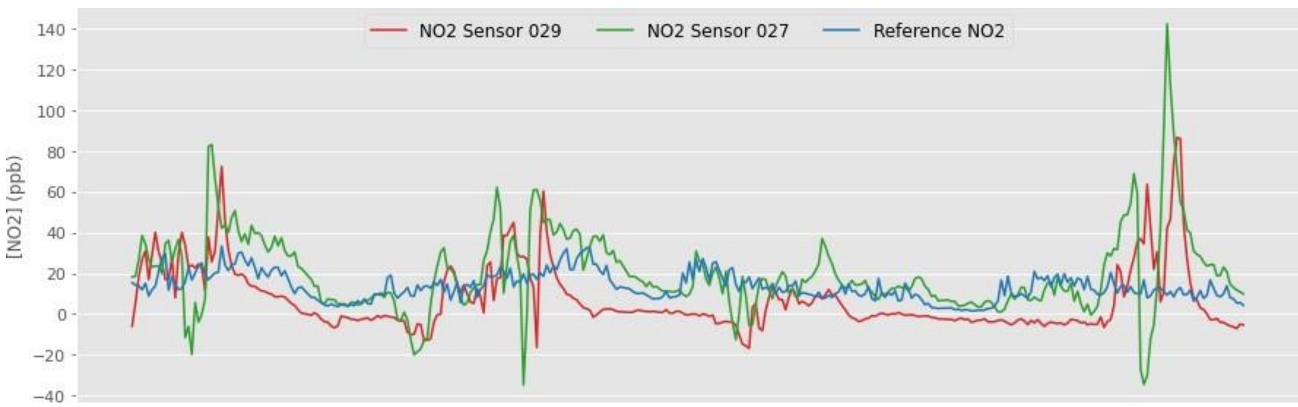


Figure 15 shows that the raw sensor outputs were less well correlated with the reference method than was observed for PM_{10}. This was not entirely unexpected, as electrochemical sensors (for NO_2) are known to be more susceptible to temperature and relative humidity interferents than the OPC type PM sensor. These environmental factors are the likely cause of the three events noticeable in the sensor timeseries during which elevated concentration were observed; these were not reciprocated in the reference method time series. On positive note, there is at least stability in the baselines for each sensor, which can be corrected for.

In addition, OxAir established that the sensors were adversely affected by a design issue which resulted in an over-estimate of ambient temperature which effected signal processing on the sensor. The design error will be corrected in future releases of the device. It can, theoretically, be corrected for within OxAir datasets; although this was not possible within the constraints of the current project.

Expanded uncertainty estimates for the raw data are presented and are poorer than expected. This is illustrated in Figure 16 for sensor 027 which shows how the sensor(s) in general struggle to measure concentrations below 20 ppb in a reproducible manner.

This observation clearly has significant implications applications within the context of LAQM, European regulatory assessments of citizen science activities. In recognition of this and to mirror the validation of EDT NO_2 datasets in section 5.3, sensor 027 observations were validated by the same AQ expert. The expanded uncertainty analysis was the reiterated and is presented in Figure 16b.

Figure 16b shows that, with the input of an AQ expert to review and remove erroneous or anomalous data points, raw NO_2 sensor datasets can be transformed into something that, visually at least, approaches acceptable sensor behaviour. However, it should be noted that this will come with significant extra costs (in a scaled-out implementation e.g. for LAQM) and does not completely fix the uncertainty issues; in Figure 16b validation deliver and expanded uncertainty estimate of ±192% as oppose to the ±788% for the raw sensor data (Figure 16a).

Figure 16a Expanded uncertainty estimates for raw NO_2 observations from PHH sensor 027, Oxford High St 2020 (calculations based on CEN Standardisation WG on equivalence spreadsheet)

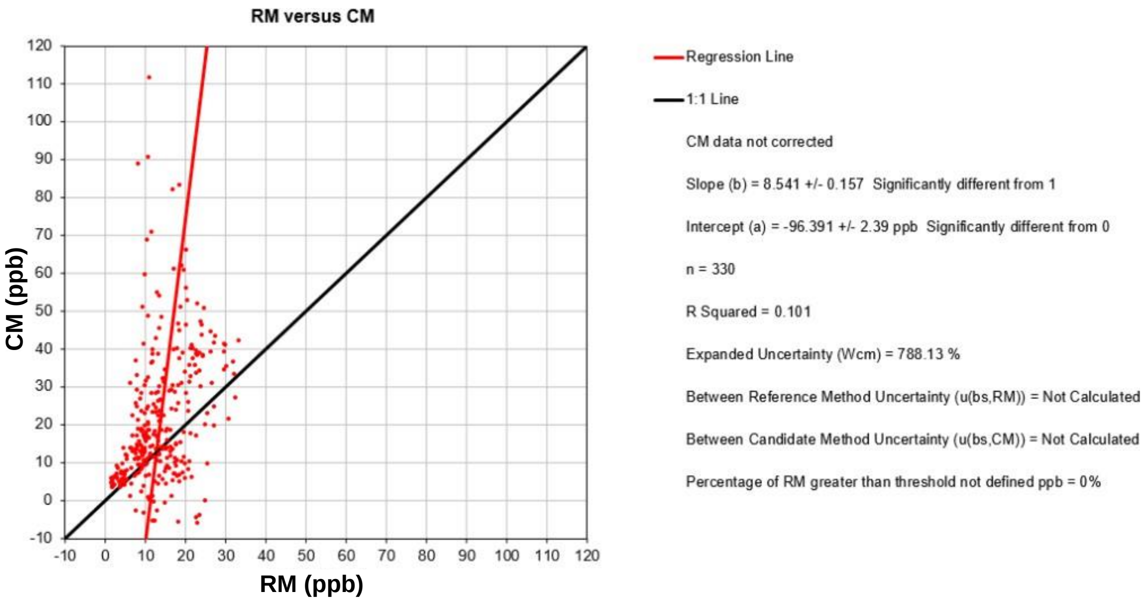
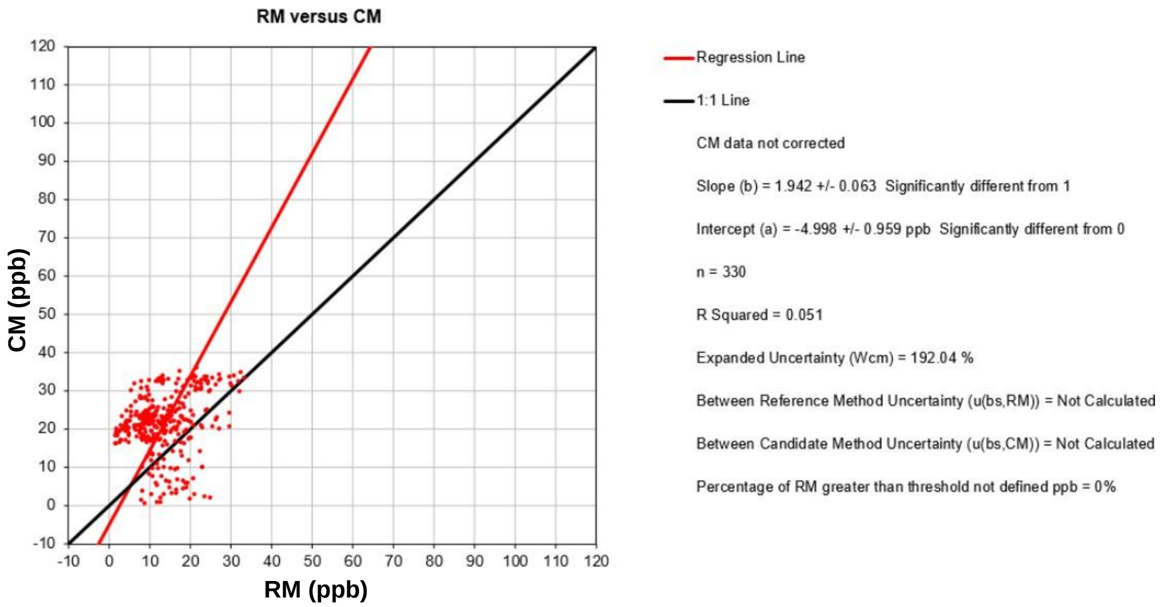


Figure 16b Expanded uncertainty estimates for AQ expert validated NO_2 observations from a PHH sensor, Oxford High St 2020 (calculations based on CEN Standardisation WG on equivalence spreadsheet)



5.5 General observations from sensor characterisation trials

Following the observations and practical lessons learned have been taken from the sensor characterisation trials:

1. Wi-Fi network connectivity (where supported) can be problematic. For the PHH sensor, there seemed to be an upper limit to the number of different Wi-Fi hotspots allowed (and stored). The maximum number of network connections recommended is 5, beyond this device connectivity became unreliable.
2. There is limited information on devices to indicate correct operation.
3. There is limited information on the EDT mobile App to indicate correct operation.
4. The PHH power connector is fragile and power requirement is very specific.
5. Internal temperature control can affect measurements.
6. Data from the sensors is initially uncorrected for temperature and humidity effects.
7. Sensor software and hardware performance at the beginning of the project required a number of devices to be returned to the supplier for repair / upgrading.
8. The stability and acquisition of GPS fix on some PHH devices was temperamental and appeared variable across the units tested.
9. The standby button on the front of the PHH sensor was overly sensitive (given intended application environments) and resulted in units being accidentally sent to standby.
10. Restart of devices from standby without a Wi-Fi connection resulted in internal restart failures which were diagnosable in the field.
11. PHH sensor are configured to restart into sample mode from power off. This behaviour is not reliable.

5.5.1 Interpretation of measurements - accuracy and uncertainty

The results from these co-location studies must be kept in perspective, particularly when drawing conclusions on possible application for sensors in the LAQM framework. Within this context we note that; (numbering continues from previous bullet point list).

12. The measurement uncertainty of raw data from low-cost sensor systems is much worse than the reference sensors used in national networks.

13. The measurement uncertainty can be improved with data validation

14. Whilst it is possible to apply traditional QC measures (similar to those applied to AURN datasets) to sensor datasets and thereby validated sensor data such that it compares favourably to a reference method e.g. for the NO_2 EDT above, this is a highly resource intensive exercise which will offset the cost-benefits calculations for low-cost AQ sensors.

15. While the variability of sensor response across a large number of notionally identical devices may be acceptable on average, at least once QC procedures have been applied, an individual user of a single device without the capability to conduct even very limited co-location studies, will not be able to place the same level of confidence in their measurements.

16. An automated method for the sensor data validation, including baseline offset and interference correction(s), is needed to support practical applications for the low-cost the sensor data presented here and other comparable sensor datasets.

17. The long-term stability of the measurements is largely undocumented and requires regular characterisation to maintain any confidence. It has not been possible to undertake this assessment within the timescales of OxAir.

By way of example, a sensor time series used for hotspot identification would need to be >50% higher than the relevant environmental objective before one could be certain that it did not just happen by chance e.g. a 1-hour measurement would need to be >150ppb (rather than 104.5ppb) before one could be certain that there is a reasonable risk of levels approaching legal thresholds. It is extremely important not to simply believe the concentration numbers provided by the sensors.

6 Preliminary sensor data validation

At the start of the OxAir project there was an expectation that sensor data outputs would require data processing to reduce signal noise / variance and allow the data to be used for LAQM or for public information.

OxAir has identified two main contributors to the majority variability in sensor data; (i) a sensor offset variable arising from calibration process during the manufacturing or instability in the calibration over typical ambient environmental conditions, and (ii) an interference variable which in the case of NO_2 and particles can be broadly described in terms of the interactions between relative humidity, temperature and / or rates of change in relative humidity and temperature.

Further to this, we identified five data attributes that are symptomatic of poor sensor performance.

1. Large positive or negative spikes in the sensor signal
2. A large positive spike followed by a negative spike (or vice versa)
3. Continuous or discontinuous noise (high frequency variation) in the sensor signal
4. Discrete changes in the sensor baseline
5. Drift in the sensor baseline

Even though, as section 5.3 has shown, sensor data can be validated to impressive standards by an AQ expert, this process is expected to be prohibitively expensive for deployment in scaled up, dense sensor networks. As a result, an automated approach is needed.

Key notes

- Data processing / validation of data from the EDT & PHH sensors (most noticeably NO_2 but to a lesser extent particles also) is essential for anything other than the most rudimentary measurement tasks
- Automated data processing methods are preferential to avoid expensive and time-consuming involvement of expert AQ practitioners
- A method that could be automated for the screening of sensor data anomalies and variable baseline offset was developed using AQ expert knowledge and statistical techniques from the analytical domain(s)
- A second method for the correction of interference effects of temperature and humidity was developed using a using a simple multivariate ordinary least square regression model
- Both methods were successfully tested on EDT and PHH NO_2 sensor data

6.1 Generalised approach to sensor data screening

OxAir has explored potential data processing methods including simple statistical methods for handling sensor signal noise, outlier tests for handling anomalous concentration spikes and un / semi-supervised machine learning techniques. As part of this process an emphasis was placed on convenience and transparency over complexity.

Using a combination of empirical and statistical methods, an automated approach to sensor data screening was developed which targeted 3 of the five symptoms described above (sensor offset, drift and outlier observations). The four-stage method is described below and illustrated in Figure 17. The impact of the methods upon internal dynamic range of sensor observations is small (the relative variation in pollution and pollution peak is mostly preserved), meaning the outputs can be used as inputs to interference correction models.

6.1.1 Stage 1 - empirical filters

The first stage in the process is the application of empirical filtering criteria to the raw sensor data. A review of the sensed pollution data and other ancillary sensor data available established thresholds for variables during periods of normal sensor performance. Table 2 presents these for NO_2 and particles.

Table 2 Empirical filters used for screening out anomalous sensor data.

Empirical filters - NO_2		Empirical filters - PM_{10}	
No. 1	-10ºC < temperature < 35ºC	No. 4	-10ºC < temperature < 45ºC
No. 2	Relative humidity > 35%	No. 5	Relative humidity > 25%
No. 3	-10 ppb < [NO2] < 500 ppb	No. 6	-10 μgm^{-3} < [PM_{10}] < 1250 μgm^{-3}
		No. 7	Sample flow rate > 2 ml/min

Filters 1 & 4 screened out data points not within conservative estimates of normal range of ambient temperature. Note that, these are expected to be stringent criteria resulting in the omission of some normal sensor behaviour - normal ranges chosen are based on shaded observations, whereas sensors are typically not located in the shade and will therefore run hotter, particularly at a 10 second time resolution. The temperature offset arising from device design artefacts are included in the upper limit.

Filter 2 & 5 screened out data points below the normal limit for average daily minimum for relative humidity. An offset has been applied for relative humidity on the particle sensor.

Filters 3 & 6 screened outliers not captured by filters 1-4

Filter 5 screened for periods of low sample flow rate on the particle sensors.

6.1.2 Stage 2 - baseline offset and drift correction

The stage 2 correction applied a statistical method developed in the analytical domain for chromatography to correct a variable baseline / baseline offset. The method used is called Adaptive Iteratively Re-weighted Penalised Linear Squares regression (airPLS). It does not require any user intervention or prior information, e.g. peak detection, and works by iteratively changing weights of sum squares errors (SSE) between the fitted baseline and original sensor signals. The weights of the SSE are obtained adaptively, using the difference between the previously fitted baseline and the original signals. The baseline estimator is fast and flexible. Illustrative effects upon a single time series are presented in Figure 17.

6.1.3 Stage 3 – minimising airPLS over-fitting for air quality

Stage 3 applied a compensation for the efficacy of the airPLS algorithm which has a tendency to over fit the baseline - leaving the corrected baseline so close to zero, (for air quality applications, where the baseline is not zero, the method is has a tendency to remove the urban, regional and rural background components). In order to correct for this artefact, stage 2 outputs were scaled by the difference between the corrected baseline and that of a local urban background (city scale background), in this case the baseline at Oxford St Ebbes, AURN station.

6.1.4 Stage 4 - removing residuals

The final stage of the correction method accounts for any remaining residual anomalies that present as negative concentrations. The majority of these will have been accounted or corrected for in stages 1-3.

Figure 17 Illustrative benefits of OxAir’s 4 stage sensor data processing technique, EDT NO_2 sensor

(0) Raw unadjusted EDT sensor.

(1) Outlier removal - empirical filters.

(2) Baseline correction – airPLS.

(3) airPLS over-fit compensation.

(4) Residual removal.

6.2 Generalised approach to sensor interference correction

Section 5.4 has shown that raw sensor observations for OxAir sensor stock, at least in their raw state, did not compare favourably with co-located measurements made with reference instrumentation. However, we further demonstrate that, with the skills of an AQ expert, it is possible to validate sensor data to a standard acceptable for LAQM applications (PM_{10}) and approaching acceptable levels for NO_2. Despite this overarching message, the reliance upon AQ expert input negates one of the key benefits of low-cost sensors, that of deployment at scale and minimal inputs from costly human expertise. As a result, OxAir explored the potential for an automated generalised interference correction method that could be deployed in tandem with the screening tools presented in the previous section.

Being well connected with research at the Universities of Oxford and Birmingham, the OxAir team were aware of some of the work developing ensemble regression modelling for sensor interference correction. In addition to informing some of our own work relationship with Oxford and Birmingham tempered ambitions for developing Machine Learning techniques within the time scales of the OxAir project.

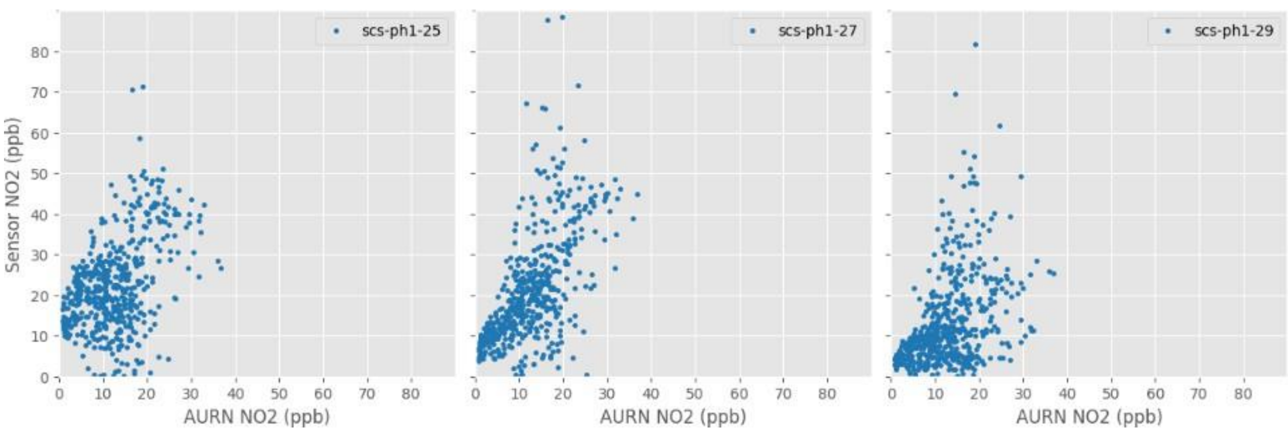
6.3 Linear regression model for sensor interference correction

The Alphasense and South Coast Science sensors used in OxAir log most of the more important environmental variables which contribute to interferences upon electrochemical and OPC sensors. For the EDT and PHH NO_2 sensor voltages from the working and auxiliary electrodes, temperature and relative humidity are logged alongside the sensed concentration values. These data, when paired with simultaneous reference measurements were used by the OxAir team to build a simple multivariate linear regression model to correct for interferences in sensor observations.

Model training was performed using the 15-minute average. Sensors 025, 027 and 029 were taken as representative of all PHH sensor behaviour. The relationships, between sensors and with the reference method are presented in Figure 18.

The 4-stage generalised screening method presented in the previous section was applied to each sensor dataset. This process corrected each dataset for anomalies and variable sensor offset prior to model training, transforming the sensor data on to a common sensor baseline. The data were then combined, with associated reference observations, into a single dataset.

Figure 18 Relationship between model training sensor data and reference method, OxAir 2020



Combined data was split randomly into two subsets; 75% of sensor observations were binned into a training dataset intended to calibrate the correlation model, 25% of sensor observations were binned into a validation dataset which, having been excluded from model training, could be used to test the performance of the model independently.

Model training and testing was performed in using Python SKLearn module. The combined model inputs and validation results are presented in Figure 19.

Figure 19 Training, and verification of the OxAir multivariate linear regression model for correcting NO2 sensor interference

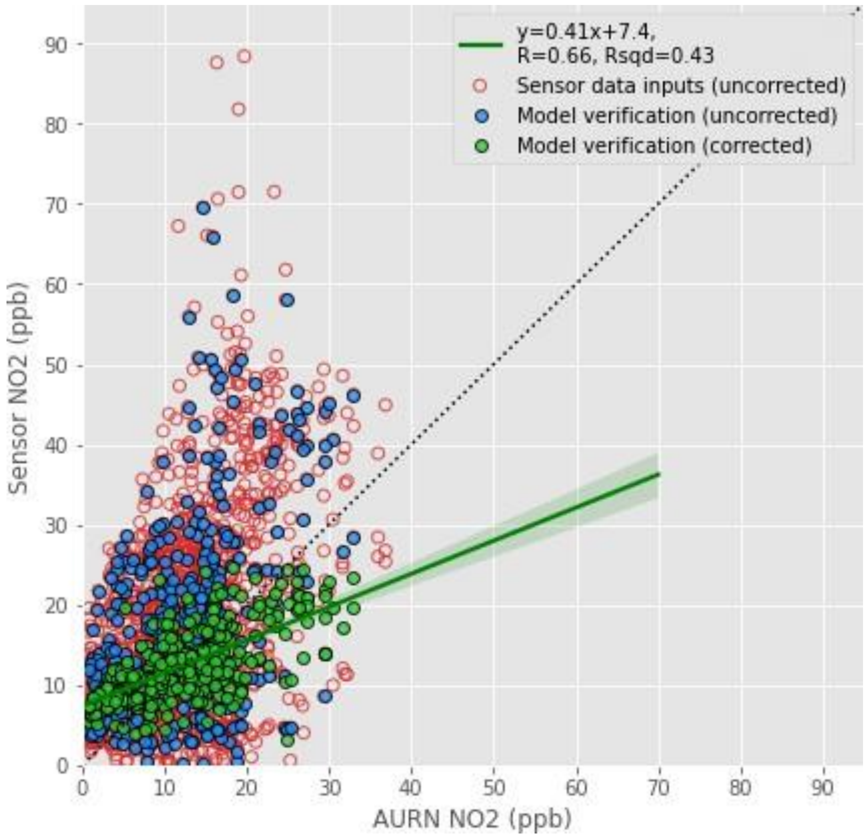


Figure 19 illustrates the variance in the combined sensor data set (red markers), a subset taken for model verification shown in blue marker (before correction) after correction (green markers). Figures 20 and 21 show that this simple multivariate model is capable of explaining a significant proportion of the variance in the sensor data relative to the reference method; reducing the uncertainty in the validation dataset from ±287% to ±51%. Further observations relating to Figure 19, 20 and 21 include;

1. The model performs well in characterising interference effects leading to large positive sensor readings, relative to the reference method
2. The model performs well in characterising interference effects leading to smaller positive sensor readings, relative to the reference method
3. These is anecdotal evidence that the model is over correcting moderate over-read in sensor observations in the 25 ppb+ range

4. Important gradient and intercept terms persist in the corrected datasets and its coefficient or correlation with reference method remains low, indicating the scope for further work to improve the model.

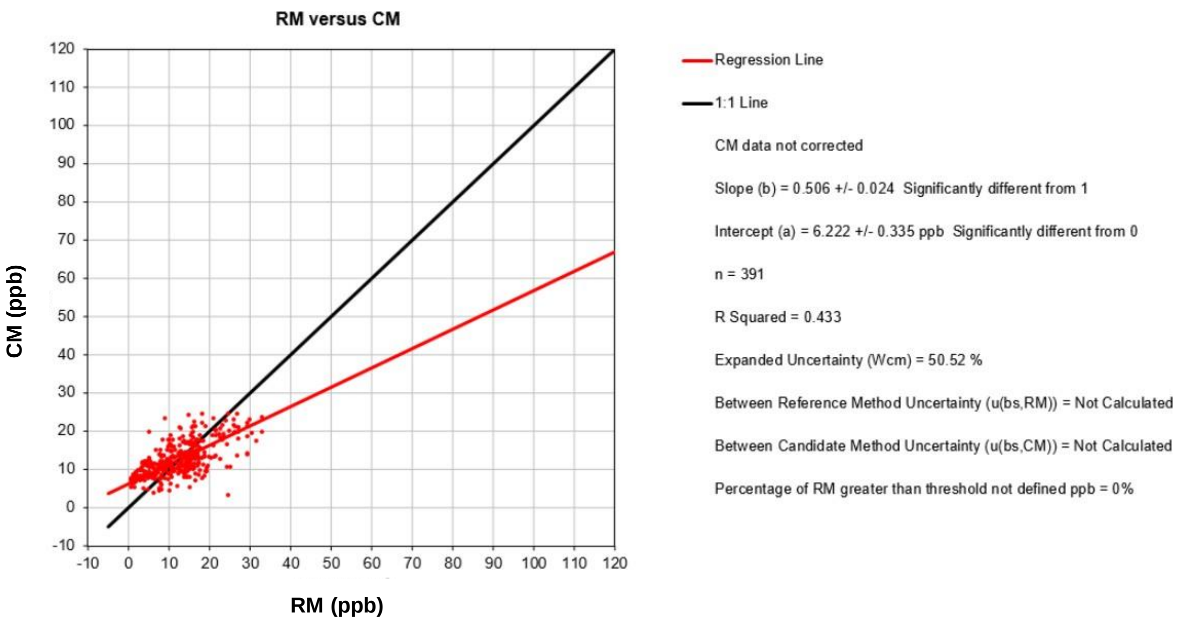
5. The verification dataset does not demonstrate and bias in distribution (at least visually) therefore we can have confidence in the observations over the concentration range shown (0 - 40 ppb)

Figure 20 CEN Standardisation WG equivalence spreadsheet outputs for unvalidated nitrogen dioxide PHH sensor observations at Oxford High St 2020

CM (ppb)

RM (ppb)

Figure 21 CEN Standardisation WG equivalence spreadsheet outputs for validated nitrogen dioxide PHH sensor observations at Oxford High St 2020



In conclusion, given the simplicity of the approach and the accessibility of the data inputs required (for the sensor technologies used), this approach to sensor interference correction, when combined with the OxAir 4-stage generalised screening method shows potential in making low-cost sensor technologies a viable component of the LAQM tool kit.

NB. Although the models evaluated for application as a correction tool were constrained to simple multivariate linear regression models, Ridge and Lasso regression methods were also explored. However, these did not present substantial improvement of the Ordinary Least Squares method presented here.

7 Sensor data analysis and data outputs

The following sections present some simple analyses of the sensor datasets in order to respond to key objectives of the study.

- To demonstrate the value of low-cost sensors (or potential value) within the LAQM framework
- To generate a reliable high-resolution local evidence base

As a pre-processing step all sensor systems measurements were internally normalised before analysis using the approach presented in section 6.1.

Key notes

- Measured average NO_2 and particle concentrations were of levels typically previously found in Oxfordshire – no substantial evidence of significant hot spots close to the sensitive receptor locations taking part in the study were identified
- Measured levels at seven locations were above the annual average limit value / objective (40 μgm^{-3} or 21 ppb), their short duration implies that levels are likely to be poorly representative of the annual mean - therefore compliance or non-compliance cannot be determined
- There were no observed exceedances of the long-term average Limit Value for PM_{10} and $PM_{2.5}$
- There were no observed exceedances of the short-term average Limit Value for NO_2
- The high resolution sensor data enabled diurnal profiles to be prepared for a number of locations. These may prove helpful for policy design and evaluation purpose under LAQM
- Fixed sensor data lent itself well to traditional AQ mapping techniques
- Data from mobile platforms were mapped using a more novel semi-quantitative heat mapping method which produced engaging and intuitive maps for engagement activities
- The value of the mobile sensing evidence base was not explored substantially – GPS issues meant that a large proportion of measurements were not geo-located. Even so, significant quantities of data were collected on some routes.

7.1 Comparisons with environmental objectives

Comparing measurements from short-term studies, such as OxAir, with legal limit values and guidelines can be highly attractive because of the added context that can be imparted. However, the ease with which comparisons can be made belies the complexity of doing so correctly and in a manner that does not mislead. If comparisons are not performed correctly, there is a danger of misinterpreting measured levels in relation to a legal limit.

In order to compare measured levels with the legal limits or advisory health standards, there are many of criteria that must be met including for example:

- Data capture (the proportion of observing time for which valid measurements are available). Usually 90% of measurements in a calendar year for high quality measurements, 75% for indicative measurements.
- Measurement methods used - which must be of known and demonstrable quality
- Detailed statistical calculation procedures must be followed for comparisons with the European Limit Values.

Furthermore, environmental legislation typically requires measurements to be undertaken with approved instrumentation, at fixed locations. which are "*representative*" of the population exposed in carefully defined measurement environments. Measurements taken following these rule sets support comparisons with similar locations where measurements are not undertaken.

As a rule of thumb, for a rudimentary comparison of measurements with a limit value or guideline, measurements are required for at least as long as the averaging time of the relevant limit value or guideline e.g. the annual, hourly or daily mean. This is because, as the level of data capture reduces (from 100%), so does the reliability of any averages derived from it and therefore any comparisons. Further information is available on Oxford City Council's Fact Sheets[7].

With these caveats above in place and recognising that the data capture rates achieved by OxAir sensors were, in general, substantially below those required by UK or EU legislative limits, the following sections attempt to impart some context on measure levels within the regulatory space. In doing so, however, no formal assessment of compliance (or non- compliance) is made or implied.

Comparisons of mobile measurements with environmental objectives have not been performed as mobile measurements do not conform with any legislative requirements.

7.1.1 Longer term average NO2 concentrations

Table 3 presents the average concentrations measured by fixed sensors over the duration of the project. Observations have been ranked by average concentration (high to low). The number of valid observations and data capture (as a percentage of a full calendar year) are presented as an important marker for how representative the sensor average is of the annual mean - lower the data capture rate ⇒ less representative ⇒ greater uncertainty in using the short-term average as an annual mean indicator.

Table 3 shows that seven sensor locations measured average concentrations above 21 ppb. Whilst these are above the annual average limit value / objective (40 μgm^{-3} or 21 ppb), their short duration implies that levels are likely to be poorly representative of the annual mean - therefore compliance or non-compliance cannot be determined. Even so, these data do act as useful marker of potential hotspots although from a little local knowledge, most are not a great surprise being located in heavily trafficked locations to the North of Oxford.

[7] https://www.oxford.gov.uk/download/downloads/id/6688/air_quality_fact_sheet_1_-_how_to_interpret_aq_data.pdf

Table 3 Ranked average NO_2 concentrations by fixed OxAir sensor locations (ppb)

Location	Sensor Type	No. samples	Min (ppb)	Max (ppb)	Std. deviation (ppb)	Mean (ppb)	% Annualised data capture
Cutteslowe A40 (cycle path)	EDT	17863	11	147	14.5	36	3
Cutteslowe Community Centre (walkway)	EDT	19472	12	93	11.1	31	4
Wolvercote Roundabout	EDT	22273	11	242	12.5	31	4
Walton Rd	EDT	44069	13	202	7.5	28	8
Cheney School	EDT	107454	13	197	6.2	25	20
Cutteslowe Community Centre	EDT	15242	14	414	6.4	25	3
Dragon School	EDT	152062	0	468	11.5	24	29
Taylor Institute	EDT	113422	0	332	11.2	21	22
Botley Road	PHH	8407	0	352	20.6	19	2
Wolvercote School	EDT	213249	0	337	11.1	18	41
St Francis School	EDT	6490	1	107	9.3	18	1
Banbury Road	PHH	150215	0	447	13.8	17	29
Hospital	EDT	142890	0	509	21.4	17	27
St James School	EDT	188045	0	195	10.5	16	36
Cutteslowe Community Centre (Worsley Rd)	EDT	50029	0	127	10.8	16	10
Walton Street	PHH	89022	0	155	11.5	16	17
Divinity Rd	EDT	14367	0	99	9.1	16	3
Abingdon Rd - Western Rd	EDT	133210	0	503	10.8	16	25
Windmill School	EDT	201686	0	492	9.4	15	38
North Oxford background	PHH	70879	0	149	13	15	13
St Josephs School	EDT	129469	0	193	8.2	14	25
North Hinksey School	EDT	203559	0	137	8.6	14	39
West Oxford Community School	EDT	184682	0	145	7.9	13	35
Cherwell School	EDT	137345	0	106	6.8	12	26
Pegasus School	EDT	198225	0	226	6.4	12	38

The capability to investigate and evaluate short-term periods of elevated concentrations because of the high time resolutions offered by sensor technology is an important benefit of the method over alternatives such as the Palmes type diffusion tube which can only deliver longer-term aggregated measurements at the highest over a 2-week duration at the levels typical experienced in the ambient environment within Oxford.

7.1.2 Short-term average NO2 concentrations

Because of the high time resolutions achievable with sensor measurements, a similar comparison to that presented above for average data can be conducted for NO_2 hourly average sensor data. The same caveats apply with regard to formal demonstration of compliance or non-compliance with the limit value / objective - 200 μgm^{-3} (105 ppb) not to be exceeded more than 18 times per calendar year.

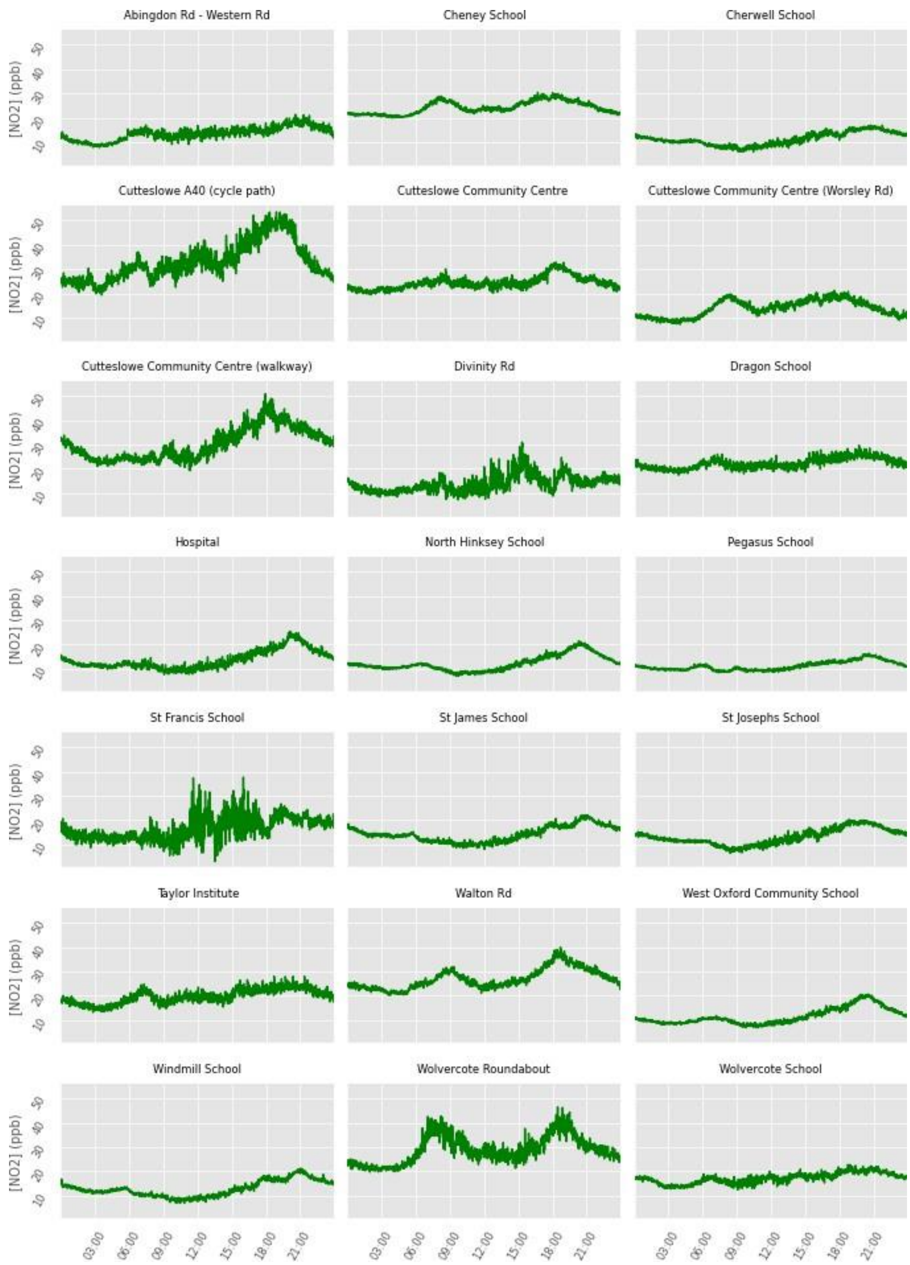
None of the sensor locations observed at least 1-hour mean concentrations above 200 μgm^{-3} (105 ppb) and as above, because of the short duration of the measurement campaign compliance or otherwise cannot be demonstrated, the observed levels indicate that the risk of exceedance is likely to be small.

7.1.3 Diurnal variations in NO2

Figure 22 presents diurnal plots of the daily NO_2 concentration profile for 24 of the fixed measurement locations. These plots show how concentrations varied through the day at each location over the duration of the project. In order to limit sensitivity to transient spikes in some sensor observations the median NO_2 concentration has been used in constructing the diurnal profiles presented.

Figure 22 shows the prevalence of two generic diurnal profiles; (i) a classic double humped profile of urban centre locations heavily influenced by road transport emissions and showing peaks in NO_2 concentration correlated with the timing of morning and evening rush hours; (ii) a single peaked profile showing a gradual rise in pollution throughout the day to a peak correlated with the evening rush hour. The capability of sensor data to generate diurnals is potentially valuable for the future of LAQM for example in measuring and tracking of how local measures have affected (flattened) the diurnal profiles and how measures may have been differentially efficient in doing so throughout the day / week. We do of course note that unexpected diurnal profiles may also be indicative of erroneous data, particularly when sensor interference have not been screened out beforehand.

Figure 22 Diurnal cycles of NO2 at OxAir fixed EDT sensor locations



7.1.4 Long-term average particle concentrations

Table 4 and Table 5 present average PM_{10} and $PM_{2.5}$ concentrations measured by fixed PHH sensors over the duration of the project. As for NO_2, the number of valid observations and data capture (as a percentage of a full calendar year) are presented as a marker for repetitiveness of the annual mean.

Tables 4 and 5 shows that, over the duration of operation, average PM_{10} and $PM_{2.5}$ concentrations were not noticeably elevated, being at the worst case ~10% below the EU and UK limit value for PM10 and $PM_{2.5}$ (40 and 25 μgm^{-3} as an annual mean respectively) . As for NO_2, annual mean equivalent data capture rates are not high. On this basis and taking into account the uncertainty of sensor techniques, formal demonstration of compliance or non-compliance is not possible. Furthermore, those locations observing highest concentrations (Botley Rd. and Woodstock Rd.) displayed very low data capture. As such the uncertainty associated with using these data as a marker for potential annual average exceedances is considered to be high.

Table 4 Observed PM_{10} concentrations at fixed OxAir PHH sensor locations.

Location	Sensor Type	No. Samples	Min (ugm^{-3})	Max (ugm^{-3})	Std. deviation (ugm^{-3})	Mean (ugm^{-3})	% Annual data capture
Banbury Road	PHH	145,277	0	950	21.3	14	28
Botley Road	PHH	7,796	0	719	48.3	36	1
North Oxford background	PHH	75,783	0	602	12.8	3	14
Walton Street	PHH	91,587	0	963	48.0	16	17

Table 5 Observed $PM_{2.5}$ concentrations at fixed OxAir PHH sensor locations.

Location	Sensor Type	No. Samples	Min (ugm^{-3})	Max (ugm^{-3})	Std. deviation (ugm^{-3})	Mean (ugm^{-3})	% Annual data capture
Banbury Road	PHH	145,289	0.00	942	7.2	5	28
Botley Road	PHH	7,796	0.10	359	37.7	22	1
North Oxford background	PHH	75,783	0.00	475	10.6	2	14
Walton Street	PHH	91,603	0.00	763	44.6	11	17

From a personal exposure perspective, the high time resolution of the sensor data allow for the proportion of observations (and therefore the amount of time) above or below a threshold concentration to be estimated. Hypothetically, if one were to assume that the observations (above) were generally representative of the levels experienced on the street, in normal day to day life[8] at these locales, it would be possible to estimate the proportion of observations and therefore amount of time above a given threshold concentration. This may then inform on possible personal exposure time to levels above for example, limit and target values.

[8] for reasons already highlighted in this report we expect this not to be true but given better data capture and lower sensor uncertainty, we would aspire to this assumption

Using OxAir sensor data as an exemplar only (noting all the caveats on sensor data capture rates and uncertainty) and using the approach above.

7.1.5 Short-term average PM10 concentrations

The short-term limit value for PM_{10} is set at 50 µgm^{-3} as a daily mean, not to be exceeded on more than 18 occasions in a calendar year. There were no exceedances of this metric. As for NO_2, formal demonstration of compliance or non-compliance is not possible. Even so, given the levels observed the likely risk of exceedance is likely to be low.

7.1.6 Diurnal variations in particles

Diurnal plots of PM_{10} and $PM_{2.5}$ concentration are presented in Figures 23 and 24 for fixed PHH sensor locations within the OxAir network with sufficient data quality. These plots suffer somewhat from low data capture. Even so, for the most heavily trafficked location (Botley Road) peak concentrations are clearly identifiable which correlate well with morning and evening rush hour. During these periods PM_{10} concentrations are typically below 30 µgm^{-3} and $PM_{2.5}$ below 25 µgm^{-3}. Other locations show less familiar concentration profiles with a peak in concentrations coinciding with the morning rush hour.

Figure 23 Diurnal cycles of PM_{10} at OxAir fixed PHH sensor locations

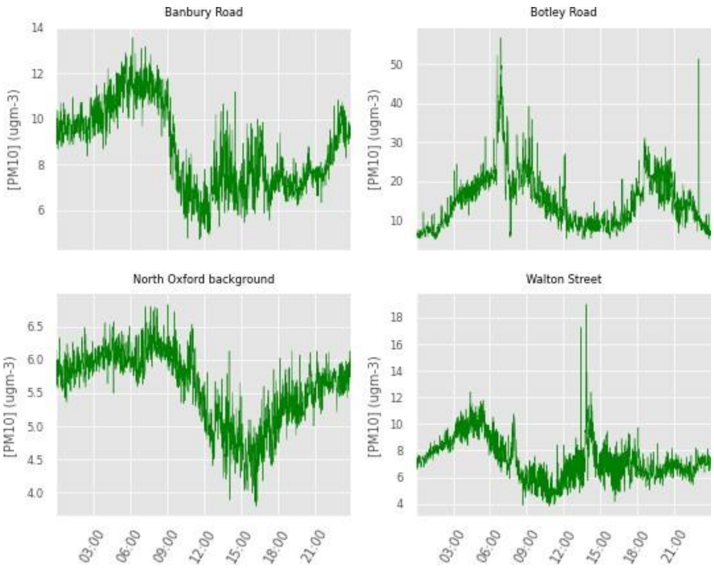
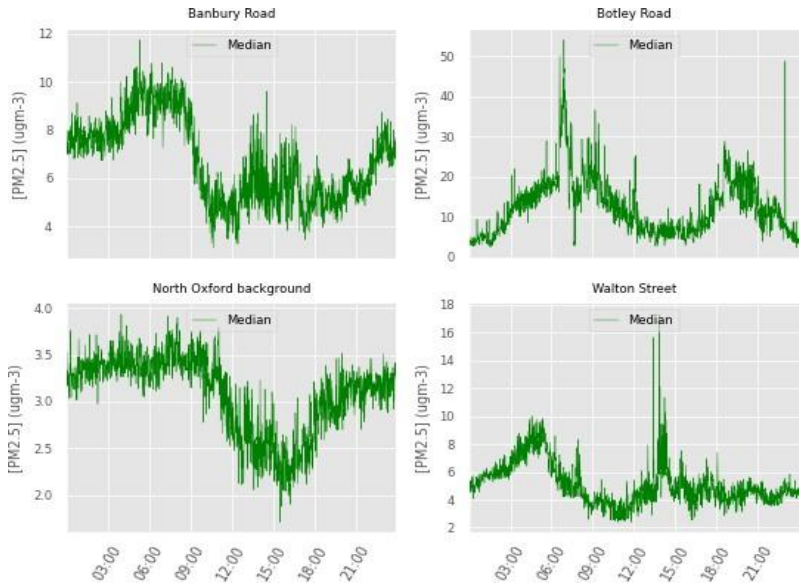


Figure 24 Diurnal cycles of $PM_{2.5}$ at OxAir fixed PHH sensor locations



7.2 Mapping Oxford's air quality

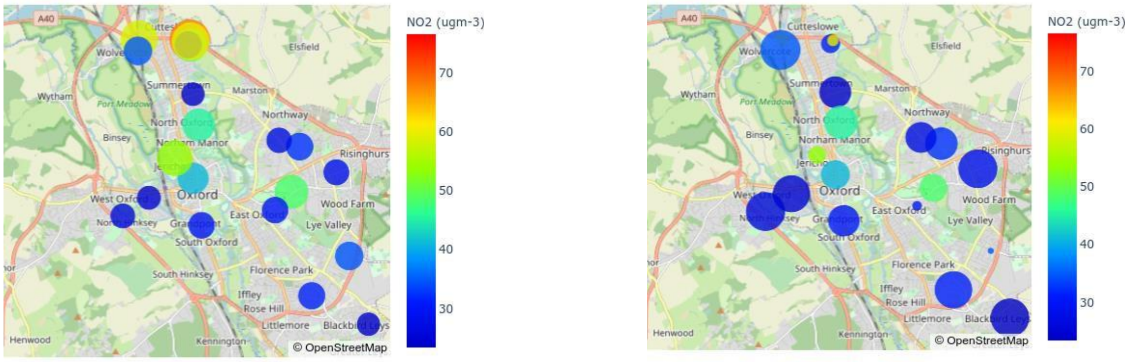
AQ maps are often valuable to the general public and experts alike as a way to visualise patterns in AQ and can be a highly effective tool for communicating research information, for public engagement and facilitating information exchange.

7.2.1 Fixed sensor maps

Figures 25 to 27 present the mapped average concentrations for NO_2, PM_{10}, and $PM_{2.5}$ measured at OxAir fixed sensor locations over the duration of the project. The data capture rates presented in Tables 3,4 and 5 apply. The figures present a pair of maps, with map (a) in each pair having symbology where colour and the radius of each marker is scaled by concentration value, whereas in map (b) marker colour is scaled by concentration and radius by data capture.

This symbology illustrates that although highest concentrations were measured to the north of Oxford, in close proximity to the A40, these sensors suffered from poor data capture and as a result are less reliable estimate of long-term concentrations - valuable insight into the validity of using measurements of short duration to imply long-term levels. Mapping of fixed measurement data in this way is relatively straightforward and shows potential as an engagement tool, perhaps in combination with data from Oxford City Council's automatic monitoring and diffusion tube monitoring data.

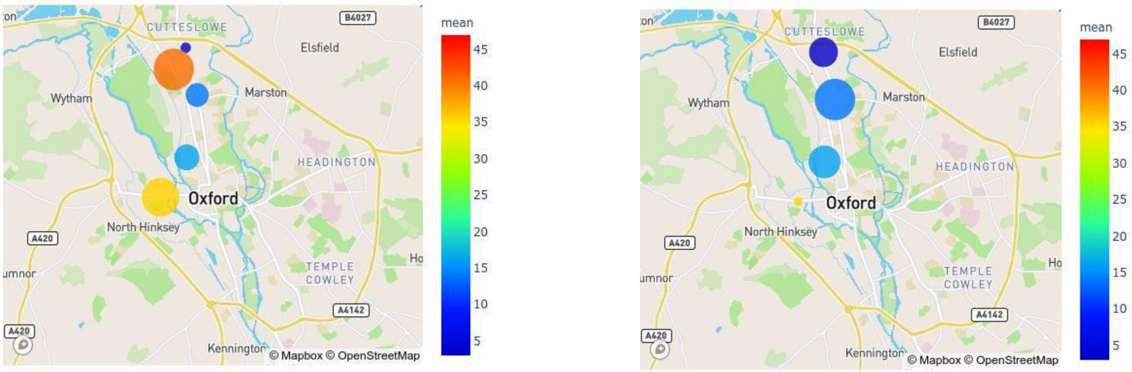
Figure 25 Average NO_2 concentration - OxAir fixed sensors ; (a) marker colour & marker size scaled by average concentration, (b) marker colour scaled by concentration, marker radius by % annual data capture.



(a)

(b)

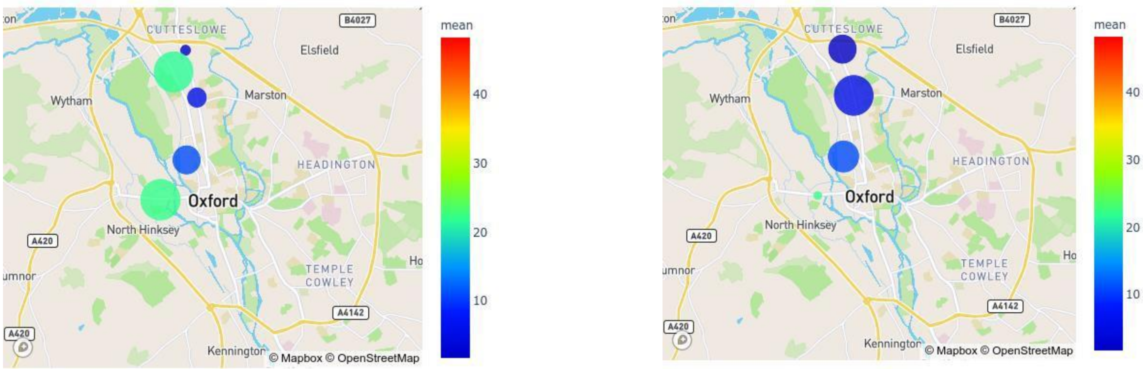
Figure 26 Average PM_{10} concentrations - OxAir fixed sensors; (a) marker colour and size scaled by average concentration, (b) marker colour scaled by concentration, marker radius by % annual data capture.



(a)

(b)

Figure 27 Average $PM_{2.5}$ concentrations - OxAir fixed sensors ; (a) marker colour and size scaled by average concentration, (b) marker colour scaled by concentration, marker radius by % annual data capture.



(a)

(b)

7.3 Mobile sensor data mapping

OxAir PHH sensors were GPS enabled, allowing the mobile platforms for assessment of AQ to be evaluated.

PHH sensors were hosted by a range of commercial and non-commercial road users e.g. a selection of Oxford Bus Company buses, private hire taxis, delivery cyclists, commuter cyclists, recreational cyclists and pedestrians within Oxford. Measurements of the 1-minute average NO_2 concentrations from these sensor hosts are presented in Figure 28 A heatmap method has been used to present a simple visual representation of pollutant levels. The heatmap method offers easy access to visualisation of data point density and relative differences in the concentration values at these points. Within the context of OxAir they provide a semi-quantitative and visually engaging way of encouraging the AQ evidence base to be explored. The maps can be easily deployed as an interactive web tool.

Figures 28 to 30 demonstrate the application of mobile AQ sensing observations to capture and map high resolution AQ pollutant information. The maps are broadly consistent with the expectations, with AQ hotspots on the maps correlating well with known heavily trafficked road sections and areas where stationary traffic is likely. Measurements on minor roads are generally lower than those major roads although this is not clearly shown by the city centre maps below - an artefact of the density of measurement on major roads taken by sensor mounted on buses.

The maps produced using this method seem sensitive to the density of observations. The heat mapping algorithm itself being influence by measurement outliers. As a result, it will be sensitive to the homogeneity of the measurement / sampling protocol conditions and interference. If these external factors can be controlled the method shows potential for adding value to the LAQM evidence base, tracking the impact of policy measures and communicating the benefits of avoiding busy roads from a personal exposure perspective. The value of this method is dependent upon delivery at scale, and this was limited to an extent by the GPS performance of the PHH sensors - only ~10-20% of observations had GPS location information of sufficient quality to map the AQ observations. Likewise, the COVID-19 emergency measures presented a significant barrier to deployment of mobile sensors in the field.

Figure 28 Mapped 1-minute mean NO_2 sensor observations from OxAir mobile AQ sensor hosts

Oxford, city & surrounds

Oxford, city centre

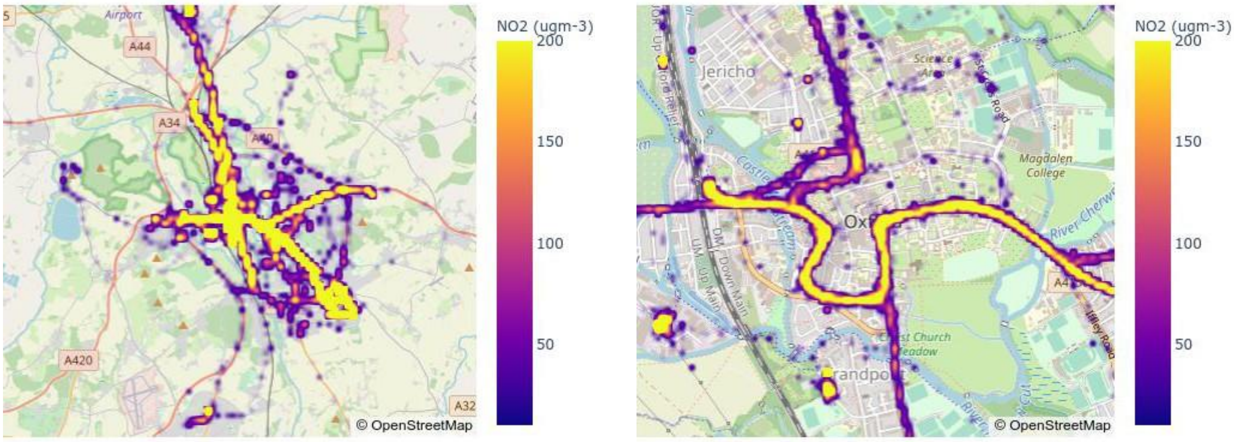


Figure 29 Mapped 1-minute mean PM_{10} sensor observations from OxAir mobile AQ sensor hosts (μgm^{-3})

Oxford, city & surrounds

Oxford, city centre

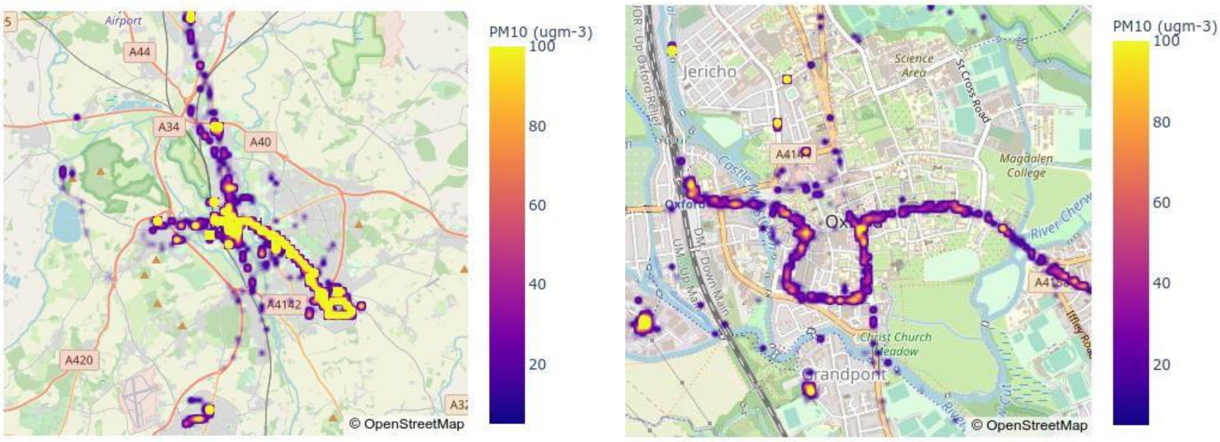
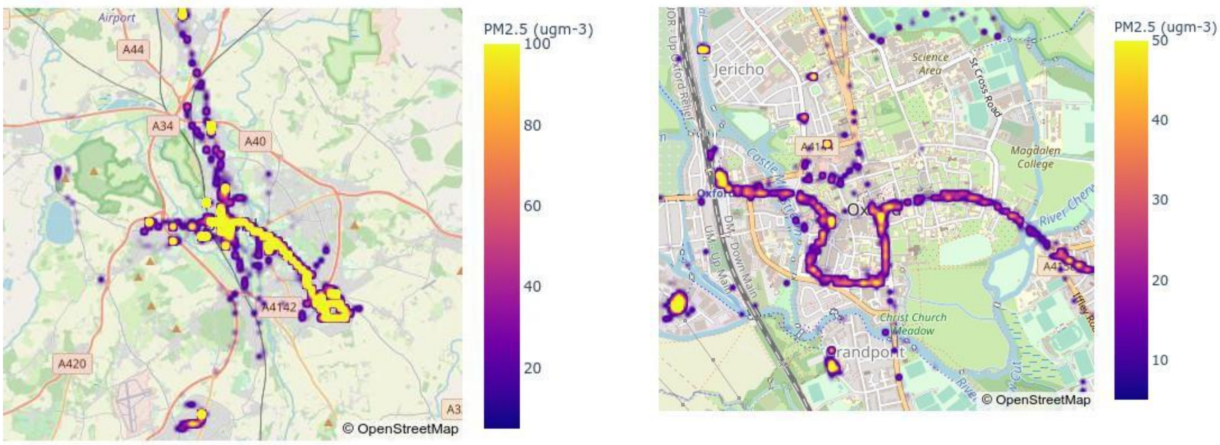


Figure 30 Mapped 1-minute mean $PM_{2.5}$ sensor observations from OxAir mobile AQ sensor hosts (μgm^{-3})

Oxford, city & surrounds

Oxford, city centre



8 Social research & public engagement activities

OxAir developed a social research protocol and undertook a range of public engagement activities in response to the projects objective to improve ‘‘information and engagement with the public on the sources, effects of air pollution and behaviours needed to improve it”. In doing so, the team reconsidered what constitutes meaningful ‘engagement’ and aimed to move beyond traditional conceptions of public engagement, which is often limited to one-way information flow directed at a homogenous ‘public’. The social research component of OxAir aimed to challenge the hierarchical relationship between AQ stakeholders found in traditional settings, which often see relationships of deference emerge, and risks neglecting local expertise and interests. We did this by employing novel social science methods to facilitate equitable dialogue between diverse stakeholder groups (represented in the OxAir Competency Group).

Key notes

- Community based qualitative data complemented and enriched traditional AQ data collection techniques and establishes an empirical basis for shifting approaches to collection AQ data from a ‘human perspective’
- Community knowledge and lived-experience could contribute to implementation of local AQ policy and realise co-benefits of shared understanding and ownership
- Technical challenges with sensors were commonplace across the CG
- There was noticeable shift in commitment level and trust in the sensor technology after technical challenges were encountered

8.1 Social research motivation

Past research has shown that knowledge production and management practices ignoring local expertise in favour of an exclusively science-based approach can fail to garner public legitimacy. They can also miss out on vital local intelligence when devising solutions and communication strategies. Given growing calls to democratise environmental knowledge via participatory methods such as ‘citizen’s assemblies’, it was important that the OxAir project was positioned to approach the broader question of what counts as relevant and ‘reliable’ evidence for AQ management with the introduction of mobile sensing.

It was imperative that the project did not discount the understandings and experiences of air pollution by residents, who are experts of their own lives and locales. To achieve this, an equitable space for discourse among Oxford residents, members of the OxAir technical team, Oxford City Council AQ team and social and public health researchers was vital. Through our adapted approach, ambitions were not to ‘solve’ the issue of air pollution in Oxford by itself, but rather to point to an alternative approach for local AQ management that consults local expertise, meets local needs, garners greater public buy-in and cultivates a more effective and equitable relationship between stakeholders in the AQ governance arena.

8.2 Social research methods

The OxAir competency group (CG) methodology, structure and activities were modelled on an analogous initiative first developed by Sarah Watmore and colleagues for local flood management in the town of

Pickering[9]. This successful example of participatory research and co-production of knowledge about the environment presented a prime model for addressing the challenge of local air pollution in Oxford. The flexibility of this method is such that it can better integrate the perspectives and experiences of residents and technical experts alike when approaching a varied landscape of opinion on certain facets of local AQ management. The outputs from the OxAir CG aim to establish an empirical basis for developing policy recommendations that consider the experiences and insights of members of the public in the face of air pollution-related challenges.

8.2.1 Recruitment of research participants

Prior to commencing our OxAir CG activities, we developed a plan for recruiting resident members for the group by drawing upon socio-economic and demographic analysis developed using 2011 Census data. Weighted averages were calculated for age, gender, ethnicity, and index of multiple deprivation (by ward) to estimate a representative sample of 20 Oxford residents, with the ideal sample consisting of 10-20 residents to allow for manageable discussion amongst all members of the group.

After three months of formal solicitation, we found that individuals from relatively affluent, white, and middle-aged groups were significantly over-represented among volunteers, and individuals from minority ethnic groups, more deprived areas, and the youngest and oldest age groups difficult to engage. Ample time for soliciting the CG group, as well as tapping local networks to share information about the project via special interest WhatsApp groups, proved most helpful at forming a representative group. The resulting CG member composition is shown in Appendix G according to its success at achieving quota estimates for each demographic variable identified during the planning phase.

8.2.2 Competency group meetings

A plan and timetable for a series of four CG sessions was established. The four original sessions were adapted in response to technological issues and disruption as a result of the COVID-19 outbreak. Ultimately, the OxAir CG held five sessions and reformulated the theme and topics for each. Prior to each meeting, agendas and thematic prompts were circulated to all members of the group. Each session was facilitated by the social researchers and featured a series of activities designed to maximize sharing and discussion. In addition, each session was audio recorded and the contents were transcribed. Following the first three sessions, the OxAir social research team held debriefing meetings to discuss outcomes from the sessions. COVID-19 related emergency measures came into force following the third session. The social research team therefore decided to hold socially distanced one-on-one sessions with each of the resident participants to make up for lost contact time when social distancing policy was relaxed sufficiently to do so.

Session plans are outline below. Each session was projected to last 2.5 hours and focused on a theme to underpin discussion, as well as featuring ‘hands-on’ activities.

Session 1 Introduction & setting out intentions.

CG session 1 presented an opportunity for members to get to know each other, share experiences, routines and histories of living and breathing in the City of Oxford. The session incorporated mapping as a technique for materialising knowledge and individual experience by asking each resident member to draw their

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[9] Landstrom and Whatmore, 2011. http://knowledge-controversies.ouce.ox.ac.uk

routes of commute and daily movements, directly onto large black and white maps of Oxford which they also annotated with anecdotal explanations behind hotspots, and indicative symbols.

In the second half of the session, resident members were introduced to the PHH and EDT monitoring instruments by the technical members and were instructed on how to operate them. Between Sessions 1 and 2 participants had the chance to carry an PHH sensor during their daily activities in Oxford. The data will be processed for review and discussion in time for Session 2.

Picture 10 Collaborative mapping exercise and discussion during CG session 1

SESSION 2 REVIEW COLLECTED DATA, DISCUSS HOW THIS ALIGNED WITH EXPECTATIONS.

CG session 2 was intended to examine visualisations of the sensor data collected by group members using the PHH sensor (on foot, bicycle and in car) and to discuss how it compared to collective experiences and expectations. Unfortunately, the sensors experienced GPS failures regularly during the time they were deployed with the CG group which severely limited the amount of useable AQ data collected, despite some highly detailed note taking by several of the participants. The decision was made to postpone the plan for session two until adequate GPS data was available to generate visually intuitive representations of each member's data collection exercise. There was discussion of recruiting a replacement participant, although a decision was made to retain the original protocol for consistency and rapport-building among the CG.

Session 2 was adapted to focus on becoming acquainted with the nuances of the PHH sensor technology, in addition to featuring short presentations on the health effects of air pollution and on relevant perspectives of Science and Technology Studies (STS) and public health.

Picture 11 CG members carrying PHH units on their journeys throughout the city

Session 3 Review & discussion following PHH deployments.

Session three featured the opportunity to review and discuss heatmap and time series graphical displays pertaining to their excursions with the sensors. The bulk of this session was dedicated to discussing and deciphering what activities the residents were engaged in when specific concentrations were registered. The group also considered lessons learnt thus far in terms of how it can be used to change and inform this process.

Session 4 Presentation & discussion of Local Air Quality Management

Session 4 took place during the COVID-19 pandemic, and as a result was held virtually. This session focused on the current state of AQ management policy in Oxford, featuring a presentation from Pedro Abreu in addition to an extensive discussion on potential outcomes of the project that were reflective of our collective conclusions.

Session 5 Finalising project outputs

Session 5 was convened as an additional session agreeing on and finessing the outputs that would emerge from the entire OxAir CG process. Specifically, we discussed details and plans surrounding their development and delivery.

8.2.3 Competency group findings

Transcripts of audio recorded during each of the CG sessions, as well as those from one-on-one conversations with group members, were reviewed and coded according to common themes. The social science research team generated their analysis from this content, while drawing on evidence and theory from the academic literature described in Sections 8.1 and 8.2. The analytical process resulted in the findings presented below in list form. Overall, this experimental approach has shown that many parts of the AQ management process can be substantively improved through the incorporation of local knowledge from residents who are experts of their own lives and locales.Achieving these benefits would require transitioning from a view of publics as variables to be worked around to one that recognises them as essential collaborators in successful governance.

Collection of qualitative data complemented and enriched traditional AQ data collection techniques and establishes an empirical basis for shifting approaches to collection AQ data from a 'human perspective'.

a) Bringing people and lived experiences into AQ management was achieved on a number of occasions and showed that social considerations can complement / enrich traditional techniques (see Output 1).

b) When our CG group sensor hosting exercise was hindered by technical issues, it inspired the group to consider alternative approaches of data collection using their local insights.

c) An outcome of (b) was a "Map of Anecdotes" which brought a human perspective to the challenge of choosing locations for sensor deployment. Our 'OxAir Hybrid AQ Data Map' likewise creates a more three-dimensional image of exposure by placing sensor readings alongside participants' empirical observations. Finally, the recommendations available in the index (Appendix H - OxAir CG Outputs 3 & 4) offers policymakers an image of what would make Oxford more liveable for the people who actually reside there.

Significant value in collective interactivity & materialisation of AQ knowledge via mapping exercise

d) Reinforced the importance of focusing on the lived experiences and context behind air pollution exposures across Oxford, while fostering personal connections within the group.

e) Illustrated common areas of concern, which were transcribed into our records and registered by the technical team.

f) Clearer protocol surrounding how these insights could translate directly into monitoring, in addition to more resources and technical team members adept at deploying the PHH sensors, could have benefited the entire process.

TECHNICAL CHALLENGES WITH THE SENSORS WERE COMMONPLACE ACROSS THE CG

g) Technical challenges associated with the PHH sensors were experienced by all members of the CG to varying degrees.

h) This contributed to a camaraderie among members of the group and the social researchers.

i) Hierarchies and communication barriers existed at times between the technical CG members and the resident members. This was characterised by varying perceptions of the role of the sensor technology when it comes to air quality governance.

NOTICEABLE SHIFTS IN COMMITMENT LEVEL & TRUST OF RESIDENTS IN THE SENSORS

j) Each CG member had the opportunity to carry the sensor and map their own personal journeys throughout the city at least twice.

k) Incorporating this exercise throughout the CG process helped dissolve preconceived notions of the certainty, stability and reliability of air pollution data, while allowing them to recognize the complexity surrounding the translation of data into LAQM and personal practices.

l) When reflecting on their multiple experiences of collecting data using the PHH sensors, members remarked on how their note taking and general approach to carrying the sensors was more 'scientific' the first time around. The second time they carried the sensors, they described a diminished commitment, stemming from a lack of trust in the device to collect complete data.

m) Challenges with the PHH sensors during the first round of sensing elevated the role of qualitative and anecdotal data: through extensive note taking, completion of travel diaries and taking photos during their journeys, in order to make sense of the data without GPS or timestamps.

n) The resident participants also remarked on the value of the sensor as a talking point. Throughout their excursions with the sensors, each participant described striking up conversations with curious passers-by and taking the opportunity to share information about the project.

SIGNIFICANT VALUE OF HOSTING ONE-ON-ONE SESSIONS WITH CG MEMBERS MID-WAY THROUGH THE PROCESS:

o) Holding one-on-one sessions proved to facilitate discussions and contributed significantly to our findings.

p) A relationship of trust and cordiality had been fostered amongst the social science researchers and each participant, owing in part to the shared challenges experienced with the sensors and a global pandemic. This contributed to a sense of camaraderie and collaboration, which was a key motivation behind the selection of the competency group methodology.

q) perspectives on the sensor technology and LAQM in general were shared more readily in the one-on-one format.

r) One-on-one sessions were time-intensive and difficult to schedule.

THE CG METHOD WAS SIMULTANEOUSLY FLEXIBLE & INFLEXIBLE

s) Provided a built-in flexibility which allowed for easy adaptation of the themes for each session.

t) Particularly advantageous following technical issues with the PHH sensors and COVID-19 contingencies.

u) The research design element of carrying all of the participants through to the end of the CG process, proved to be restrictive and contributed to the loss of valuable perspectives very early on in the process.

8.2.4 Other outputs

THE OXAIR HYBRID AIR QUALITY DATA MAP

The Hybrid map combines two types of data: qualitative, contextualising reflections from CG resident participants on perceived air pollution hotspots and their possible causes, alongside quantitative representations of the same routes recorded by sensors when carried by the CG resident participants. The goal of the Hybrid Map is to provide interested publics and practitioners with a tool for visualizing these two forms of empirical evidence, usually held and used entirely separately, in a mutually complementary way. In its current prototypic state, the Hybrid map output is not intended to be used as an instrumental tool, but rather as a heuristic ‘snapshot’ that illustrates an alternative way of looking at AQ and its intersections with community experiences.

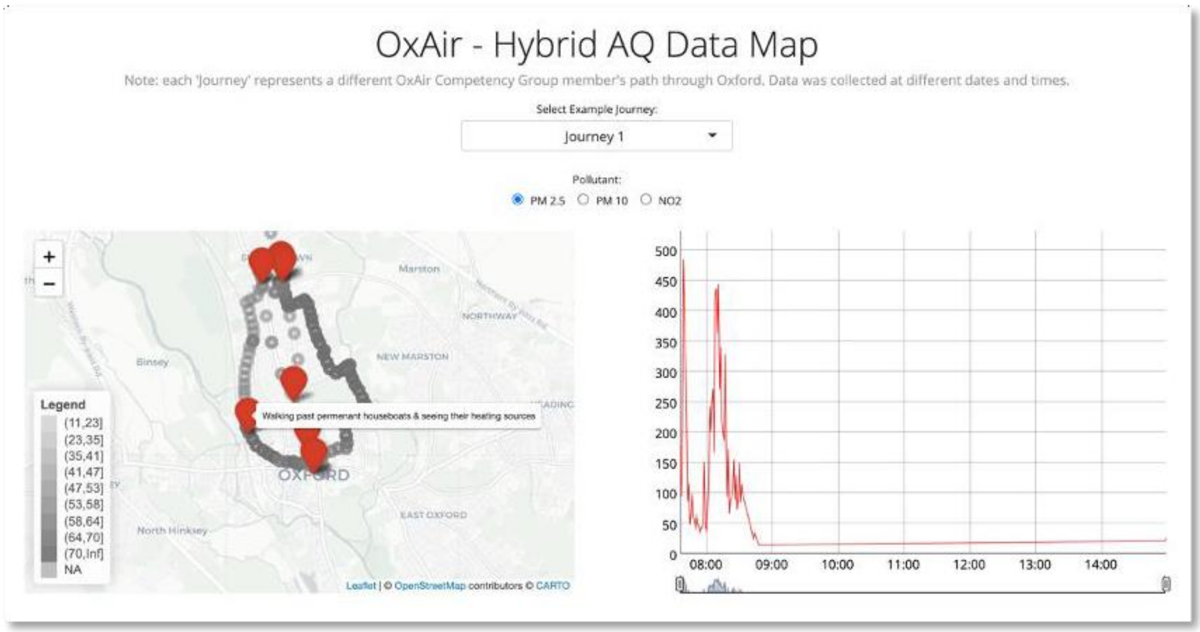


Figure 31 Prototype OxAir Hybrid AQ Data Map

THE OXAIR HYBRID AIR QUALITY DATA MAP

The Oxford Open Map of Air Quality Anecdotes is intended to be a live, visually intuitive and interactive platform for users to input entirely anecdotal information about perceived hotspots around Oxford. Members of the public are able to ‘pin’ inputs on a map of Oxford, along with photographs or other media. Over time, the goal is to facilitate the emergence of a citizens' consensus that would show practitioners where sensing activities should be concentrated, while pointing policymakers where to look for possible AQ infrastructure investments. The Map of Anecdotes is a direct outgrowth of the CG process, where extensive conversation surrounding informational needs was able to materialise into a potential solution. The Map has been live for several months and has already garnered the interest of other local authorities, while facilitating the expansion of an active, usable citizen science database that can inform future sensor deployment, maximise resource efficiency, and most importantly best serve the Oxford community.

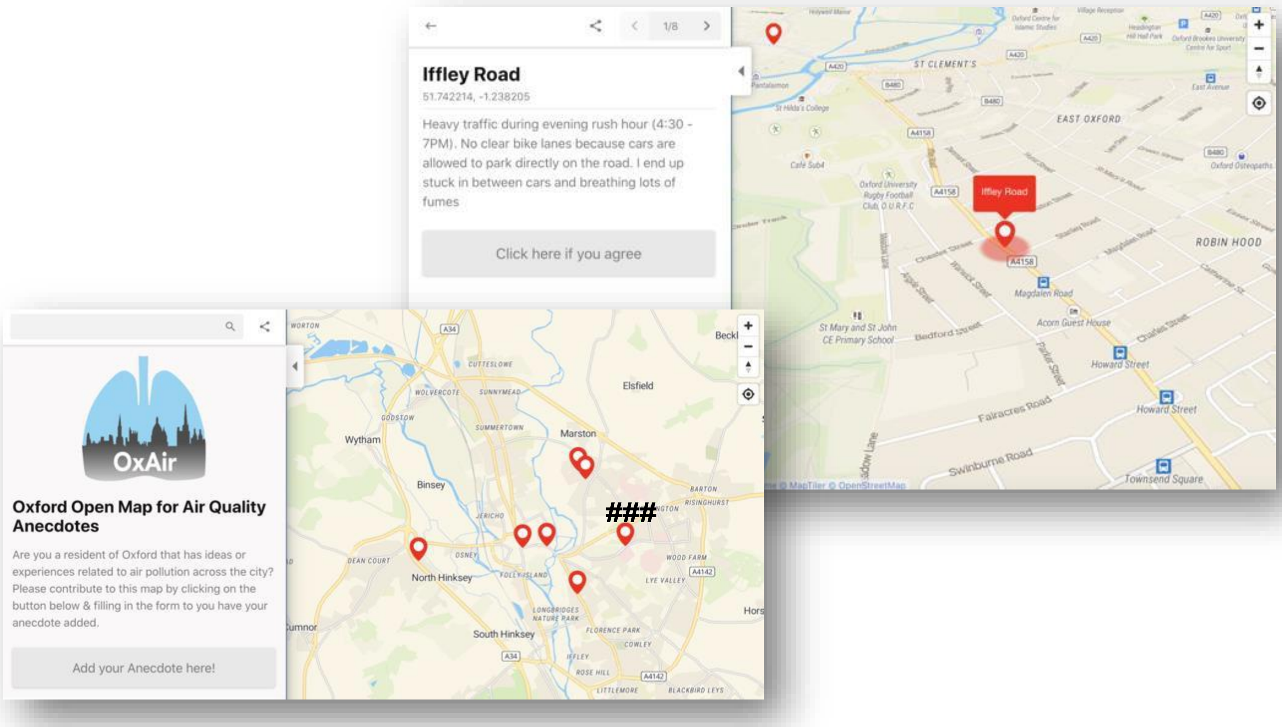


Figure 32 Landing page for the Oxford Open Map of Air Quality Anecdotes & example anecdote

Human Perspectives': What information matters to OxAir CG resident members within the context of LAQM and future mobile monitoring.

This broadly-defined output comprises the recommendations emerging from the CG process that address the project's objective of better integrating 'human perspectives' of AQ at each stage of monitoring and management processes. These recommendations come in two forms. Firstly, a number of key considerations advocated by the social research team, extrapolated from our research analysis and pertaining to general changes that can be made to the ethos and objectives of AQ research. Secondly, a more specific list of suggestions amalgamated from across discussions held in the CG meetings. The latter is provided in response to a need for greater channels of communication between practitioners, policy makers and members of the public regarding all the above's informational needs and key interests. The list thus offers an indication of areas of agreement between participating members, and can be explored in greater detail in Appendix H.

Sensor Usability Feedback

Resident use of the sensors was central to the CG framework, and thus provided an opportunity to reflect on our chosen sensors' usability. While the response to this mandate is contained in the Sensor Usability

Indicators section of the report, a significant portion of the insights contained there were gathered during the CG sessions and one-on-one interviews with resident participants. See Appendix B: PHH sensor issues log, Appendix H: list of CG information needs and Appendix C: Standard Operating Procedures for OxAir AQ sensors.

Virtual 'Open House' presentation on the OxAir CG social research process

As a way of extending the benefits of this project beyond the final report and share some of our findings with the Oxford community, the CG group hosted a presentation of our key findings and methods for local residents, policymakers and members of the academic community. This addresses a considerable local interest in the outcomes of the CG framework and represents an important gesture in ensuring that Oxford city sees benefits from the project. The event took place via Zoom on Wednesday October 7th from 12:00 - 1:00PM. It was recorded and the recording is available via the OxAir website here:
https://www.oxair.org/virtual-open-house

Executive Summary of key findings for the Oxford/UK AQ practitioner communities

A 4-page executive summary was developed to describe the motivation, methods, findings and outputs emerging specifically from the public engagement and knowledge transfer components of the OxAir project. The document is designed for quick and easy dissemination throughout local Oxford channels, as well as through national and international organisations that maintain interest/focus on environmental communication endeavours. It can be found in Appendix I: Executive Summary of key findings for the Oxford/UK AQ practitioner communities.

https://www.oxair.org/outputs

8.3 Public engagement activities

8.3.1 Schools

Some schools in Oxford are very interested in AQ already and were highly motivated to support the project. Our website led to several enquiries for advice and support and eventually to the schools joining the project.

Oxfordshire Schools Air Quality meeting

On UK Clean Air Day 2019, OxAir participated in an air quality event organised by Oxfordshire County Council, bringing together parents, teachers and council programmes to support schools such as STOP (idling) and the WOW walk to school initiative.

8.3.2 Presentations

Six presentations were given by members of the OxAir steering committee to a variety of stakeholders across multiple disciplines including.

- the inaugural Oxford Air Quality Meeting, hosted at Keble College at the University of Oxford.
- Oxfordshire County Council's 2019 UK Clean Air Day event(s) for schools
- 3 x Oxford Friends of the Earth hosted events

8.3.3 Public events

Three public-facing sensor demonstrations were performed.

- The Oxford Green Week public event in June 2019.
- The Eid Extravaganza in June 2019.
- Botley Big Green Day Out in February 2020.

Picture 12: Demonstrating live data collection using optical particle counter at the Eid Extravaganza Festival in June 2019

9 Discussion and conclusions

Detailed observations on best practice, sensor performance and lessons learned have been included as 'key notes' in each of the top-level sections of this report. In this section we offer some concluding remarks and discussion on the main points linked to core project objectives. Please refer to the relevant sections for detailed commentary.

OxAir has been successful in investigating the potential for reputable low-cost sensor technologies to support the delivery of LAQM related activities, local-level decision making, policy design, progress monitoring and broader research questions on personal exposure monitoring and public information needs. In parallel, the project engaged with Oxford City communities to exchange a shared experience of AQ in Oxford, for bi-directional learning to improving understanding of local AQ cause and effect and fostering a sense of ownership.

The project has shown that raw data, direct from low-cost sensors is unlikely to meet the broad data quality requirements of of LAQM (at the time of writing). OxAir has shown that raw data from low-cost sensors can, and frequently does, display a variable offset, signal noise and suffer from interferences that make applications within the LAQM framework problematic. This extends to broader applications for hotspot identification, awareness raising and education. In addition, we note that, the sensors selected by OxAir were chosen by AQ measurements experts with prior knowledge of the domain and a day-to-day appreciation of reputable sensors, systems and components. As such, they we were expected and probably are representative of the top-end / better performing sensor systems in this market sector. Their below par performance is illustrative of the difficulties that AQ experts, local authorities, community groups, lobbyists and educators face in making the correct sensor choice with the current level of open access information on sensors. If low-cost sensors are to realise a meaningful place within the LAQM toolkit and other user groups, this must change.

It goes without saying, that sensor technologies are expected to, if not must, improve on all angles; accuracy, precision, usability. This project has in itself provided valuable feedback into the manufacturing process for the two sensor systems used and their next generation. Despite these short comings at the present time, OxAir has shown significant positives in developing and demonstrating automatable techniques for data processing to improve data quality. Using relatively simple statistical techniques, OxAir has shown up to factor of 5 improvements in raw sensor data expanded uncertainty scores, delivering processed sensor data which approaches the requirements of LAQM and European AQ Directive even with relatively unsophisticated correction models. We see this as a significant achievement, particularly given the simple nature of the models used. Further research by AQ data users into developing more sophisticated correction models is anticipated to be the most cost-effective next step(s) towards delivering sensor data that meet the data quality objectives for LAQM and the many associated benefits.

Section 1 of this report set out several key objectives for low-cost sensors to support in the delivery of;

- A higher spatial and temporal evidence base for LAQM and public information
- Better data to support cost benefit analysis of major policy interventions
- More relevant information and engagement with the public on sources, effects of air pollution and behaviours and travel choices to limit it
- Progress towards improved estimates of personal exposure to air pollution

Despite low-cost sensors being well placed to respond to better spatial and temporal resolution objectives through delivery at scale and their fine resolution logging capabilities, it is clear that the uncertainty characteristics of raw sensor outputs limit the application for these objectives within the timescales for this work. As noted, above, with the development of processing methods we anticipate and hope these limitations to recede.

Outside of the main focus of research outlined above, OxAir has also set out a framework for standard operating procedures and best practice advice which may be adapted and used for alternative applications. There are potentials to extend this advice taking into account the outcomes of this project regarding raw vs. processed sensor data uncertainty and to cover how community actions dialogue can complement LAQM and vice versa.

The team concluded that neither sensor system was wholly suitable for high resolution personal exposure assessment; the EDT having restricted sampling time resolution, limited to 1 gas sensor and no GPS capability, the PHH exhibiting glitchy logging and GPS capability in the field and fractionally too large for comfort. Even so, for the 10-20% of PHH measurements with GPS data, mapped outputs look encouraging and warrant ongoing e.g. effects of vibration on the sensors and some exploratory analysis of the data.

Given the issues highlighted above OxAir has shown there is a clear need for a platform for evaluating and sharing sensor technology performance. Whereas the project has not been able to progress development (besides the administrative logistics for co-location trials at Oxford St Ebbes and High St locations), it is anticipated that such a platform will include a physical location for co-located sensor trials in a polluted environment e.g. roadside location and a web resource for information sharing.

Via the Competency Group, novel modes of knowledge exchange enabled OxAir to engage with residents more effectively and equitably. Using this format, the project was successful in establishing a more relevant exchange of local AQ information between residents and the City Council; a sampling strategy guided by local insight being one of the examples which was ultimately likely to dissolve barriers for public participation in formal air quality knowledge production processes, while expanding trust in both qualitative and quantitative data formats by AQ managers, practitioners and publics alike.

9.1 Recommendations

Based on the evidence and experiences collected by the OxAir project team the following recommendations are made;

1. Low-cost sensor data should be used with caution for informative, educational and profile-raising applications because of the likely variability and uncertainty in raw sensor data
2. Lobbyists and community groups should acknowledge the potential uncertainty in sensor data that that they commission compile and plan for handling of it
3. The current state of the art in sensor low-cost sensor systems should only be used for LAQM applications with discretion and with traceable documentation attesting the handling uncertainty and / or absence of environmental effects in sensor signals e.g. use a model to correct for environmental interferences

4. Further research is needed to develop sophisticated correction models which can be used easily by all sensor users to handle the interfering effects of environmental parameters

5. Low-cost sensor performance should be regularly checked by co-locating with reference instrumentation at a heavily polluted environment such as a roadside / kerbside location e.g. before and after deployment (and at intervals in between, for long deployments)

6. When purchasing new equipment it is recommended to arrange a returns / exchange policy with the vendor for sensors that can be demonstrated as having atypically behaviour(s) e.g. unsatisfactory signal noise, baseline offset for the intended application

7. Sensor vendors are encouraged (should) be open about interferences from environmental effects (temperature and relative humidity) and any testing that has been done in this regard for their products

8. To facilitate the benefits of active engagement on AQ policy and bi-directional flow of information on local AQ issues, a web-based resource for logging AQ issues on a web-map and creating open, traceable dialogue should be evaluated e.g. the OxAir Map of AQ Anecdotes.

9. Sensor users to keep a watching brief on new sensor developments from vendors on data processing, algorithms and models for the correction of environmental interference effects

10 Acknowledgements

The OxAir team and Oxford City Council would like to thank the individuals and organisations for their contribution and support in the design and delivery of OxAir.

Oxford Bus Company
OxWash
Low Carbon Oxford North (LCON)
The University of Oxford
The University of Birmingham
Royal Cars
Oxford schools
Pedal & Post Ltd
Oxfordshire County Council

South Coast Science Ltd
Alphasense Ltd

Pegasus Primary School
Dragon School
St Joseph's Catholic Primary School
Cherwell School
Cheyney School
Windmill Primary School
North Hinksey Church of England Primary School
Larkrise Primary School
Rose Hill Primary School
Church Cowley St James C of E Primary School
Tayloriana Institute, St. Giles
Cutteslowe Primary School
West Oxford Community Primary School
Mind UK, Walton Street
Wolvercote Primary School
St Francis C of E Primary School
Summertown Cycles, Banbury Road
Walton Street Cycles, Walton Street
Warlands Cycles, Botley Road

The Oxford public for research suggestions & interest
The ever-cheerful competency Competency Group

APPENDIX A The OxAir team and list of locations monitored

PROJECT TEAM

Name	Organisation	Role
Jake Backus	Empathy Sustainability Ltd	Project manager
		Data collection
		Team & partnerships development
Tony Bush	Apertum	Air quality SME
		Data analysis
Brian Stacey	Ricardo EE	Air quality SME
		Technology SME
Kayla Schulte	Oxford University	Social researcher
		AQ visualisation SME
Karl Dudman	Oxford University	Social anthropologist
Pedro Abreu	Oxford City Council	Governance & oversight
		Air quality SME
		Oxford City Council Air Quality Officer
Dr Suzanne Bartington	Birmingham University	Public Health SME
		Air quality research SME
Richard Kuziara	Oxfordshire County Council	Active Oxfordshire

PROJECT PARTNERS / PARTICIPANTS

Organisation
Oxford Bus Company
OxWash
Low Carbon Oxford North
Royal Cars
Oxford schools
General public through research suggestions and Competency Group

Pegasus Primary School	Dragon School	St Joseph's Catholic Primary School
Cherwell School	Cheyney School	Windmill Primary School
North Hinksey Church of England Primary School	Larkrise Primary School	John Radcliffe Hospital
Rose Hill Primary School	Church Cowley St James CofE Primary School	Tayloriana Institute, St. Giles
Cutteslowe Primary School	West Oxford Community Primary School	Mind Shop, Walton Street
Wolvercote Primary School	St Francis CofE Primary School	Abingdon Road
Divinity Road	Cowley Road (stolen)	Summertown Cycles, Banbury Road
Walton Street Cycles, Walton Street	Woodstock Road	Warlands Cycles, Botley Road
Cutteslowe Roundabout	Woodstock Roundabout	

APPENDIX B Sensor issues / improvements list and Usability Feed

SENSOR ISSUES / IMPROVEMENTS LIST

Design

1 Portability, shape and size: The PHH handheld device is designed to be portable. However, the power button and the NO2 sensor are located just where the sensor would be held or strapped. This limits how the device can be carried e.g. on a bicycle, on the shoulder etc. Also, the on-off button is easily turned off accidentally because of its location. Suggestion: move the NO2 sensor and on-off button (ideally up).

2 Resilience: The device does not seem very robust. If knocked or dropped it stops working / seems broken.

3 Security: There are no built-in secure fixings, i.e. to support it being attached to mobile transportation, or in a static location from being stolen.

4 The device is not waterproof, making it not very useful for portable use in wet weather without some sort of special housing.

Power

5 The power button is much too sensitive. It is extremely easy to accidentally turn it off.

6 If power gets turned off the device seems to need to be at a Wi-Fi location that it is pre-programmed with.

7 Light: The power light is extremely bright.

8 Type C connector: Location and sensitivity. Some devices do not charge well because the power connection is quite sensitive. I.e. it might need to be wiggled or placed “just so”. We have had a sensor out in the field returned as it would not charge, and sensor # below (see photo) turns itself off even when on charge.

9 One sensor started to isophase on and off and there was nothing we could do to reset it.

Wi-Fi

10 There seems to be a limit to the number of Wi-Fi addresses the device can be programmed with.

GPS

11 The devices can take a differing amount of time to acquire a GPS signal. On some occasions it hasn’t found one after an hour of being outside, whilst others can get it within 10-20 minutes. Non-professional users are likely to set off without having gained a GPS signal.

12 The GPS signal is best acquired in the horizontal position, although users will often carry the device vertically.

13 It may be necessary to turn the device on and off again (within Wi-Fi signal) in order to try to get GPS more quickly. Also, it may find it quicker if the location has not changed since the previous acquisition.

Noise

14 The fan is quite noisy for quiet environments

OxAir CG Output 4: Sensor Usability Feedback

The CG group and one-on-one sessions established an opportunity for reflection on the PHH sensors' usability and opportunities for improvement. This document/appendix contains insights gathered from the CG resident participants derived from audio recordings during our sessions, as well as via a document that was circulated with the following prompt:

Tell us about what you found easy or difficult about using the sensors during your outings. We'd like to hear both about the physical/technical aspects (e.g. the shape of it, or how easy the screen is to read etc.) and also some broader thoughts on the general experience of using it. What is it like to use these sensors as someone without technical expertise in this area? Do you feel as though there are any remaining gaps in your understanding of how the sensors work and are used?

Name	**Feedback**
CG Member 3	*"The sensor was rather heavy and needed to be in a carrier/rucksack of some kind to feel safe with it. As I was expecting data to be recorded I didn't really look at the screen except to see the GPS indicator. It wasn't a user-friendly screen."* *"In terms of viewing results of the monitoring, the date/time graphs were easy to use, but needed guidance to interpret - i.e.. to know what a 'bad' result would be. It would be good to have a clear map output that could be easily interpreted by non-technical users, in terms of presenting a combination of moving and stationary data, and also some indication about what level might be of health concern. An idea for a non-technical user cycling about would be some kind of combined indicator of air quality, which goes 'red' if it exceeds some recognised health-related limit of concern, though I'm not sure how you would calculate that from the continuous data."* *"It would be good to have some way to mark on the graphs/map outputs which was indoor and which was outdoor data, though not sure if that can be automated?"* *"In the process of testing out the sensors, we observed some issues with recording of location and sensitivity to humidity. As we have learnt that air pollution is affected by weather conditions, it is clear that data collection has to be well organised and repeated to produce good insights. Will sensors at some point be ready and available to citizen groups so they can collect data on specific routes on a regular basis, or is this going to be managed by the council/researchers directly? Having seen some of challenges involved through this project, I think citizen use of sensors needs to be accompanied with training and advice in order to produce "good" information useful for science and policy-making. It will be great if scientists, government and citizens can continue to collaborate."*

Name	Feedback
CG Member 2	*“The sensor was difficult to carry while cycling. The second time I used the sensor I used the rucksack that strapped diagonally across my body which was easier for cycling with it. “* *“The sensors were certainly a talking point. Passers by looked curiously at them - some were interested but others showed some concern about it - thinking I was videoing.”* *“Having a rubber case on it or a more protective covering would have been useful. I recall the case it was in if I remember correctly, it fell out of the case.”*
CG Member 1	*Participant described PHH as cumbersome and heavy. Participant was of older age and emphasized the age-incompatibility of the device.* *“[Tony said] that the sensors are only useful on a continuing basis as used by volunteers does not give us some more data. There's a comp there's a need to continually monitor. So he was fundamentally saying that the whole exercise wasn't based on anything because I still don't understand why they supply the sensors. Knowing how little use they would be in terms of results.* *“But you see, because you got seduced by the idea of such sophisticated measuring equipment, you could have done exactly the same thing on the social side with ‘Flows’ (Plume Labs), which would have been cheaper, it would have been easier, it would have been reliable. And it would have been against the background of large numbers of other measurements. And I think that because you were seduced by this idea of the quality that you get from the sensors, and the whole sociological side got completely lost.”* *“But the tech guys said that they said, well, even to be reliable, you need them to be small. And that's it. What you see the thing that struck me was that you went, you could have used both rather than either or.”*
CG Member 4	*“I think the sensors are probably, in terms of the entire competency group, I think were the driving tool for how engaged people were. I think everyone was quite sort of eager to, to sort of have a play with them and keep them for basically as long as possible. And they were not the best tools to use I think. I don't know in the grand scheme of it but I think having a more user friendly tool that would be useful, even if it doesn't record in the level of depth that you might need for more professional sense of [air quality], but I think if there was a general tool that was more user friendly, but in that user friendly-ness, you might lose some of your accuracy in especially, I don't know, tiny particles or something like that. I think that people would still get engaged with it because a lot of times when you've got a sensor, you're not gonna, like, you know, worried about really, in my view, really specific details, you want a general idea of how bad or how good the pollution is the areas where you are.”* *“With something that's maybe slightly smaller, easier to use, and I think people will be a lot more engaged in, in, in taking them [the sensors] out. So I think in that sense that's probably slightly off point. But I think in general, people are very interested in taking them out. I think if there was some sort of scheme where people could have more opportunities to sort of help out, I think*

Name	Feedback
	people like people would jump at that. Not everyone, but a lot of people would be quite interested ever, because everyone wants to know what it's like where they are. like, you're less interested in areas that don't affect you. But everyone always wants to know what their route is like, what their bus stops is like, what their house and road is like. And I think that I would definitely help engagement even if it doesn't necessarily produce anything scientific for the community" *"the biggest thing is probably that they're quite unwieldy. I know someone at the meeting had one of those miniature ones (Flow by Plume Labs). Yeah. And if there was some sort of compromise between the two, two extremes, I think that would be ideal. I think they weren't necessarily designed with like anyone in mind"* *"I think if there was any sort of new one being developed that had people like non scientists in mind, and that would be quite useful. Just like the size is quite big, the buttons quite tempting to press, they're quite temperamental, just anything slightly more robust and slightly smaller would be quite useful. Even if it doesn't necessarily give, you know, to the same degree of accuracy, I think the ones we had gave every 10 seconds but even if it just gave every minute or so, where you could just reduce the size and make it more usable for the general person at the expense of some of the more technical aspects that the other one brings. I think most people, but I can't speak for most people, but certainly I would be fine with something that does that. And I think the easier it is to sort of use and carry around, the more people will be likely to [use the sensors]"* *"With the big one is, you know, you've got to either attach it to your bag or you can't just sort of like, put it around your neck really if you go out cycling or anything like that. So um, or it does look a bit like a bomb if you leave it outside your houses. Someone did say, yeah, just something that, you know, looks more normal."* *Didn't know whether it was running or working all the time - unclear from a design perspective.*
CG Member 5	*Participant described how a curious and slightly alarmed neighbour asked about the sensor. They described how sparked a lively conversation about the project and about air quality, and they joked about it looking like a bomb.* *"Even like when devices are not working you were coming all the way to giving us and giving us instruction no matter what time of day it was you were always there to reply and even when we were having a group discussion, you guys were telling us a lot of more stuff. Plus listening to us. And then giving your point of view and listening to our point of view, which was really good."*
Tony Bush	*"Come the second stint of sensor hosting I think I had found the rucksack - they were in fact water bottle carriers for running which work round the waist or shoulder. I agree they were the best I have found for the odd shaped things.* *I prefer carrying them on my back in laptop bag webbing or in the bottle carrier.* *I hated the rubber cases. For me they made them bulkier & as you say they fell out of them pretty*

Name	Feedback
	easily. *We have only had 1 confirmed sensor fatality. "*

*Direct language and experiences from resident participants are "" in quotations

**Additional context/reflections from social research team are in *italics*

APPENDIX C Sensor placement strategy

CONSTRAINTS

Limited number of sensors, limited time, limited funding, potentially large area to cover.

PRIORITISATION OF LOCATIONS

- Competency group direction
- Socio-economically representative coverage
- Demographically representative coverage
- Geographically representative coverage
- Schools and Key routes (versus quiet routes) -arterial coverage, i.e. popularity coverage and human impact coverage.

We focussed on areas where there is the potential for something to change to improve air quality, (as well as some particularly bad areas). I.e. we will prioritise schools, hospitals, and arterial routes where walking, cycling, public transport and park and ride are alternatives. Our project is to measure the human impact of air quality, therefore, remote high traffic areas where people do not live, or commute are not a first priority.

SENSOR CHOICE

Our EDTs record 1-minute NO2 averages which are fine for walking but less good for cycling or with vehicles, since a greater distance is covered between readings. When they became available, the PHH sensors were better for mobile use, since they work at 10 second averages. Therefore, we started out using the EDT for all AQ data capture, but then moved EDTs to static locations and PHH sensors for mobile sensors, (when these became available mid project). During lock-down, since few people were travelling, we moved some of the mobile PHH sensors to static locations where we could find a power supply and suitable Wi-Fi signal.

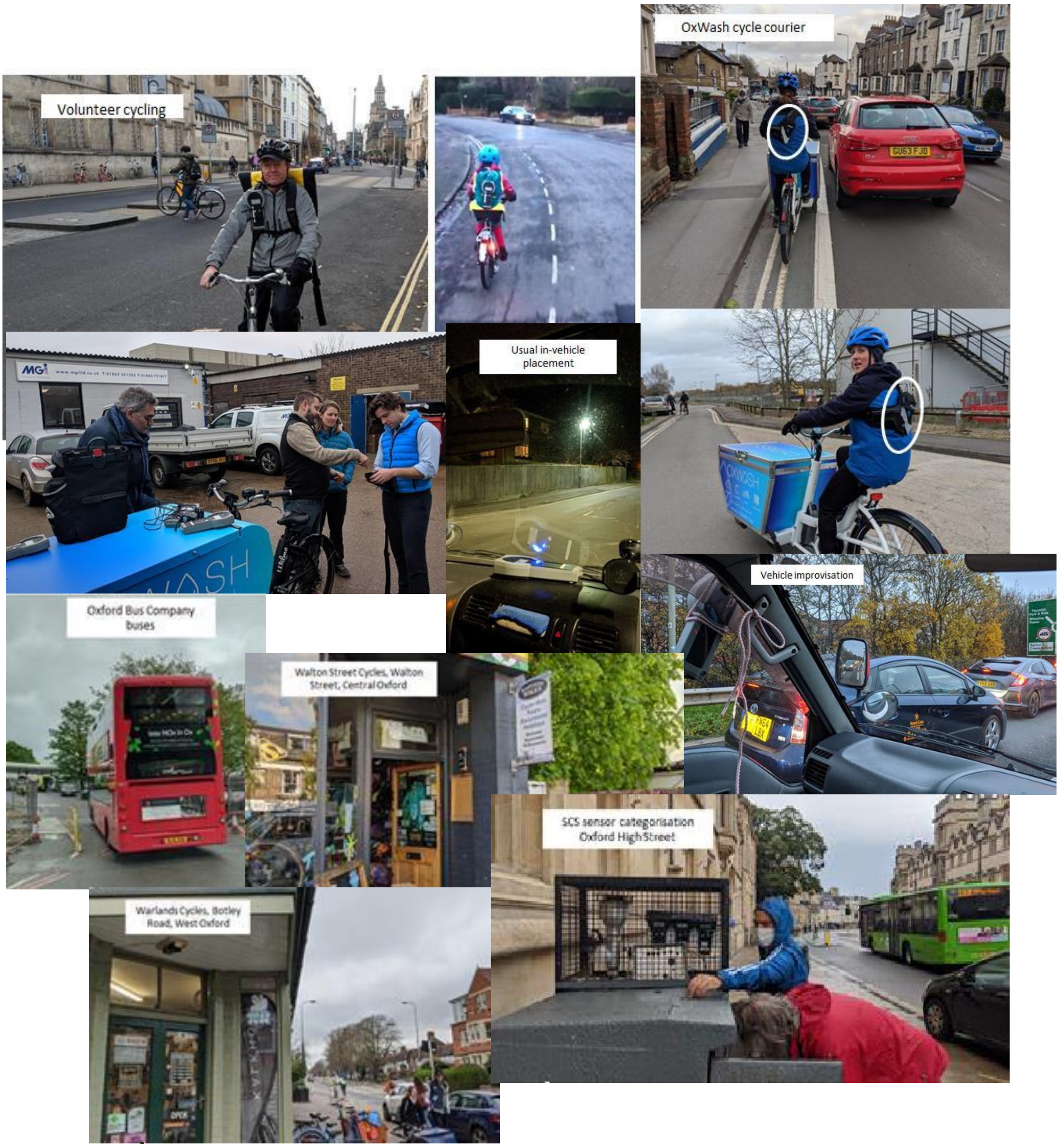
DATA VOLUME VERSUS PERSONALISATION

Discreet, personalised data collection might be good for user engagement and social research, but at best it is indicative and does not have the reliability of “painting” a key route multiple times over an extended period of time and in different weather and traffic conditions etc.

Part of our research will need to collect volume data and therefore we sought out professional partnerships with companies who could cover the same route multiple times, couriers, bus and taxi companies, who are out for extended periods of time throughout the day and week. Also, people commuting or travelling to school every day along the same / similar routes.

STATIC SENSOR PLACEMENT

Outside schools, sensors were placed, typically on lamp posts, set back from the road and on the boundary of school property at a height of 2 metres. See photos for actual locations.


Volunteer cycling
OxWash cycle courier
Usual in-vehicle placement
Vehicle improvisation
Oxford Bus Company buses
Walton Street Cycles, Walton Street, Central Oxford
SCS sensor categorisation Oxford High Street
Warlands Cycles, Botley Road, West Oxford


3001 Pegasus Primary School
South East Oxford
Side road


3061 (1) Cherwell School (Secondary)
North Oxford
Playground lamppost


3061 (2) North Hinksey
Primary School
West Oxford


3067 Cycling


3067 Rose Hill Primary
School
South Oxford

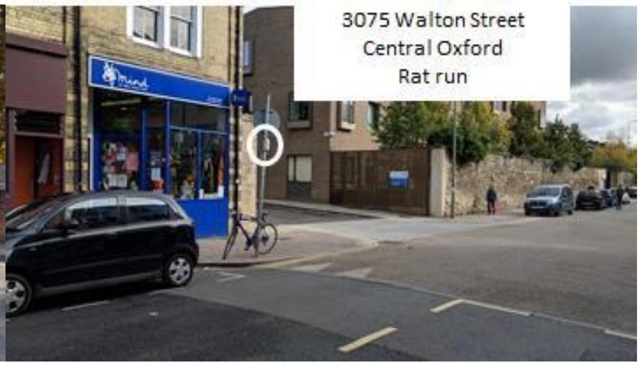
3073 (1) Cutteslowe
Roundabout
North Oxford


3073 (2) Wolvercote Roundabout
North Oxford


3073 (3) Dragon School
North Oxford


3073 (4) St Giles
Central Oxford


3074 / 3096 Church
Cowley St James
Primary School
East Oxford


3075 Walton Street
Central Oxford
Rat run


3075 (2) JR Hospital
Central East Oxford


3076 (1) Cheney Secondary School
Central East Oxford
20


3076 (2) Abingdon Road
South Oxford
Arterial road


3076 (3) Abingdon Road
S. Oxford Arterial road


3078 (1) Larkrise Primary School
S. Oxford


3078 (2) Divinity Road
East Oxford Rat run


3078 (3) Cherwell School (Secondary)
North Oxford


3078 (4) Cherwell School
(Secondary) N. Oxford


3084 (1) Cutteslowe Primary School
& N. Oxford Children's Centre Walkway


3084 (2) Cutteslowe Primary School
& N. Oxford Children's Centre Ring road


3084 (3) Cutteslowe Primary School
& N. Oxford Children's Centre Front


School
3084 (4) Cutteslowe Primary School
& N. Oxford Children's Centre Side –Wolsey Road


3084 (5) West Oxford Community
Primary School West Oxford


3089 (1) St Francis Primary
School
S.E. Oxford


3089 (2) St Joseph's Primary School #1
East Oxford
St. Joseph's
Catholic
Primary School


3089 (3) St Joseph's Primary School #2
East Oxford

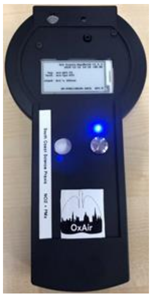

3089 (4) St Joseph's Primary
School #3 E. Oxford


3095 Cycling N.Oxford-City Centre


3096 Windmill
Primary School


3098 Wolvercote Primary School
North Oxford

APPENDIX D Standard Operating Procedures (SOPs)



NORMAL OPERATION

Under normal operation, the devices will look like as shown on page 1.

- The software version is displayed on the top line. Date & time are on the next line & are updated every minute. Check to make sure the date & time are correct.
- Wlan0: when the device connects to a Wi-Fi network, the name of the network will be displayed
- OK:PUBLISHING DATA – should be displayed when the device is connected to a network.
- The blue LED should be on at all times
- GPS:0 or GPS:1 – GPS:1 will be displayed when the device is able to calculate its location. When it is indoors, the device will probably display GPS:0.

Please keep the device running at all times. When possible, keep the device connected to mains power & running. Keep the device on charge overnight.

DEVICE APPEARANCE

The metal button on the front of the device cycles the power. Please avoid pressing the button. It is easy to do & on our improvements list! If you press it while it is running, the device will go into standby mode after about 30 seconds, as shown below:

In standby mode, the LED goes off, the wlan0: connection is lost & STANDBY is displayed. Press the power button to get it running again. After about 2 minutes, it should return to normal operation.

POWER

The internal battery will last over 12 hours from full charge before you need to charge it again. If the battery runs out, the only indication will be that the LED goes out. There is no low battery warning, another thing on our improvements list.

RECHARGING

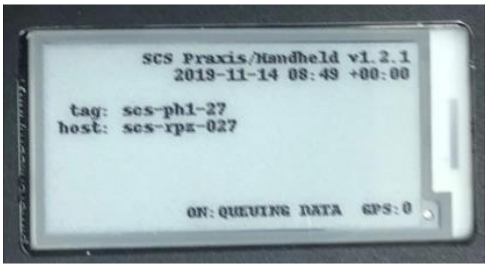
After sampling is completed for the day, connect the device to the mains, using the Raspberry Pi logo'd chargers in the micro USB port. Keep them on charge & running until the next campaign. The battery will go from empty to full in about 4 hours. It is best to find a way to cradle the device whilst on charge so that the power connection isn't fouled & the sampling apertures on the front are unobstructed as far as is possible.

Connect the charger to the port shown above. Please use the chargers provided they provide a defined output which will ensure the device is charged correctly.

WI-FI CONNECTIVITY

When in range of a pre-set, known Wi-Fi network, the device will automatically connect to download data. This arrangement allows for measurements to be uploaded to the cloud after each leg of the sampling campaign. The pre-sets can only be configured by OxAir staff at the end of each campaign.

While the device is running, but not connected (to Wi-Fi), the display will look like this:



UPLOADING MEASUREMENTS TO THE CLOUD

When the devices are connected to Wi-Fi, they push the following data to the cloud every 10 seconds:

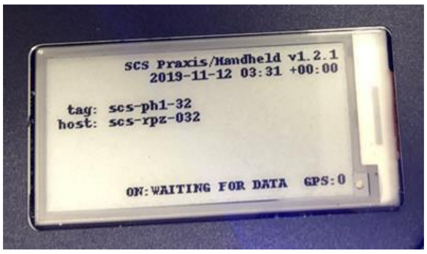
- Nitrogen dioxide - NO_2
- Particles - PM_{10}/$PM_{2.5}$/PM_1
- Temperature/Relative Humidity
- Location - GPS

TROUBLESHOOTING

During normal operation, you may be able to hear a quiet, high pitched hum from the device. This is the particles sensor fan & is normal.

The screen will also occasionally turn completely black & then white, before displaying information again. This is also normal.

It is possible that the device will not start-up properly when the power button is pressed. If this happens, the following message will be displayed, note the 'waiting for data' message



The time will update but it will be wrong.

You should contact OxAir if you see this displayed – no data is being collected & we would like to remedy that as soon as possible.

ADDITIONAL USE INSTRUCTIONS FOR "PHH" AIR QUALITY DEVICE -OXAIR PROJECT

1 **Power:** Always keep the sensor **charged and plugged in**. Especially over-night. (It should last about 9 hours on full charge though.)

2 The power button light is blue. If it is too bright you can cover it with some tape. However, check regularly that it is on.

3 If the sensor gets turned off accidentally, turn it on again where you have Wi-Fi e.g. at home.

4 Some devices have a red light on the front which comes on when the device is charging correctly.

5 At home there is a mains lead. In-vehicle there is a USB to cigarette lighter lead.

6 **Fan:** You should hear a slight fan noise in the background when it is on & working. **# Advise us if not.**

7 **GPS**: The device needs to have GPS in order to know where it is However, it can take some time to get a GPS signal. (You can tell when it has a GPS signal by the number 1 or 2 in the bottom right of the display. 2 is a very good signal.)

8 It may be necessary to **put the sensor outside** (not in the rain) for some time before travelling in order to pick up a GPS signal e.g. 10-20 minutes, ideally away from buildings. If no other options, then on the car dashboard. It needs to be horizontal, i.e. with the screen uppermost. (After acquiring GPS the device is usually happy to be in any position.)

9 Check from time to time that the device has found a **GPS signal**, (showing 1 or 2). **# If it fails to do so let us know -we can probably replace it.**

10 **Data collection:** Please place the device on your dashboard as far forward as possible to aid getting a GPS signal. This can be on the passenger side. Keep it powered.

11 If driving, **drive as normal with air vents open or from open a window** etc. No heating or air con please. If you have to use these at this time of year e.g. a client asks for it, suggest you place the sensor a little away from the vents.

12 **Data uploading:** The device needs to connect to a known Wi-Fi signal in order to upload (automatically) the data. Bring the device into your house / within Wi-Fi signal overnight and plug it in with the mains adapter.

13 **Wi-Fi:** Check that the device has your Wi-Fi details in the screen window. **# If not, let us know**.

DO NOT DO

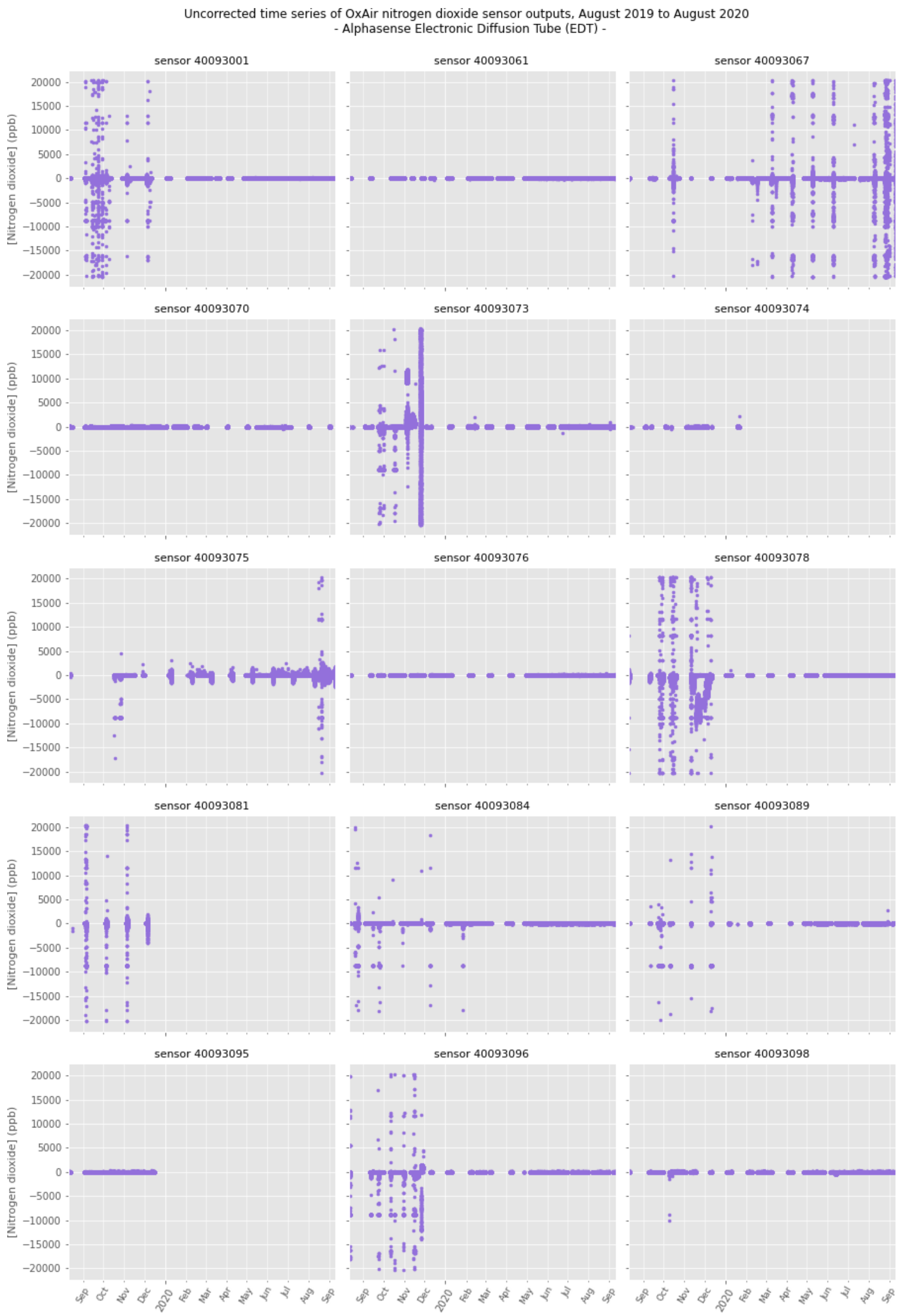
1 Don't get it too wet. Please keep the sensor as dry as possible and out of the rain.

2 When charging, ensure that not too much pressure is on the device so the charger plug doesn't get bent.

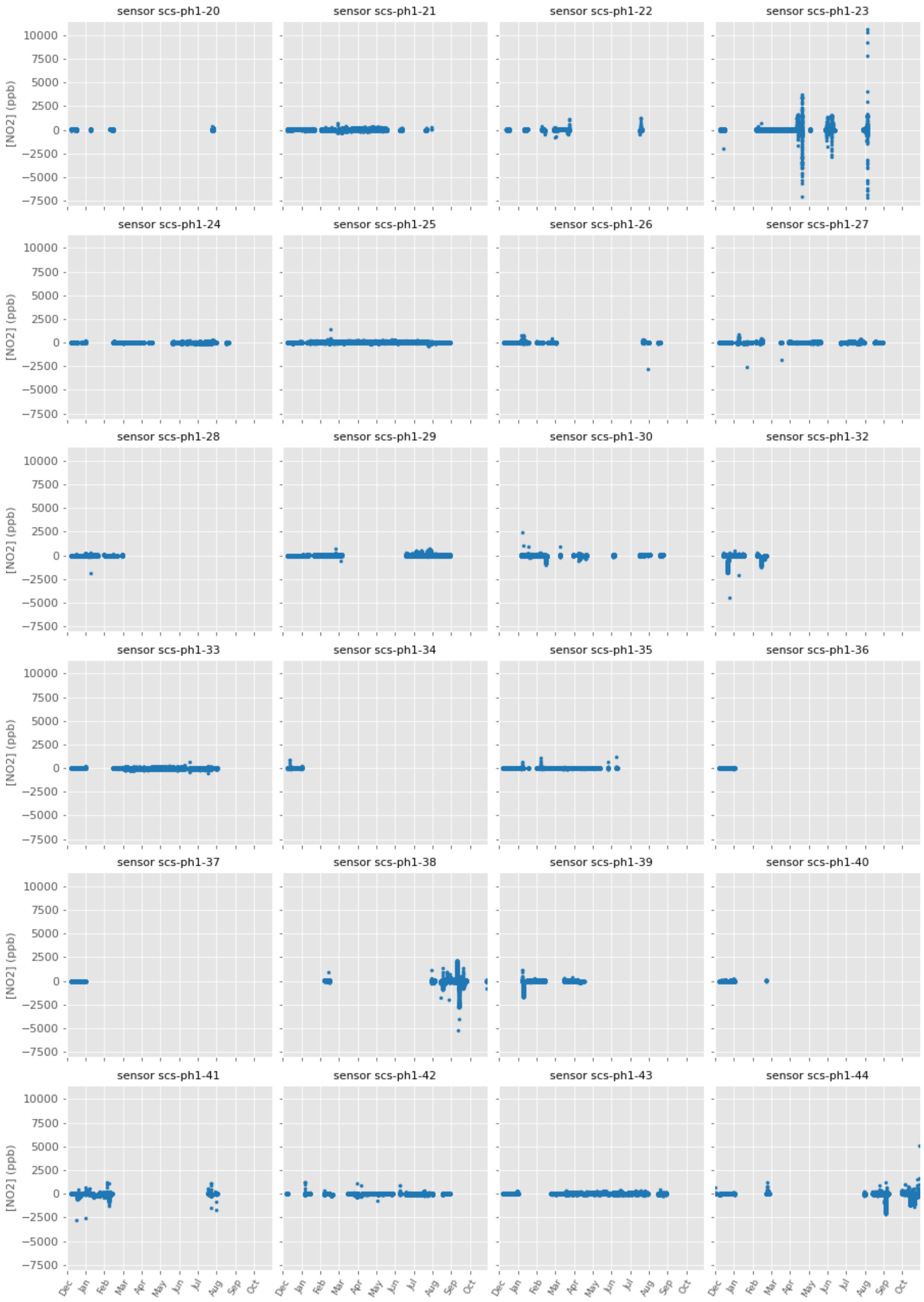
3 Do not drop the sensor! (They are very sensitive and will likely fail. They cost us £750 each:-)

4 Don't hesitate to tell us if there are problems. This is a time restricted study, so we need to keep the sensors as operational as possible.

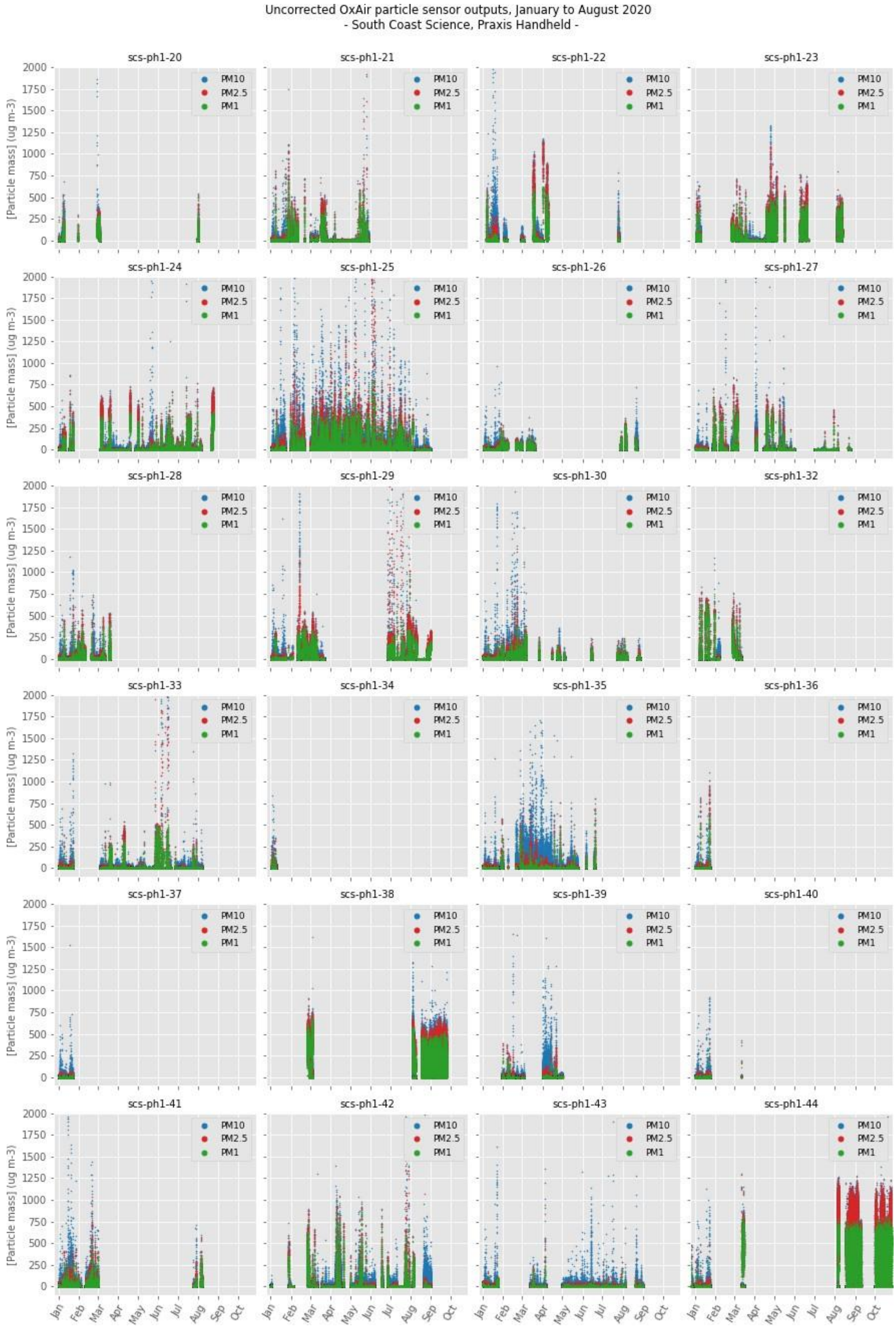
APPENDIX E Raw NO2 sensor outputs



Uncorrected time series of OxAir nitrogen dioxide sensor outputs, January to August 2020
- South Coast Science, Praxis Handheld -



APPENDIX F Raw particle sensor outputs



APPENDIX G OxAir competency group participant consent form & demographic alignment with 2011 Oxford census

DEPARTMENT OF SOCIOLOGY
42 Park End Street · Oxford · OX1 1JD

UNIVERSITY OF OXFORD

Melinda Mills (PI)
email: melinda.mills @sociology.ox.ac.uk | tel: +44 (0) 1865 281 740

Kayla Schulte
email: kayla.schulte@sociology.ox.ac.uk | tel: +44 (0) 1865 281493

Researching Experiences of Air Quality

PARTICIPANT INFORMATION SHEET

Central University Research Ethics Committee (CUREC) Approval Reference: Ref. SOC_R2_001_C1A_19_11

Purpose of Study: The purpose of this project is to help generate new knowledge about how air quality data is collected and communicated. By taking part in this research, you will help generate reliable, meaningful air quality data for key routes and open spaces in Oxford.

Please initial each box

1 I confirm that I have read and understand the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

2 I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, and without any adverse consequences or penalty.

3 I understand that research data collected during the study may be looked at by authorised people outside the research team. I give permission for these individuals to access my data.

4 I understand that this project has been reviewed by, and received ethics clearance through, the University of Oxford Central University Research Ethics Committee.

5 I understand who will have access to personal data provided, how the data will be stored and what will happen to the data at the end of the project.

6 I understand how this research will be written up and published.

7 I understand how to raise a concern or make a complaint.

8 I consent to having air pollution data collected

Template Written Consent Form Version 3.1 September 2019 1

9 I consent to having my GPS data collected

10 I consent to being audio recorded

11 I consent to being video recorded

12 I consent to having my photo taken

13 I understand how audio recordings / videos / photos will be used in research outputs [please delete as appropriate]

14a I agree to the use of direct quotes, attributed to my name, in research outputs **OR**

14b I agree to the use of pseudonymised quotes in research outputs **OR**

14c I agree to the use of anonymised quotes in research outputs **OR**

14d I do not wish to be directly quoted

15 I agree to take part in the study

16 I agree for research data collected in this study to be given to researchers, including those working outside of the EU, to be used in other research studies. I understand that any data that leave the research group will be fully anonymised so that I cannot be identified.

27 I agree that my personal contact details can be retained in a secure database so that the researchers can contact me about future studies.

Name of Participant   dd / mm / yyyy Date   Signature

Name of person taking consent   dd / mm / yyyy Date   Signature

Template Written Consent Form Version 3.1 September 2019 2

Demographic Variable	Quota	Achieved (pre-CG)	CG 1	CG 2	CG 3	CG 4	CG 5
<19	1.5	0	0	0	0	0	0
20-29	3	3	3	3	3	3	3
30-39	2	3	3	2	2	2	2
40-49	1	1	1	0	1	1	1
50-64	1.5	1	1	1	1	1	1
65-75	0.5	2	1	0	0	0	0
>75	0.5	1	1	1	1	1	0
male	50%	5/11	4/10	2/5	2/6	2/6	2/6
female	50%	6/11	6/10	3/5	4/6	4/6	4/6
white british	6	7	6	6	6	6	5
white non-british	1.5	2	1	1	1	1	1
mixed ethnicity	0.5	0	0	0	0	0	0
Asian	1	1	1	1	1	1	1
Black	0.5	0	0	0	0	0	0
most deprived area	1	0	0	0	0	0	0
least deprived	2	1	1	1	1	1	0

Demographic alignment of the OxAir Competency group with the 2011 Oxford City Census. Two members of the technical team are included as residents of Oxford city.

WITHIN 0.5 persons of quota = green, within 1 persons = orange, falls in range less than or greater than 1 persons = red. 0 is red or orange depending on distance from quota.

APPENDIX H OxAir competency group outputs 3 & 4

For CG outputs 1, 2, 5 & 6 please view the Social research & public engagement section in the main document or visit www.oxair.org/outputs

OxAir CG Output 3: Human Perspectives - What information matters to OxAir CG resident members within the context of LAQM and future mobile monitoring.

Below is a list of recommendations and considerations extrapolated from across the Competency Group discussions. Many of them represent recurring themes, distilled to their key points. Crucially, this list does not represent a complete, costed set of policies, and externalities remain for the most part unconsidered. The point is, in line with the 'Human Perspectives' ethos, to identify in raw terms what people want in regard to addressing air pollution, and therefore what a human-oriented management approach unfettered by financial and political considerations might look like. The considerations are categorised under 4 key themes: access to information, infrastructure changes, new tools and changes in focus. In practice, these themes often crossover.

ACCESS TO INFORMATION

In order to answer the question of what matters to people, it is important to identify what kinds of information is desired and required by different actors. There was broad consensus that 1. greater understanding of what members of the public want to know will help technical practitioners and policy makers furnish them with relevant information. 2. Members of the public need better channels for making their own ideas and needs heard and understood by policy makers. As such, there is a need for:

Investment in an easy-to-find, public-facing website that provides more spatially and temporally granular information on. This could include:

Information on active sensors in the city and their live readings

Information and recommendations regarding clean and safe cycle routes through the city with easy-to-follow resources. Coordinate with https://change4climate.uk/travel/

One potential solution might be replicating LondonAir's model or subscribing to API like Breezometer or Plume.

Some of these services are already provided by the existing Oxfordshire website (https://oxfordshire.air-quality.info/) but it was acknowledged that this platform requires significant revisions and much greater public visibility.

The provision of publicly accessible daily forecasts and 'broad brush' information regarding the condition of local.

Examples given included the availability of daily AQ updates in local newspapers, as seen already in London's free newspapers; or the availability of interactive street signs giving ready information on local conditions or indicating polluting behaviour in the same vein as LED speeding signs.

INFRASTRUCTURE CHANGES

These are ideas put forward by members of the CG of potentially transformative changes to residents' livelihoods, that require some investment into existing infrastructure.

A ban on picking up and dropping off children within 300m of school

"...far too many of the private schools certainly in our area of fast conglomerations of traffic, dropping off children right at school entrances. This causes a lot of local pollution. And I'm sure there are lots of other things like that, which as a group, we could perhaps suggest to the councillors and the powers that be" - OxAir CG Session 4

Work with another local organisation (Liveable Streets, OxFOE) to establish a campaign & band together residents in a group committed to not dropping within 300 meters of school.

Promote alternative routes to school such as walking, cycling and buses. Support parents to organise group transportation of children to school by foot or on bikes.

Promote School Streets as a concept. This is currently being trialled at one or more state primary schools across Oxford - review results & propose additional schools.

Improve options for individuals travelling from rural areas (e.g. park & stride/ride options).

Introduction of resident-only streets.

'I saw this morning on my walk it in Jericho - St Bernard's road - has signs at the entrance: 'resident-only streets'. Current rat runs would be much less polluted if those could be introduced more generally. It wouldn't cost a lot of money and it would be politically very popular'.

Particular attention should be paid to public perception in areas where this has been implemented. This type of monitoring is useful for policymakers, but also prompts greater public conversation. Florence Park and St Mary's were given as examples.

NEW TOOLS

These suggestions refer to the provision of new tools and resources that would fulfil existing information needs of public, practitioner and policymaker alike.

Provide access to portable monitoring equipment that is scientifically valid & helpful for examining in areas of concern. This would enable ongoing use of portable sensors and engagement of Oxford residents in sensing practices. Various ideas were raised such as borrowing schemes or more organised activities that utilize the sensors purchased for the OxAir project. New partnerships between the city council, university and local organisations could produce innovative local schemes for public access to sensing technology. This would likely require additional funding.

Investment in the OxAir 'Map of Anecdotes'

The Map of Anecdotes received widespread support from the group for its ability to allow citizens to corroborate their concerns and communicate them to central management. This would act as an effective public engagement tool which could also enable better governance by identifying 'hotspot' areas.

This could require hosting and development support from Oxfordshire County Council and/or Oxford City Council. As stated previously, the capacity of the website would need significant improvements.

CHANGES IN FOCUS

These recommendations suggest, in a broader sense, changes to the ways in which AQ is understood and engaged in centralised management practices. Thus, they call for a more holistic re-evaluation of current protocols than previous suggestions.

Focus on clean indoor air

There should be greater connectivity between the ways that AQ is monitored and managed outdoors and indoors, reflecting individuals' changing exposure from home, to work, and back.

Partnership with landlords, employers, etc. could lead to more 'joined up' conceptualisation of exposure as well as practical efforts to mitigate it. There should also be some accountability in the former to ensure safe conditions.

Local government should make use of existing local networks

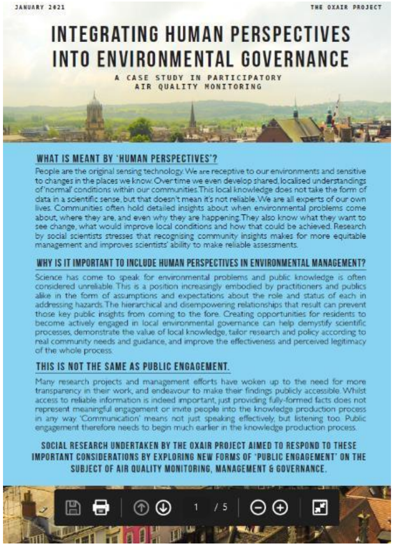
Participants often mentioned networks of local organisations, parents, and campaigns who would make ready partners in identifying and implementing areas for local change. This is especially the case during discussion of school drop-off, for example.

Focus on promoting active travel

Particularly within the context of short-distance commuting and travel to and from school.

APPENDIX I Summary of key findings for the Oxford / UK AQ practitioner communities

https://www.oxair.org/outputs



JANUARY 2021 THE OXAIR PROJECT

INTEGRATING HUMAN PERSPECTIVES INTO ENVIRONMENTAL GOVERNANCE

A CASE STUDY IN PARTICIPATORY AIR QUALITY MONITORING

WHAT IS MEANT BY 'HUMAN PERSPECTIVES'?

People are the original sensing technology. We are receptive to our environments and sensitive to changes in the places we know. Over time we even develop shared, localised understandings of 'normal' conditions within our communities. This local knowledge does not take the form of data in a scientific sense, but that doesn't mean it's not reliable. We are all experts of our own lives. Communities often hold detailed insights about when environmental problems come about, where they are, and even why they are happening. They also know what they want to see change, what would improve local conditions and how that could be achieved. Research by social scientists stresses that recognising community insights makes for more equitable management and improves scientists' ability to make reliable assessments.

WHY IS IT IMPORTANT TO INCLUDE HUMAN PERSPECTIVES IN ENVIRONMENTAL MANAGEMENT?

Science has come to speak for environmental problems and public knowledge is often considered unreliable. This is a position increasingly embodied by practitioners and publics alike in the form of assumptions and expectations about the role and status of each in addressing hazards. The hierarchical and disempowering relationships that result can prevent those key public insights from coming to the fore. Creating opportunities for residents to become actively engaged in local environmental governance can help demystify scientific processes, demonstrate the value of local knowledge, tailor research and policy according to real community needs and guidance, and improve the effectiveness and perceived legitimacy of the whole process.

THIS IS NOT THE SAME AS PUBLIC ENGAGEMENT.

Many research projects and management efforts have woken up to the need for more transparency in their work, and endeavour to make their findings publicly accessible. Whilst access to reliable information is indeed important, just providing fully-formed facts does not represent meaningful engagement or invite people into the knowledge production process in any way. 'Communication' means not just speaking effectively, but listening too. Public engagement therefore needs to begin much earlier in the knowledge production process.

SOCIAL RESEARCH UNDERTAKEN BY THE OXAIR PROJECT AIMED TO RESPOND TO THESE IMPORTANT CONSIDERATIONS BY EXPLORING NEW FORMS OF 'PUBLIC ENGAGEMENT' ON THE SUBJECT OF AIR QUALITY MONITORING, MANAGEMENT & GOVERNANCE.

1 / 5

THE OXAIR 'COMPETENCY GROUP 'CASE STUDY EXPERIMENT

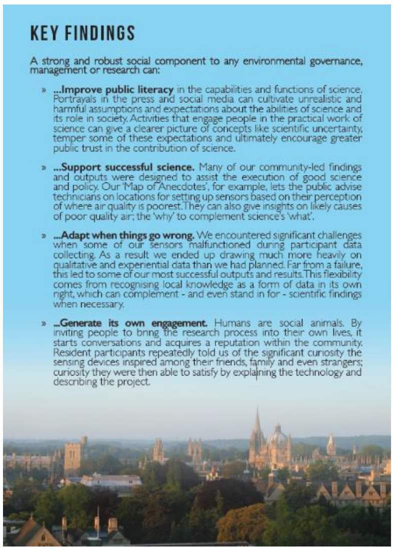
BACKGROUND

Regulatory conceptions of air pollution are rigid, and vary significantly from those held by affected members of the public. From a societal standpoint, regulators, scientists and other technical position holders are the ones conventionally attributed authority to determine what counts as evidence of air pollution existing. Common critiques reinforce how, despite good intentions, the consultations, questionnaires and survey typically employed in environmental governance projects, approach the incorporation of local perspectives in management plans as a more instrumental relationship that does not enable residents to exert any meaningful influence[1]. The Competency Group (CG) experiement was designed to approach these challenges as part of the overarching OxAir project, which was a Defra-funded initiatve managed by the Oxford City Council to trial lower cost, portable air quality sensing devices. Our research objectives included establishing a process for dismantling the hierarchical relationship among AQ stakeholders found in traditional settings, and generating new knowledge about local air quality monitoring and management more aligned with local expertise and interests.

METHODS

The structure and activities of the OxAir CG were inspired by the success of a similar study on flood risk in Yorkshire[2]. We thus developed a protocol to solicit a demographically representative group of Oxford residents to take part in a series of successional meetings over a period of six months. We then designed four, in-person sessions each focused around a theme and featuring a unique set of 'hands-on' activities, including mapping, collecting air pollution data using handheld sensors and discussing the results as a group. The OxAir CG ultimately held five sessions in total: three in person prior to COVID-19 physical distancing restrictions, a series of virtual one-on-one sessions with the resident CG members, and finally two virtual group sessions.

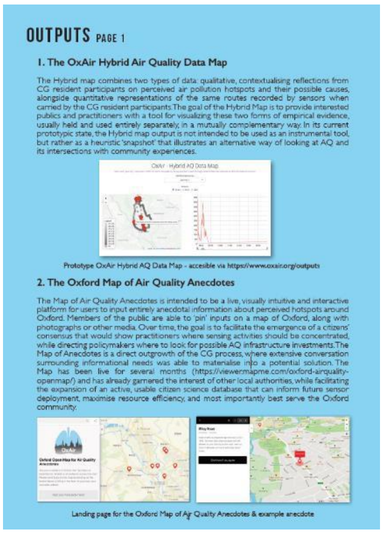
2



KEY FINDINGS

A strong and robust social component to any environmental governance, management or research can:

- **...Improve public literacy** in the capabilities and functions of science. Portrayals in the press and social media can cultivate unrealistic and harmful assumptions and expectations about the abilities of science and its role in society. Activities that engage people in the practical work of science can give a clearer picture of concepts like scientific uncertainty, temper some of these expectations and ultimately encourage greater public trust in the contribution of science.
- **...Support successful science.** Many of our community-led findings and outputs were designed to assist the execution of good science and policy. Our 'Map of Anecdotes', for example, lets the public advise technicians on locations for setting up sensors based on their perception of where air quality is poorest. They can also give insights on likely causes of poor quality air; the 'why' to complement science's 'what'.
- **...Adapt when things go wrong.** We encountered significant challenges when some of our sensors malfunctioned during participant data collecting. As a result we ended up drawing much more heavily on qualitative and experiential data than we had planned. Far from a failure, this led to some of our most successful outputs and results. This flexibility comes from recognising local knowledge as a form of data in its own right, which can complement - and even stand in for - scientific findings when necessary.
- **...Generate its own engagement.** Humans are social animals. By inviting people to bring the research process into their own lives, it starts conversations and acquires a reputation within the community. Resident participants repeatedly told us of the significant curiosity the sensing devices inspired among their friends, family and even strangers; curiosity they were then able to satisfy by explaining the technology and describing the project.



OUTPUTS PAGE 1

1. The OxAir Hybrid Air Quality Data Map

The Hybrid map combines two types of data: qualitative, contextualising reflections from CG resident participants on perceived air pollution hotspots and their possible causes, alongside quantitative representations of the same routes recorded by sensors when carried by the CG resident participants. The goal of the Hybrid Map is to provide interested publics and practitioners with a tool for visualizing these two forms of empirical evidence, usually held and used entirely separately, in a mutually complementary way. In its current prototypic state, the Hybrid map output is not intended to be used as an instrumental tool, but rather as a heuristic 'snapshot' that illustrates an alternative way of looking at AQ and its intersections with community experiences.

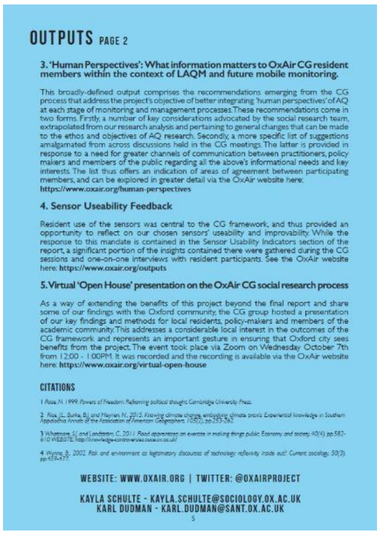
OxAir - Hybrid AQ Data Map

Prototype OxAir Hybrid AQ Data Map - accesible via https://www.oxair.org/outputs

2. The Oxford Map of Air Quality Anecdotes

The Map of Air Quality Anecdotes is intended to be a live, visually intuitive and interactive platform for users to input entirely anecdotal information about perceived hotspots around Oxford. Members of the public are able to 'pin' inputs on a map of Oxford, along with photographs or other media. Over time, the goal is to facilitate the emergence of a citizens' consensus that would show practitioners where sensing activities should be concentrated, while directing policymakers where to look for possible AQ infrastructure investments. The Map of Anecdotes is a direct outgrowth of the CG process, where extensive conversation surrounding informational needs was able to materialise into a potential solution. The Map has been live for several months (https://viewer.mapme.com/oxford-airquality-openmap/) and has already garnered the interest of other local authorities, while facilitating the expansion of an active, usable citizen science database that can inform future sensor deployment, maximise resource efficiency, and most importantly best serve the Oxford community.

Landing page for the Oxford Map of Air Quality Anecdotes & example anecdote



OUTPUTS PAGE 2

3. 'Human Perspectives': What information matters to OxAir CG resident members within the context of LAQM and future mobile monitoring.

This broadly-defined output comprises the recommendations emerging from the CG process that address the project's objective of better integrating 'human perspectives' of AQ at each stage of monitoring and management processes. These recommendations come in two forms. Firstly, a number of key considerations advocated by the social research team, extrapolated from our research analysis and pertaining to general changes that can be made to the ethos and objectives of AQ research. Secondly, a more specific list of suggestions amalgamated from across discussions held in the CG meetings. The latter is provided in response to a need for greater channels of communication between practitioners, policy makers and members of the public regarding all the above's informational needs and key interests. The list thus offers an indication of areas of agreement between participating members, and can be explored in greater detail via the OxAir website here: **https://www.oxair.org/human-perspectives**

4. Sensor Useability Feedback

Resident use of the sensors was central to the CG framework, and thus provided an opportunity to reflect on our chosen sensors' useability and improvability. While the response to this mandate is contained in the Sensor Usability Indicators section of the report, a significant portion of the insights contained there were gathered during the CG sessions and one-on-one interviews with resident participants. See the OxAir website here: **https://www.oxair.org/outputs**

5. Virtual 'Open House' presentation on the OxAir CG social research process

As a way of extending the benefits of this project beyond the final report and share some of our findings with the Oxford community, the CG group hosted a presentation of our key findings and methods for local residents, policy-makers and members of the academic community. This addresses a considerable local interest in the outcomes of the CG framework and represents an important gesture in ensuring that Oxford city sees benefits from the project. The event took place via Zoom on Wednesday October 7th from 12:00 - 1:00PM. It was recorded and the recording is available via the OxAir website here: **https://www.oxair.org/virtual-open-house**

CITATIONS

1 Rose, N. 1999. *Powers of Freedom: Reframing political thought.* Cambridge University Press.

2 Rice, J.L., Burke, B.J. and Heynen, N., 2015. *Knowing climate change, embodying climate praxis: Experiential knowledge in Southern Appalachia. Annals of the Association of American Geographers, 105(2)*, pp.253-262.

3 Whatmore, S.J. and Landström, C., 2011. *Flood apprentices: an exercise in making things public. Economy and society, 40(4)*, pp.582-610 WEBSITE: http://knowledge-controversies.ouce.ox.ac.uk/

4 Wynne, B., 2002. *Risk and environment as legitimatory discourses of technology: reflexivity inside out?. Current sociology, 50(3)*, pp.459-477.

WEBSITE: WWW.OXAIR.ORG | TWITTER: @OXAIRPROJECT

KAYLA SCHULTE - KAYLA.SCHULTE@SOCIOLOGY.OX.AC.UK
KARL DUDMAN - KARL.DUDMAN@SANT.OX.AC.UK

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