Literature Review of Air Quality Sensors and their Application in Ventilation

Analysing the Various Low-Cost Sensors used to Measure Air Pollution.

Robert Lockett

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Abstract

Contents

Chapter 1

Introduction

1.1 The Background

Air Pollution has been defined by the European Environment Agency as ”The presence of contaminant or pollutant substances in the air at a concentration that interferes with human health or welfare, or produces other harmful environmental effects.” [1]

It has been described as the greatest health risk in Europe and Worldwide with data from the World Health Organisation (WHO) suggesting that 9 out of 10 people breathe air that exceeds the WHO guideline limits containing high levels of pollutants and is the cause of around seven million deaths each year. [2]

The source of pollution is multi-factoral and is specific to it’s context. However the main causes of ambient air pollution is said to be fossil fuel combustion, which occurs in the use of motorised vehicles, power generation and industry. Along with ambient air pollution there is household air pollution which is mainly caused by cooking and heated fuels and is accountable for 3.8 of the 7 million air pollution related deaths each year. [2]

The main species of air pollution are nitrous oxide (N02), PM2.5, PM10 and Ozone O3. N02 is primarily sourced from the use motorised vehicles and power plants. PM2.5 is composed of inhalable particles of metals which are $< 2.5\mu m$ in size, with the metal in a diesel exhaust, diesel particulate matter, being an example of PM2.5 pollution. PM10 which is composed of inhalable particles which are $< 10\mu m$ in size. Ozone O3 is a harmful pollutant which occurs most pertinently during warmer weather where it is at it's most harmful.

As a result of the huge loss of life and income from the effects of air pollution, lessening the effects and monitoring air pollution is of major concern to authorities all across the globe. Therefore, low-cost and efficient air pollution sensors are gaining attention.

1.2 The Need for Air Quality Sensors

Currently in the UK there are around 300 air quality sensors in the UK [3] and therefore the data collected is sparse. Especially considering the irregular nature of air quality data due to the large number of external factors which will affect results. Therefore, if a low-cost sensor become readily available and worked with decent accuracy more sensors could be

installed in many different locations in the UK, which would make air quality monitoring possible to a
larger scale.

The signals from the sensors depends on many factors as well as the pollutant that is being analysed. These factors include the temperature, pressure, signal drift and other interfering compounds in the air. Therefore at times where there is much smaller concentrations of air pollution compared to the interfering compounds in the air, making the signal is weaker. This uncertainty created makes the use of low-cost air quality sensors more difficult as the quality of the results depends on technology and the implementation of the sensor, it's application, location and set up, and due to the influence of meteorological parameters on a sensor signal, simple correction is not always possible [4]. However, when in well defined situations, the levels of uncertainty in the results can be optimised to reach the levels of the approved measurement systems.

1.3 The Aim of this Study

Therefore, as the low-cost air quality sensors could potentially be optimised to lessen the inhibiting effects this study will seek to optimise the air quality sensors.

The key aims of this study will be:

1. To analyse these Air quality (AQ) sensors in specific locations and characterise the irregular patterns and anomalies that can be measured.
2. To therefore increase the accuracy of AQ sensors.
3. To give reasons or causes of the irregular patterns in the AQ measurements. The main causes are from emission sources and impacting factors from emissions to AQ sensor.
4. To identify the emission source, impacting factors and link these irregular patterns to the AQ to optimise the use of ventilation system and thus find how these ventilation system can be optimised.

Chapter 2

Discussing Impacting Factors

2.1.1 Air Pollutants and their Key Emission Sources

The key species of pollutants in urban cities are Nitrous Oxide NO2, PM2.5, PM10 and Ozone O3. These pollutants are typically analysed by using an AQ sensor, these sensors tend to be in the form of fixed stations deployed in urban cities.

However, due to the multi-factoral nature of air quality, the air quality in a city can vary greatly in different areas. Furthermore air quality is also influenced by other external impacting factors such as the weather conditions of the city (i.e. its humidity, atmospheric pressure or temperature), urban density, the transport and traffic congestion, volume, type, density, acceleration, speed or other human activities, large emitters, longer range transposed emissions and varying land uses in the area.

Figure 1: Species of Pollutant and their Key Sources

Pollutant Species	Key Sources of Pollu-Tant	Impacting Factors in Urban Environments
NO_2	Road Vehicles (Such as cars, buses and HGVs) Factories and Power Stations [6].	Location : Being in close proximity to busy roadside areas or industry sites and NO_2 emissions are positively correlated. Extreme temperatures: Low temperatures can cause NO_2 emissions to be trapped near to the ground and high temperatures can cause high concentrations of ozone to be created and thus convert more NO into NO2 [6].
PM2.5	Domestic Combustion ~ 43% Manufacturing and Construction ~ 18% Road Vehicles ~ 12 % [7]	Location : Being in close proximity to busy roadside areas or construction sites and PM2.5 emissions are positively correlated.. Wind: PM2.5 concentrations and wind speed are negatively correlated [8]. Humidity: PM2.5 concentrations and humidity are positively correlated
PM10	Road Vehicles, in particular heavy-duty vehicles. [9]	Location : Being in close proximity to busy roadside areas or construction sites and PM10 emissions are positively correlated.. Wind: PM10 concentrations and wind speed are negatively correlated [10]. Humidity: PM10 concentrations and humidity are positively correlated

Ozone O_3	Secondary pollutant, Reactions between existing NOx and VOC. Road Vehicles causing ozone precursors.	Temperature: Ozone levels and temperature are positively correlated. A reduction of ozone precursors can even lead to an increase of ozone concentrations, the weekend effect [11].

2.1.2 The Air Pollutants and Air Quality Index AQI categories

The "USEPA establishes an AQI for five major air pollutants regulated by the Clean Air Act. Each of these pollutants has a national air quality standard set by EPA to protect public health (ground-level ozone, PM2.5 and PM10, CO, Sulphur dioxide S02, NO2)"[35]. It is measured for a daily index and differently per pollutant "The ozone and CO AQI is an 8-hour index; NO2 and SO2 is 1 hour; for particle pollution, it's 24 hours."[35] It is measured from 0 – 500 that can be seen in the figure below.

AQI CATEGORY	PM10 (MG/M3 IN 24HR AVG)	PM2.5 (MG/M3 IN 24HR AVG)	NO2 (PPB IN 1H AVG)	O3 (PPB IN 8H AVG)	CO (PPB IN 8H AVG)	SO2 (PPB IN 1H AVG)
Good (0-50)	0-54	0-12	0-53	0-54	0-4.4	0-35
Moderate (51-100)	55-154	12.1-35.4	54-100	55-70	4.5-9.4	36-75
Unhealthy for sensitive (101-150)	155-254	35.5-55.4	101-360	71-85	9.5-12.4	76-185
Unhealthy (151-200)	255-354	55.5-150.4	361-649	86-105	12.5-15.4	186-304
Very unhealthy (201-300)	355-424	150.5-250.4	650-1249	106-200	15.5-30.4	305-604
Hazardous (301+)	425+	250.5+	1250+	405+	30.5+	605+

2.2 Current Air Quality Sensors.

There are many different AQ sensors available and these sensors largely differ in cost and quality with there tending to be a positive correlation between the cost of an AQ sensor and it's quality. However, with calibration and the use of networks the low cost AQ sensors, analytic and machine learning potentially these could meet a similar standard to that of the high quality costly sensors. There are potentially 3 division in quality and cost of 'low cost' sensor for domestic to limited commercial usage; 'medium cost' with most commercial usage an innovate phase; finally reference sensors used by regulatory authorities. In general 'low cost' are within hundreds of £ and medium cost in thousands of £ to purchase.

2.2.1.1 The quality divisions of AQ sensors

The quality of the AQ sensor can abstractly be stated to be the ability to accurately and precisely measure the AQ condition within a designated radius of the AQ sensor. The urban environment the AQ sensor is within can largely affect its ability but the quality should be an ability with a radius in any urban environment. An AQ sensor can therefore have a manufactures quality level and an in situ level of quality attributed to every AQ sensor installed. Its quality can be measured then by its accuracy and precision of measurement within this radius. This includes ability to measure complex scenarios (large plumes of air pollutant, fast flowing plumes, spiralling plumes), avoid temporal drift and urban environment irrelevant anomalies (smoking near sensor, obstructions, vandalism). This allows a level of accuracy of measurement. The quality is determined again in ability to be sensitive to high and low air pollution levels. Once an optimal level of quality within the radius is ensured then the measurement outside of the radius is the aim. This is both vertically and horizontally. For PM2.5 the impact of high humidity is particularly problematic and high relative errors are seen at concentrations below 20-30 µg/m3. The is often completed by other methods including modelling, satellite measurements, mobile sensors, supplementary sensors or statistical predictions. It is stated in EEA assessment of low cost sensors "Most sensors currently on the market do not meet the requirements set for official monitoring stations under the Ambient Air Quality Directives. This means that they are not yet suitable for replacing official air quality monitoring networks and instruments." Therefor supplementary analysis is required for every medium or low cost AQ sensor.

2.2.1.2 The other divisions of AQ sensors

There are many divisions among AQ sensors other than cost and quality. There are static fixed AQ sensors or mobile AQ sensors. There various methods of measurement per air pollutant with PM have the largest variations and length of installation. There is also the usage aim for the AQ sensor. There is also the frequency of sampling.

Division of AQ sensors	**Examples**
Indoor or Outdoor	In a room or lamppost
Mobile or Static or handheld or wearable	On a lamppost or mobile vehicle, handheld sampling or wearing of routes etc..
Measurement Methods per air pollutant	NO2: Luminesce, Diffusion Tube etc.. PM: Laser PM count, Litmus or other

	Paper Count
Usage aim	Roadside, Rural, Construction site, school
Length of installation	6 month or constant
Calibrations amount	Month calibration or mobile limited
Frequency of sample	10 sec, 1 min, 15 min etc…
Robustness to environment	Protected from damage or obstruction or weather diffusing measurements or limited
Height of Sensors	Above vandalism height on a lamppost or on top of a vehicle. Many don't have installation where prams are exposed to air pollutants or even pedestrian or near 1st or 2nd floor windows.
Sensitivity to sensor drift	Medium cost sensor try not to drift in measurement accuracy over time yet some do. Many low cost sensors drift in accuracy over time.
Sensitivity to factors that impact air pollutants	Urban density, meteorological factors, traffic volume, land use

2.2.1.3 Indoor and Outdoor

These are different AQ sensors and markets. There is however a larger difference from low cost and medium cost to reference sensors. Often Indoor sensors are highly inaccurate. There a are large amount more air pollutants including VOC's, formaldehyde, mould, radon, biological pollutants, industrial pollutants, ground pollutants, odour and CO2. Individual measures can be accurate in CO2 and CO. There are many more sources of emissions and impacting factors. The AQ levels are often lower so reporting with accuracy is difficult. They both often have humidity and temperature sensors included.

The figure below describes some of the emission sources of IAQ.

Table 1. Examples of types of pollutant sources found in different indoor environments

Internal environments (buildings only)	Pollutant sources										
				Consumer activities							
	Outdoor air	Construction materials	Furnishing materials	Decorating paints, adhesives and varnishes	Washing and cleaning products	Combustion products from e.g. gas appliances	Office equipment e.g. photocopiers, electrical goods	People	Animals (e.g. pets, assistance dogs, pests, mites)	Tobacco smoke	Ground/ contaminated land
Domestic	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Offices	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Schools	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Hospitals	✓	✓	✓	✓	✓	✓	✓	✓			✓
Hotels	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Restaurants	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Public places e.g. museums	✓	✓	✓	✓	✓		✓	✓	✓		✓
Industrial / factories	✓	✓	✓	✓	✓	✓	✓	✓			✓
Shops and shopping malls	✓	✓	✓	✓	✓			✓	✓		✓

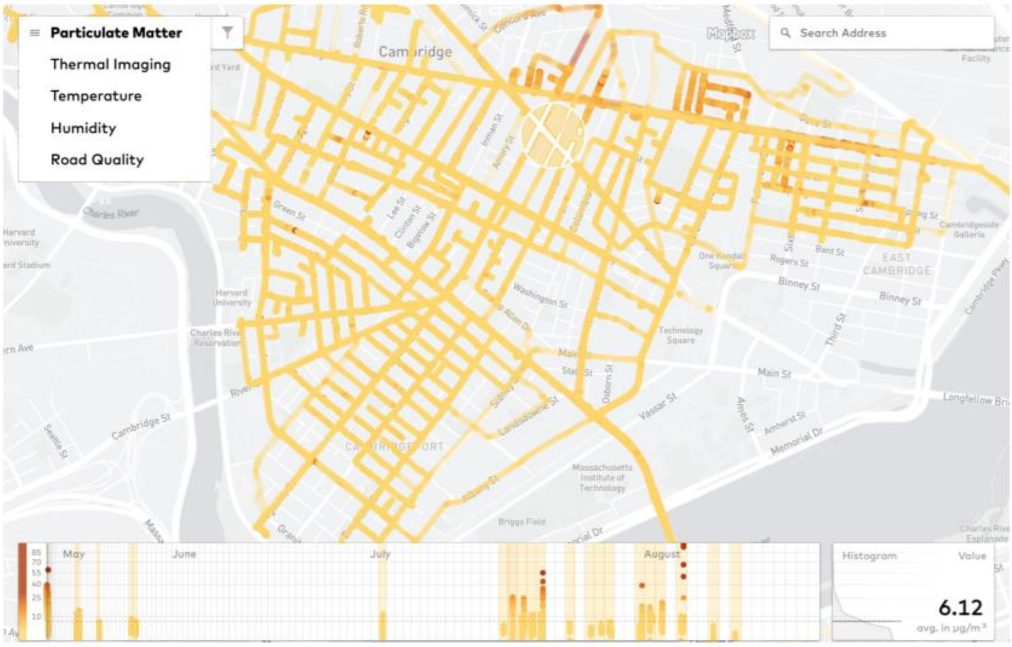
The figure shows these emission sources and the air pollutants.

Table 2. Examples of types of pollutants emitted from different sources likely to affect indoor environments

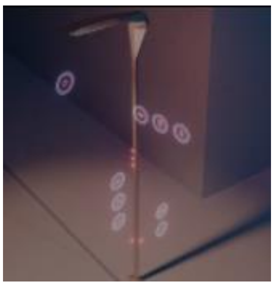
Pollutant sources	Pollutants												
	Carbon dioxide (CO_2)	Carbon monoxide (CO)	Moisture	Odour, fragrances	Particles (PM_{10}, $PM_{2.5}$, dust, fibres)	Volatile Organic Compounds (VOCs)	Formaldehyde	Biological/ Allergens e.g. mould and spores	Nitrogen oxides (NO_x)	Ozone (O_3)	Methane	Radon	Ammonia (NH_3)
Outdoor air	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Construction materials					✓	✓	✓						
Furnishing materials				✓	✓	✓	✓						
Decorating (Paints, adhesives and varnishes)			✓	✓	✓	✓	✓						
Washing and cleaning products			✓	✓		✓	✓						✓
Combustion products from e.g. gas appliances	✓	✓	✓		✓				✓				
Electrical goods e.g. photocopiers					✓					✓			
People (including personal care products)	✓		✓	✓	✓	✓		✓			✓		
Animals	✓		✓	✓	✓	✓		✓			✓		
Tobacco smoke	✓	✓	✓	✓	✓	✓	✓		✓				
Ground						✓					✓	✓	

2.2.1.4 Mobile or Static

Mobile AQ sensor are in 2021 innovate research projects because of the difficulty to calibrate the AQ sensors and performance of the AQ sensors. They are often fixed to a vehicle either a unique vehicle or vehicle with a fairly conclusive schedules and coverage of a domain. These could be taxis or waste vehicles. This has firstly been completed by Google and Aclima in California and London with the data available on the Breathe London website and available in a dashboard format. The figure below shows the sample dashboard from mobile sensing project showing the spatial and temporal variations of AQ measurements. This differs from the static AQ sensor which have on one spatial location with decreasing accuracy of measurement within a radius.



The static AQ sensors are often attached to lampposts. This provides an optimum and nearly equal distance from the road per AQ sensor so they can be easily compared. It is also the most effective installation instead of asking permission from often commercial property managers. Both mobile and static AQ sensor are at fixed heights. The figure below shows a lamppost which could have an AQ sensor and static AQ sensors in Southampton. There are many locations where the AQ is not known.



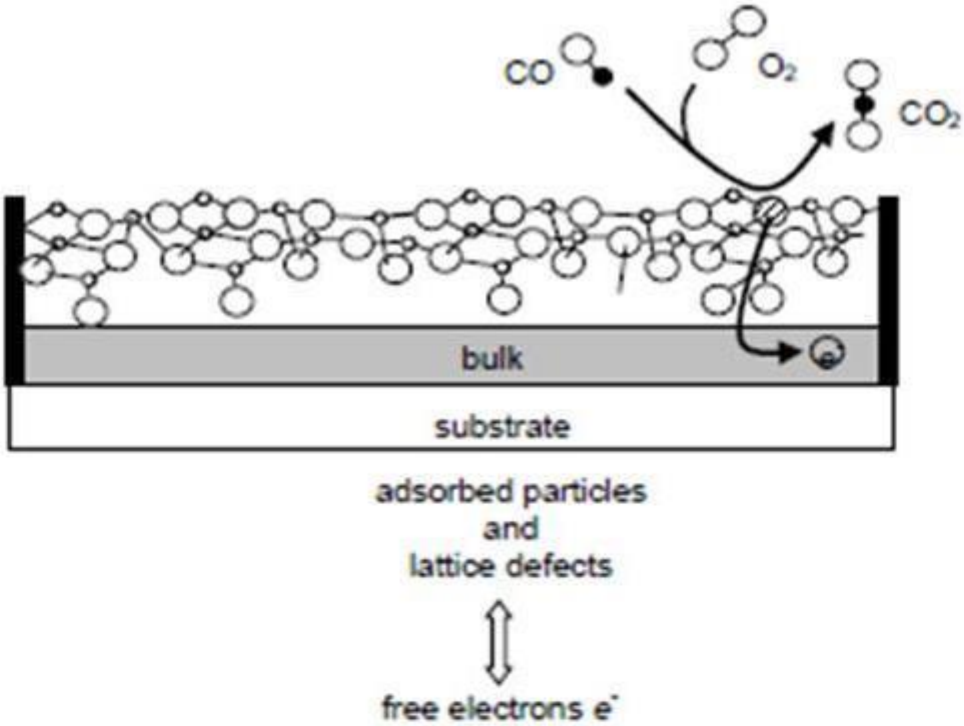
Other emerging domains are handheld and wearable AQ sensors. These are quite inaccurate but allow measurements that are not possible with either vehicle or static AQ sensors. These can more easily be linked to users AQ exposure. The handheld sensors are quite advanced having been used on construction site in regulatory measurements. The wearables are often DIY sensors for citizen science research.

2.2.1.5 Methods of Sensing

There are multiple air pollutants which require individual measurement methods within one sensor i.e. gas sensing is different particular counting. The majority of sensor can measure on the sensor and dataset is available in real time if connected through server. There are diffusion tubes which can sample the air and be sent to a laboratory for analysis to produce a measurement. These can be quite accurate because of the use of a laboratory. They don't product real time measurement and are often used to supplement regulatory measuring and modelling. Some of the advantage of diffusion, gas and particular sensor can be seen in the figure below.

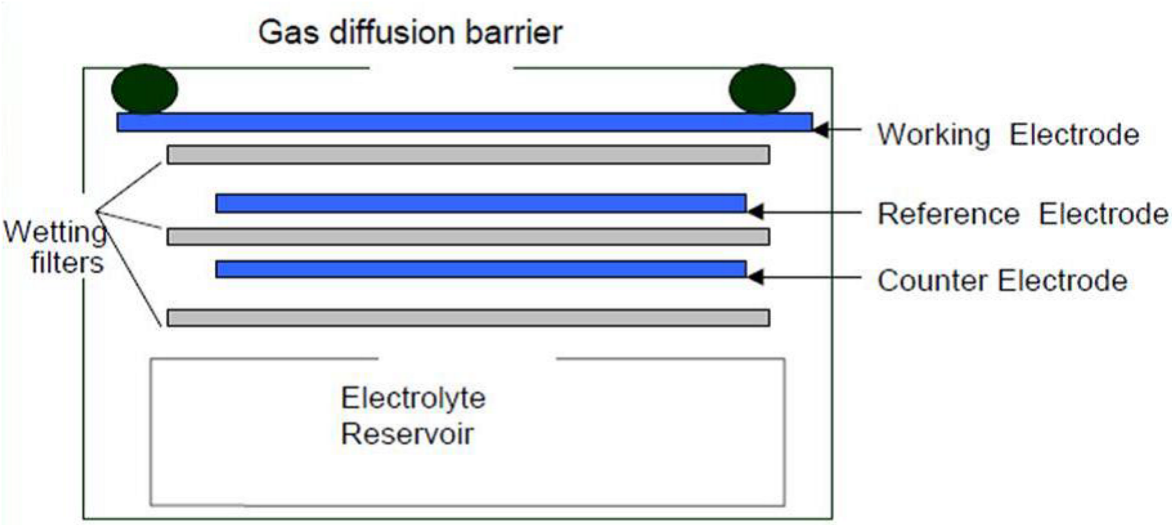
	Advantages	Disadvantages
Passive samplers (diffusion tubes)	Usually cheap Easy to handle Reliable Good for large-scale data collection Good for setting up measurement networks	No continuous measurements, cannot link to near real-time monitoring systems Need to be analysed in a laboratory Not for all main air pollutants
Gas sensors	Can be relatively cheap Can measure time series Good for large-scale data collection Good for setting up measurement networks Rapidly evolving technology	Sensitive to temperature Sensitive to humidity Interference from other gases Not easy to process data Not always reliable Can lose responsiveness over time
Particle sensors	Can be relatively cheap Can measure time series Good for large-scale data collection Good for setting up measurement networks Rapidly evolving technology	Particulate matter mass not measured directly Sensitive to humidity Not always reliable Not easy to process data Can lose responsiveness over time

There are many methods for measuring both gases and particulates. There many sensor manufactures who correlate these measurement devices into a sensor. There are companies that produce these measurement devices. Some the measurement device companies are linked to sensor manufacture company to try to dominate the market like AQ Mesh and AlphaSense. These measurement device have benchmarks of accuracy that determines the quality. The main companies are AlphaSense, City technology, Membrapor and SGX SensorTech. The sensor manufacture have benchmarks for accuracy that determine the sensor quality and benchmarks for calibration when installing. The measurement device techniques are a research topic and moving quickly especially for PM and ammonia. One difference for PM is that PM can vary in mass concentration, size distribution and chemical composition. These are often not measured only the particulate count. There are new standards being released which divide many medium cost sensors from low cost sensor. One of these for gas sensor is CEN/TC 264 - AIR QUALITY. The various methods are: Semiconductor metal oxide sensors consist of one or more oxides from the transition metals. Commercially available gas sensors are mainly made of SnO_2 in the form of porous pellets or thick or thin films deposited onto an alumina or silica substrate. The sensing properties are based on the reaction between the semiconductor metal oxide and oxidizing or reducing gases in the atmosphere which lead to changes in conductivity. This change in conductivity is measured over a pair of interdigitated electrodes embedded into the metal oxide. A (mostly platinum) heating element is used to regulate the sensor temperature. The sensors have to be heated to 200 to 400 degrees Celsius to increase sensitivity and decrease response time.



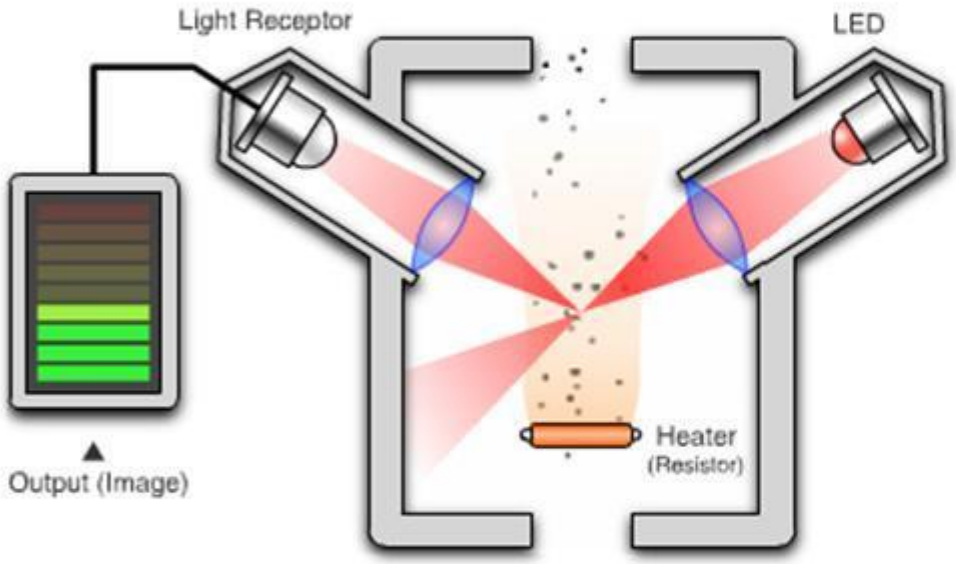
Schematic metal oxide gas sensor

Electrochemical sensors operate by reacting with the gas of interest and producing an electrical signal proportional to the gas concentration. The sensor consists of a sensing electrode (also called working electrode), and a counter electrode separated by a thin layer of electrolyte. Gas that comes in contact with the sensor diffuses through a hydrophobic solid polymer membrane, eventually reaching the sensing electrode surface. The sensing electrode either oxidizes or reduces the target gas with the counter electrode balancing the generated current. These reactions are catalyzed by the electrode materials specifically developed for the gas of interest. However, the sensing electrode potential does not remain constant due to the continuous electrochemical reaction taking place on the surface of the electrode causing a deterioration of the performance of the sensor over an extended period of time. Consequently, a reference electrode is placed within the electrolyte in close proximity to the sensing electrode. The reference electrode anchors the working electrode at the correct bias potential. The value of the bias voltage applied to the sensing electrode makes the sensor specific to the target gas. With a resistor connected across the electrodes, a current proportional to the gas concentration flows between them. The current can be measured to determine the gas concentration. Because a current is generated in the process, the electrochemical sensor is often described as an amperometric gas sensor or a micro fuel cell. When gas concentrations are measured in the ppb range, the generated currents can be as small as a few nano-amperes.



Schematic electrochemical gas sensor

A low pulse is output from the sensor when the light receptor detects light scattered by particles. The particle concentration can be estimated based on a manufacturer provided curve of concentration versus the percentage of time the sensor is reporting a low pulse. Higher sensitivity versions of optical particle counters go beyond using “percent time” as the indicator but quantify based upon the strength of the light scattering detected.



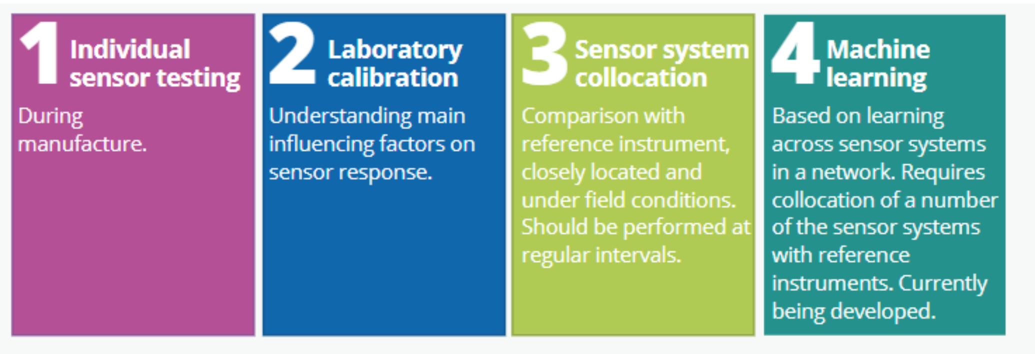
PM sensor operation diagram

2.2.1.6 Usage aim and length of installation

The majority AQ sensor were initial installed by government for regulatory purposes. The air pollution has only in the last 30 years become a contenuious domain and it was deemed that these few sensors per nation was enough to monitor, manage and regulate air pollution levels. Therefor the sensor with the majority of datasets are the national AQ sensors. It is difficult to do accurate trend analysis without at least 5 years of 15 min sampled AQ dataset. Some local authorities, researchers, policy advisor, commercial organisation and enthusiast have installed AQ sensors which has been completed in the last 10 years. These are still most only for one purpose and the dataset are often biased to that aim. Some commercial datasets are emerging which could be used for multiple purposes and these are gaining accuracy and interest.

2.2.1.7 Calibration

Many AQ sensor have initially been calibrated in a sensor farm were there are similar sensor at the same location and high quality reference sensor to determine the accuracy for a two week sample time. Most medium cost sensor have accuracy benchmark that can be used when installing the sensor. In certain regions there are reference sensor that can be used through the usage of the sensor even if 10 metres away. This is significant in regions in Africa were there are no reference AQ sensors and accuracy of low cost and medium cost sensor is uncertain. The EEA recommended calibration process can be seen in the figure below.



Most medium cost sensor have the EEA calibration and reference sensor often have 10% inaccuracy and many medium cost sensors have 20% inaccuracy. Most low cost sensor have no calibration and use some machine learning in the AQ repository to learn anomalies or biases or outlier or irregular patterns. Most handheld, mobile and wearable sensor cannot be calibrated and need reference sensor and machine learning to increase accuracy.

2.2.1.8 Robustness to environment

The majority of medium cost sensor are for commercial usage and robust to the environment. There is a possibility of obstruction and for smoking next to these that cause anomalies. The low cost sensors are often sensitive to damage and malfunction without monitoring.

2.2.1.9 Height of Sensor

This highlights the limitation of sensor that they are on accurate for a small radius around the sensor. The air pollution can massively vary in height and the sensor cannot adapt to it even on mobile sensors. On mobile sensor ability is further reduced by variability of emissions from the vehicle itself and motion of the vehicle.

2.2.1.10 Sensor drift

The majority of low cost sensor have a problem with sensor drift after a short time. Initially it can be removed in the AQ dataset repository yet sensors of a few years can cause problems. Medium cost sensor often don't yet there are instances where the early signs of sensor drift. There methods to avoid sensor drift both on a sensor and in a AQ dataset repository yet it is easy to miss both technically and by an AQ expert analyser.

2.2.1.11 Sampling

The majority of medium cost sample every 1 min or more frequent and use a 15 min average for most accuracy. The low cost sensors sometime only sample every 15 min because of battery usage saving. There are large problems that some of these sensors average out large or fast flowing plumes of air pollutions or miss them completely.

2.2.1.12 Sensitivity to factors that impact air pollutants

The sensitivity can vary when large or fast flowing plume cause anomalies and not the whole plume is sensed. Some sensors of gases are sensitive to temperature and humidity with some medium cost sensors being able to be robust to this to certain levels of temperature. Many medium cost sensors have difficulties when air pollutant levels are high or low to measure precisely or even accurately. Some meteorological factors can obscure air quality measurements in some sensor more than other sensors.

This section will seek to make a survey of the available sensors, with the primary focus being on the low to medium cost outdoor static fixed sensors with an overview of indoor, mobile, handheld, wearable and AQ reference sensors.

2.2.2 Outdoor 'Medium Cost' Static Fixed AQ Sensors

2.2.2.1 Envirowatch E-MOTE

The E-MOTE system was produced by Envirowatch in 2010 and contains a network of 'motes' which are small wireless devises which link to a 'gateway' device which collects the data before sending it to the database server. The E-MOTES record air quality every minute before communicating other motes and the gateway using a custom ad-hoc wireless communication protocols. The Gateway then forwards the data from the E-MOTE using GPRS to the EnviroView software for analysis [12].

The E-MOTE was deployed for a year, October 2016 to September 2017, and monitored NO, NO2, CO in Sheffield City Centre [13]. The report stated that ”E-MOTEs were able to successfully capture the temporal variability such as diurnal, weekly and annual cycles in air pollutant concentrations and demonstrated significant similarity with reference instruments”[13].

2.2.2.2 Libelium Waspmote Plug and Sense Smart Environment Pro

Libelium have produced many different sensors that link to it's Plug and Sense system, and with the parameters that we're measuring in mind, the most applicable sensor would be the Smart Environment Pro. The Smart Environment Pro measures four different parameters which could include NO_2, particle matter (10 and 2.5) and Ozone, which are crucial for analysing urban data. Along with the pollutants that are measured Smart Environment Pro can measure other parameters such as, temperature, humidity and atmospheric pressure. The sensors can be powered by using an attached solar panel and the sensors can be utilised as a network as the motes can use wifi or 4G to connect to each other and a sensor board [14].

The Libelium Waspmote Plug and Sense system is currently being used for monitoring the air quality around the construction of the Bilbao Metropolitan South Bypass in Spain. The sensors have been set up as a network, whilst being connected by Sigfox, measuring the AQ from different areas around the construction site before being analysed by eNatura for real time AQ data
[15].

2.2.2.3 AQMesh

AQMesh is a low cost AQ censoring system that provides real-time localised air quality information and data analysis. AQMesh's system contains small pods (with a height, width and length of 430, 220,170 mm respectively and a weight of around 2kg) which can analyse up to 6 pollutants, including the four aforementioned key species no_2, O_3, $PM_{2.5}$ and PM_{10}. The system can also measure external meteorological parameters such as wind speed and direction along with temperature, pressure and humidity. The AQ mesh can be powered by lithium batteries or can be powered by an inbuilt solar panel. The frequency of the recordings can be set to be any value between one minute to an hour. The sensors can be connected to the network and the AQMesh Data Server through either wifi or 4G in near to real time [16].

AQMesh sensors have been used for the Breath London pilot study, with the studies data freely available online. The study used 100 AQMesh sensors in the city on London to gain an understanding into the cities AQ levels. The study gave results that was deemed "comparable with those of reference equipment" [17]. In fact in research by the National Physics Library, when completing regression analysis with the AQMesh and reference data for NO_2 and $PM_{2.5}$,two pollutants this study is focusing on, the R^2 value was above 0.9 [17]. This highlighted the merits of using a large network of low-cost AQ sensors.

2.2.2.4 Envira Nanoenvi EQ

The Nanoenvi is a low cost AQ sensor system produced by Envira. The Nanoenvi can be powered by solar panel or lithium batteries and the device is small in size with the sensor having a height, length and width of 270,180 and 80 mm. The Nanoenvi can measure up to 5 sensors which can measure pollutants such as NO_2, O_3, $PM_{2.5}$ and PM_{10} along with other parameters such as wind direction and speed, temperature, humidity, pressure and also VOC's which were highlighted as an impacting factor of Ozone in 2.1 [18].

2.2.2.5 Earthsense Zephyr

Zephyr is a compact and lightweight air pollution monitor that measures ambient pollutants and particle matter. The Zephyr can be powered by a solar panel or DC power supply and measures all key pollutants including NO_2, O_3, $PM_{2.5}$ and PM_{10}. The pollutants levels are recorded in real time and then sent to MyAir software for analysis. The Zephyr devices are highly mobile and does not need to be fixed in place, as the device includes an inbuilt GPS that provides positional information for each measurement [19].

2.2.2.6 Clarity Node-S

We are a mission-driven organization that takes joy in empowering our customers in their battle to protect human health. Clarity was founded in 2014 to tackle the global air pollution crisis, and our team has grown to include talented members from diverse backgrounds. With 16 employees and seed funding in the US. It is 165 mm (W) x 84 mm (H) x 79 mm (D) and senses NO2, PM1, PM10 and PM2.5 using a solar panel for electricity.

2.2.3 Outdoor 'Low cost' static fixed AQ Sensors

2.2.3.1 PurpleAir

The PurpleAir PA-II[36] product has a regular price of $249.00. It is 3.5 in x 3.5 in x 5 in**.** The PA-II is an air quality sensor that measures real-time PM2.5 concentrations for residential, commercial, or industrial use. Built-in WiFi enables the air quality measurement device to transmit data to the PurpleAir map, where it is stored and made available to any smart device. PurpleAir uses PMS5003 and PMS1003 laser particle counters. These sensors count suspended particles in sizes of 0.3, 0.5, 1.0, 2.5, 5.0, and 10um. These particle counts are processed by the sensor using a complex algorithm to calculate the PM1.0, PM2.5, and PM10 mass concentration in ug/m3. PMS5003 and PMS1003 sensors come factory calibrated. Each PurpleAir sensor includes a BME280 pressure, temperature, and humidity sensor.

2.2.3.2 Cleair

Providing air pollution transparency to cities, neighbourhoods & communities. Using minimal infrastructure, Cleair provides localised pollution insights by leveraging IoT and AI, filling in the gaps left by costly traditional monitoring methods based in Kolkata.

http://cleair.io/

2.2.3.3 Airly PM, NO2, O3

It costs £1020 and senses PM1, PM2.5, PM10, NO2, O3. Airly is based in the US California and Poland. It has a mobile app, letschoolbreathe for school with free sensors for schools and forecasts. https://airly.org/en/pricing/airly-sensors-for-home/

2.2.4 Outdoor Reference Static Fixed AQ Sensors

2.2.4.1 Automatic Urban and Rural Network (AURN)

The AURN is the automatic monitoring network used by DEFRA and the UK government to analyse the levels of harmful pollutants in the UK. AURN takes hourly measurements of all key pollutants, including NO_2, O_3, $PM_{2.5}$ and PM_{10}, and other external parameters such as pressure, temperature, humidity, wind speed and direction. The AURN is a high cost and large system, which as a result means there are few sites across the UK. However AURN produces the most accurate results, with their data typically used as the reference equipment [20]. These are produced and maintained by Ricardo an engineering and environmental consultancy.

2.2.4.2 AQUILA

The EU-wide network of air quality reference laboratories. AQUILA was established in 2002, chaired by the Joint Research Centre (JRC) of the European Commission (EC, 2019a). AQUILA's objectives include:

• providing expert information on equipment measuring air quality;

• promoting the harmonisation of air quality measurements among European countries;

• coordinating quality assurance and control initiatives;

• participating in activities related to standardising air quality measurement methodologies;

• providing a forum for information exchange between countries.

2.2.5 Summary of all Aforementioned AQ Sensors

Figure 2: Aforementioned AQ Sensors

AQ Sensor	Cost	Parameters Measured	Unique Features
E-MOTE	Medium Cost	$NO_2, O_3, PM_{2.5}, PM_{10}$	Small devices. Self sufficient.
Libelium	Medium Cost	$NO_2, O_3, PM_{2.5}, PM_{10}$ Temp, humidity, pressure.	Small devices. Self sufficient.
AQMesh	Medium Cost	$NO_2, O_3, PM_{2.5}, PM_{10}$ Temp, humidity, pressure and wind speed and direction	Tests wind parameters, which were shown to be impacting factors in section 2.1.
Nanoenvi EQ	Medium Cost	$NO_2, O_3, PM_{2.5}, PM_{10}$ Temp, humidity, pressure and wind speed and direction and Tests wind parameters	Small device Tests wind parameters .
Zephyr	Medium Cost	$NO_2, O_3, PM_{2.5}, PM_{10}$	In-built GPS allows mobile use.

AURN	High Cost	NO_2,O_3,$PM_{2.5}$,PM_{10} Temp, humidity, pressure and wind speed and direction and Tests windparameters 13	Large and costly but gold standard for AQ analysis.

2.2.6 Indoor Low Cost AQ sensors

2.2.6.1 PurpleAir PA-I-Indoor

The PurpleAir PA-I-Indoor has a regular price of $199.00. With the PA-I-Indoor PM 2.5 sensor's full-color LED, the resulting glow indicates air quality at a glance from across the room. Sporting a simple design that sits comfortably on a counter or tabletop, the PA-I-Indoor detector measures real-time PM2.5 concentrations. Built-in WiFi enables the PM2.5 indoor air quality sensor to transmit data to the PurpleAir map, where it is stored and made available to any smart device.

2.2.6.2 **TSI AIRASSURE INDOOR AIR QUALITY MONITOR**

The 6-gas AirAssure™ IAQ Monitor measures SO2, O3, NO2, CO, tVOCs, CO2, particulate matter, barometric pressure, temperature and relative humidity. It cost $1500.00 USD

2.2.6 Handheld AQ sensors

2.2.6.1 TSI Q-Trak XP™

It measures PM1, PM2.5, PM10 size fractions and total particle concentration. Accommodates up to 6 optional, pre-calibrated gas sensors. It has built-in % of outdoor air workflow. It has field calibration and simple replacement of sensors minimizes downtime and keeps costs low

It is used for IAQ surveys and investigations, proactive IAQ monitoring (especially schools and office buildings), building commissioning (e.g., LEED, USGBC, WELL) and evaluating thermal comfort (temperature and relative humidity).

2.2.6.2 Aeroqual - S500 (OZU 0-0.15) Or Aeroqual PM

The Aeroqual Series 500 handheld monitor can be used with a wide range of gas sensor heads. The device uses a sensitive metal oxide semiconductor that relies on the conductance of heated tungstic oxide (WO3). In the presence of ozone, surface conductance of WO3 decreases. Changes in the conductance are calibrated to measure ozone concentrations. During a "flow" state the sensor responds to incoming ozone the sensor conductance decreases. The ozone measurement is proportional to the sensor conductance difference between a no-flow and flow states. It has dimensions: 195 x 122 x 54 mm, weight: <460 g and PM or O3 sensor.

2.2.8 Wearable AQ Sensors

2.2.8.1 Plume labs

The plume labs Flow 2 is the next generation of Plume Labs award-winning personal air quality monitor. It sense NO2 and VOC and retail at $199.

2.2.8.2 Atmotube

Wearable, portable device that monitors the quality and safety of the air you breathe. Atmotube PRO detects PM1, PM2.5, and PM10 pollutants, like dust, pollen, soot, and mold, plus a wide range of Volatile Organic Compounds (VOCs) in real time for $199. https://atmotube.com/ or Atmotube PLUS for $49.00. Atmotube PLUS detects a wide range of Volatile Organic Compounds (VOCs).

2.2.8.3 AirBeam

AirBeam is a low-cost, palm-sized air quality instrument that measures hyperlocal concentrations of harmful microscopic particles in the air, known as particulate matter, as well as humidity and temperature. The AirBeam measures particulate matter with proven accuracy and when used in conjunction with the AirCasting platform - or a custom solution - helps community-based organizations, educators, academics, regulators, city managers, and citizen scientists map air pollution and organize for clean air. It cost $249 and senses particulate matter, humidity, and temperature.

2.2.8.4 Aero

Aero is a portable air quality monitoring device for those who live in urban areas or suffer from conditions such as Allergic Rhinitis, which causes irritation and allergic reactions to pollutants in the air. A functioning model was created with key components to monitor pollutants including Particulate Matter and Volatile Chemicals. An overall rating for air quality out of 100 is created every 20 seconds and represented visually by the colour changing LED ring, going from Light Turquoise to Deep Red, depending on how hazardous the air is.

2.2.8.5 University of Cambridge PAM

In many circumstances a wearable air quality monitoring system that also makes use of a complementary range of sensing technologies will be the optimum way to provide a reliable information set: Electrochemical, NDIR, and metal oxide sensors can all be included in the system. ASL metal oxide sensors give early warning of the accumulation of atmospheric components that pose either toxic or fire hazards but also allow for energy economy through on-demand use of ventilation systems. We take the use of metal oxide gas sensors to a new level of both sensitivity and selectivity through an elegant approach to sensor management and signal processing and our system opens the door to new applications. ASL has developed the technology to advance the capabilities of metal oxide gas monitoring to hitherto unachievable levels. In the past semiconductor gas sensors have proved useful in a limited range of applications in the detection of flammable and/or toxic gases in the environment. Although such devices are inherently robust and inexpensive their wider application has been precluded by poor selectivity between analyte gases in some cases and by inadequate sensitivity in others. In the ASL system sensors based on purpose-designed materials formulations are supported by advanced control and read-out electronics that overcome such limitations in both sensitivity and selectivity.

2.2.8.6 Dyson Trial in 2021 air quality backpack

Dyson scientists initiated the project to explore how exposure could affect athletic performance. Re-working existing technology used in Dyson purifiers, the Dyson air quality backpack is a portable air-sensing device. Armed with on-board sensors, a battery pack and GPS, it is able to measure pollution data on the move. The collected data was also paired with indoor air quality data from Dyson's connected purifiers in the athlete's home, to develop a picture of how indoor and outdoor air quality can impact wellbeing. These steps allowed the athletes to understand what might have caused the pollution and how they might be able to lower their exposure in the future. This highlights how air quality can be impacted by daily activities: Increased exposure to Nitrogen Dioxide (NO_2) and PM2.5 pollution was monitored when some of the athletes drove towards city centres. This is unsurprising as these are pollutants commonly associated with vehicle emissions as well as brake and tyre wear. Five out of the six athletes cooked during their period of data collection, registering spikes in PM2.5 or NO_2. The combustion process while cooking releases particulates into the air, likely contributing to this increase.

2.2.8.7 Curejet P750 and G200

P750 Particle & Gas Sensor, with size only 29x 29x 4.9 mm, is the world's smallest all-in-one air sensor with only 1/16 volume compared with others.

P750 uses laser light with Mie scattering theory to measure PM2.5, PM10 and even PM1.0. P750 also integrates BME680 Environmental Sensor that can detect VOC gas, show the ventilation status, sense barometric pressure for weather glass or altitude difference. It also detects ethanol and may be developed as alcohol breath tester, or drunk driving prevention alarm system. There is a gas sensor G200 sensing VOC at 23.6 x 15.2 x 3.5 mm.

2.2.8.8 Breathe London Wearables study

The Breathe London Wearables study of (i) Plume Flow, (ii) Airbeam2, (iii) University of Cambridge PAM and (iv) Dyson wearable sensor. is a public engagement campaign that aims to characterise London school children's exposure to air pollution and present this information in a way that the school community can understand, relate and act upon. In order to achieve the study's objectives, a suitable wearable air pollution sensor had to be identified, tested and selected. The sensor requirements were as follows:

1. Monitor PM2.5 pollutant concentrations and GPS position at a time resolution of at least 1 minute. Monitored nitrogen dioxide (NO2) concentrations were also desirable, but not essential.

2. Small and light enough to be carried by school children aged 5 – 11 years

3. Battery life of at least 10 hours to cover a full school day

4. Sufficiently low cost to allow at least 20 units to be deployed within a budget of £20,000

5. Sufficiently robust and reliable to deliver valid results despite potentially rough treatment by children.

6. Demonstrable accuracy and precision sufficient to allow robust comparison between sensors and illustrate spatial variation in pollutant concentrations.

2.2.9 Full evaluation of AQ sensors

PM Sensors							
Sensor Image	**Make** (Model)	**Est. Cost** (USD)	**Pollutant(s)**	***Field R^2**	***Lab R^2**	***Field MAE (µg/m³)**	***Lab MAE (µg/m³)**
	**Aeroqual** (AQY v0.5) Discontinued	$3,000	$PM_{2.5}$	0.84 to 0.87	0.99		28.8 to 36.0
	**Aeroqual** (AQY v1.0)	$4,000	$PM_{2.5}$	0.76 to 0.81	0.99	4.2 to 5.3	5.4 to 15.1
			PM_{10}	0.56 to 0.68		35.4 to 38.8	
	**Aeroqual** (S500-PM)	$1,490	$PM_{2.5}$	0.46 to 0.67	0.99	4.4 to 6.2	11.9 to 32.4
			PM_{10}	0.15 to 0.24		13.5 to 18.0	

	**AethLabs** (microAeth)	$6,500	BC (Black Carbon)	0.79 to 0.94			
	**Airly**	$1,000	$PM_{1.0}$	0.79 to 0.89		4.2 to 5.3	
			$PM_{2.5}$	0.83 to 0.89		4.5 to 5.0	
			PM_{10}	0.34 to 0.37		19.3 to 19.7	
	**Air Quality Egg** (2018 Model)	$249	$PM_{1.0}$	0.86 to 0.88	0.99	2.1 to 2.3	7.0 to 7.3
			$PM_{2.5}$	0.84 to 0.85	0.99	4.4 to 5.3	6.1 to 6.6
			PM_{10}	0.12 to 0.13	-	16.4 to 19.2	
	**Air Quality Egg** (Version 1)	$200	PM	~ 0.0			
	**Air Quality Egg** (Version 2)	$240	$PM_{2.5}$	0.79 to 0.85			

			PM_{10}	0.31 to 0.40			
	**AirThinx** (IAQ)	$1,000	$PM_{1.0}$	0.68 to 0.70		2.4 to 2.5	
			$PM_{2.5}$	0.54 to 0.57		4.8 to 5.0	
			PM_{10}	0.03 to 0.05		19.7 to 19.8	
	**Airviz Inc.** (Speck)	$150	$PM_{2.5}$	0.32			
	**Alphasense** (OPC-N2)	$310	$PM_{1.0}$	0.63 to 0.82	0.99		
			$PM_{2.5}$	0.65 to 0.80	0.99		
			PM_{10}	0.45 to 0.57	0.99		
	**Alphasense** (OPC-N3)	$338	$PM_{1.0}$	0.78 to 0.82	0.99	4.4 to 5.0	39.0 to 43.2

			$PM_{2.5}$	0.52 to 0.67	0.99	7.1 to 9.2	40.3 to 46.9
			PM_{10}	0.45 to 0.52	0.99	18.0 to 24.1	39.2 to 48.0
	**Applied Particle Technology** (MINIMA)	$995	$PM_{1.0}$	0.84 to 0.89		5.0 to 5.6	
			$PM_{2.5}$	0.86 to 0.89		5.8 to 6.5	
			PM_{10}	~0.37		39.4 to 40.3	
	**AQMesh** (v3.0)	$7,800	$PM_{1.0}$	0.55 to 0.73		2.4 to 3.4	
			$PM_{2.5}$	0.47 to 0.79		2.7 to 7.5	
			PM_{10}	0.24 to 0.58		11.4 to 23.1	
	**AS-LUNG** (Air Quality Station)	$2,000	$PM_{1.0}$	0.42 to 0.88		3.2 to 7.3	

			$PM_{2.5}$	0.59 to 0.81		8.0 to 12.1	
			PM_{10}	0.15 to 0.23		18.6 to 21.2	
	**AS-LUNG** (Portable)	$1,000	$PM_{1.0}$	0.86	0.99	3.2 to 4.3	2.6 to 3.4
			$PM_{2.5}$	0.78	0.99	6.8 to 8.2	12.8 to 13.5
			PM_{10}	0.11 to 0.14	-	18.9 to 21.6	
	**Atmotube** (Pro)	$189	$PM_{1.0}$	0.91 to 0.93	0.99	3.6 to 4.6	1.9 to 6.4
			$PM_{2.5}$	0.88	0.99	4.9 to 5.9	2.9 to 3.8
			PM_{10}	0.22	-	20.9 to 22.9	-
	**Blues Wireless** (Airnote)	$149	$PM_{1.0}$	0.68 to 0.86		4.3 to 6.8	
			$PM_{2.5}$	0.67 to 0.75		4.4 to 7.1	

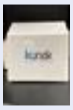
			PM_{10}	0.04 to 0.11		20.2 to 34.8	
	Cair	$200	$PM_{(1-2)}$	0.43 to 0.51			
			$PM_{(3-10)}$	0.39 to 0.51			
	Clarity (Node)	$1,300	$PM_{2.5}$	0.73 to 0.76	0.99	3.0 to 3.4	9.3 to 10.6
	Davis Instruments (Airlink)	$179	$PM_{1.0}$	0.85 to 0.88		2.2 to 2.8	
			$PM_{2.5}$	0.74 to 0.81		4.9 to 5.9	
			PM_{10}	0.25 to 0.31		12.1 to 26.0	
	Dylos (DC1100 Pro)	$300	$PM_{(0.5-2.5)}$	0.65 to 0.85	0.89	4.2	
	Dylos	$475	$PM_{2.5}$	0.58 to	0.95	24.3 to	198.3 to

	(DC1700-PM)			0.68		28.5	209.4
			PM_{10}	0.15 to 0.18	-	43.9 to 53.8	
	**Ecowitt** (WH415B)	$100	$PM_{2.5}$	0.35 to 0.47		8.2 to 15.4	
	**Edimax** (AirBox)	$249	$PM_{2.5}$	0.61 to 0.87		4.4 to 5.5	
	**Edimax** (Edigreen Home)	$299	$PM_{2.5}$	0.82 to 0.83		3.3 to 4.4	
	**Elitech** (Temtop LKC-1000S+)	$140	$PM_{2.5}$	0.91 to 0.92	0.99	3.1 to 3.6	11.1 to 21.9
			PM_{10}	0.31 to 0.35	-	11.7 to 17.9	-
	**Elitech** (Temtop M2000 2nd Generation)	$100	$PM_{2.5}$	0.77 to 0.82	0.99	2.1 to 3.2	13.3 to 21.5
			PM_{10}	0.17 to 0.28	-	12.1 to 14.1	-

	**Elitech** (Temtop P20)	$70	$PM_{2.5}$	0.42 to 0.87		3.8 to 6.1	
	**Elitech** (Temtop PMD 351)	$960	$PM_{1.0}$	0.68 to 0.75		2.4 to 3.8	
			$PM_{2.5}$	0.71 to 0.74		3.8 to 5.8	
			PM_{10}	0.27 to 0.46		9.1 to 18.6	
	**FabLab** (Smart Citizen Kit V2.1)	$119	$PM_{1.0}$	0.94	0.99	2.9 to 3.0	11.0 to 11.5
			$PM_{2.5}$	0.76 to 0.77	0.99	8.3 to 10.7	11.8 to 14.5
			PM_{10}	0.06 to 0.09		48.2 to 56.9	

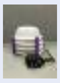
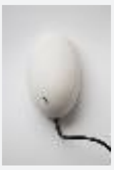
	**Foobot**	$200	$PM_{2.5}$	0.55			
	**HabitatMap** (AirBeam)	$200	$PM_{2.5}$	0.65 to 0.70	0.87	15.6 to 29.0	203.5 to 271.9
	**HabitatMap** (AirBeam2)	$250	$PM_{1.0}$	0.71 to 0.74	0.99	2.9 to 3.0	16.5 to 18.1
			$PM_{2.5}$	0.63 to 0.75	0.99	3.3 to 3.7	11.3 to 13.5
			PM_{10}	~ 0.0	-	25.8 to 28.0	

	**Hanvon** (Hanvon N1)	$200	$PM_{2.5}$	0.52 to 0.79			
	**Igienair** (Zaack AQI)	$3000	$PM_{1.0}$	0.78 to 0.83		6.3 to 6.5	
			$PM_{2.5}$	0.80 to 0.82		3.8 to 4.2	
			PM_{10}	0.69 to 0.71		14.4 to 23.9	
	**IQAir** (AirVisual Pro)	$270	$PM_{2.5}$	0.69 to 0.73	0.99	4.4 to 4.7	26.8 to 37.0
			PM_{10}	0.24 to 0.41	-	16.6 to 22.7	
	IQAir	$270	$PM_{2.5}$	0.63 to	0.99	3.5 to	1.8 to

	(AirVisual Pro FW1.1683)			0.81		5.5	10.8
	**Kaiterra** (Laser Egg 2+)	$199	$PM_{2.5}$	0.81 to 0.85	0.99	3.3 to 4.0	15.2 to 23.3
			PM_{10}	0.17 to 0.25	-	8.0 to 17.3	
	**Kunak** (Air A10)	$3,000	$PM_{1.0}$	-	0.99	-	10.4 to 17.1
			$PM_{2.5}$	0.69 to 0.75	0.99	5.4 to 6.4	4.3 to 14.4
			PM_{10}	0.60 to 0.68	0.99	18.7 to 21.9	8.9 to 23.5
	Lunar Outpost (Canary-S)	$1,070	$PM_{2.5}$	0.83		3.3 to 3.8	
			PM_{10}	0.14		27.4 to 28.6	
	**Magnasci SRL** (uRADMonitor A3 HW105)	~$500	$PM_{1.0}$	0.81 to 0.85		4.0 to 5.2	
			$PM_{2.5}$	0.72 to 0.81		5.2 to 8.9	

			PM_{10}	0.15 to 0.38		20.3 to 29.1	
	**Magnasci SRL** (uRADMonitor INDUSTRIAL HW103)	~$1,300	$PM_{1.0}$	0.74 to 0.83		2.7 to 3.7	
			$PM_{2.5}$	0.70 to 0.78		4.1 to 8.1	
			PM_{10}	0.13 to 0.34		18.1 to 25.7	
	**Magnasci SRL** (uRADMonitor SMOGGIE-PM v1.101)	$110	$PM_{1.0}$	0.84 to 0.86	0.99	4.8 to 5.6	25.3 to 26.8
			$PM_{2.5}$	0.60 to 0.81	0.99	2.1 to 2.8	19.5 to 22.9
			PM_{10}	0.03 to 0.06		17.5 to 25.2	
	**Met One** (E-Sampler)	$5,500	$PM_{1.0}$	-			
			$PM_{2.5}$	0.55 to 0.62		10.9 to 15.2	
			PM_{10}	-			

			TSP	-			
	**Met One** (ES-405)	$5,200	$PM_{1.0}$	0.84 to 0.91		2.8 to 3.6	
			$PM_{2.5}$	0.80 to 0.92		3.5 to 4.0	
			PM_{10}	0.78 to 0.92		4.5 to 8.9	
	**Met One** (Neighborhood Monitor)	$1,900	$PM_{2.5}$	0.53 to 0.67		6.0 to 8.4	
	**Moji China** (Airnut)	$150	$PM_{2.5}$	0.81 to 0.88			
	**Origins**	$200	$PM_{2.5}$	0.58			

	(Laser Egg)		PM_{10}	~ 0.0			
	**Perkin Elmer** (ELM)	$5,200	PM	~ 0.0		20.6 to 30.5	
	**Plume Labs** (Flow 2)	$199	$PM_{1.0}$	0.01 to 0.14		6.6 to 9.1	
			$PM_{2.5}$	0.01 to 0.13		7.3 to 10.6	
			PM_{10}	0 to 0.04		19.3 to 28.3	
	**PurpleAir** (PA-I)	$150	$PM_{1.0}$	0.93 to 0.95	0.95		
			$PM_{2.5}$	0.90 to 0.92	0.99		
			PM_{10}	0.32 to 0.44	0.97		
	**PurpleAir** (PA-I-Indoor)	$180	$PM_{1.0}$	-	0.99		5.1 to 9.5
			$PM_{2.5}$	0.75	0.99		18.7 to 27.7
			PM_{10}	0.36 to	0.97		4.4 to

				0.46			20.4
	**PurpleAir** (PA-II)	$200	$PM_{1.0}$	0.96 to 0.98	0.99		11.7 to 15.9
			$PM_{2.5}$	0.93 to 0.97	0.99		1.7 to 4.2
			PM_{10}	0.66 to 0.70	0.95		15.6 to 20.5
	**Redspira**	$180	$PM_{2.5}$	0.73 to 0.87		4.7 to 7.1	
			PM_{10}	0.31 to 0.37		30.8 to 33.1	
	**RTI** (MicroPEM)	$2,000	$PM_{2.5}$	0.65 to 0.90	0.99	6.4 to 8.3	

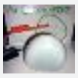
	**SainSmart** (Pure Morning P3)	$170	$PM_{2.5}$	0.71 to 0.74	0.99	4.8 to 5.4	
	**Samyoung S&C** (SY-DS-DK3)	$100	$PM_{2.5}$	0.60 to 0.62	0.98	4.8 to 11.4	36.1 to 51.8
	**Sensirion** (Nubo) Discontinued	$2,000	$PM_{1.0}$	0.96	0.99	2.8 to 3.2	1.9 to 4.5
			$PM_{2.5}$	0.91	0.99	4.7 to 5.2	4.9 to 7.6
	**Sensirion** (Nubo Air)	$1,700	$PM_{1.0}$	0.77 to 0.89		2.9 to 3.5	
			$PM_{2.5}$	0.73 to 0.83		5.2 to 6.5	
	**Sensirion** (SPS30)	$100	$PM_{1.0}$	0.91	0.99	1.3 to 1.4	0.8 to 1.4

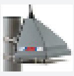
			$PM_{2.5}$	0.80 to 0.83	0.99	2.0 to 5.1	5.4 to 6.5
			PM_{10}	0.07 to 0.20	-	10.8 to 24.7	-
	**Shinyei** (PM Evaluation Kit)	$1,000	$PM_{2.5}$	0.80 to 0.89	0.93		
	**TSI** (AirAssure)	$1,500	$PM_{2.5}$	0.81 to 0.83	0.99		32.4 to 55.0
	**TSI** (BlueSky)	$400	$PM_{2.5}$	0.65 to 0.76	0.99	4.9 to 5.9	3.1 to 6.2
			PM_{10}	0.09 to 0.21		22.7 to 26.3	

	uHoo	$300	$PM_{2.5}$	~ 0.0		9.5 to 17.8	

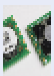
Gas-Phase Sensors

Sensor Image	Make (Model)	Est. Cost(USD)	Type	Meas.	*Field R^2
	2B Technologies (POM)	$4,500	UV absorption (FEM Method)	O_3	1.00
	Aeroqual (AQY v0.5) Discontinued	$3,000	Electrochem	NO_2	0.77
			Metal Oxide	O_3	0.95

	**Aeroqual** (AQY v1.0)	$4,000	Electrochem	NO_2	0.60 to 0.77
			Metal Oxide	O_3	0.96 to 0.97
	**Aeroqual** (S-500)	$500	Metal Oxide	O_3	0.85
	**Airly**	$1,000	Electrochem	NO_2	0.54 to 0.80
				O_3	0.90 to 0.94
	**Air Quality Egg** Ver. 1	$200	Metal Oxide	CO	0.0
				NO_2	0.40
				O_3	0.85
	**Air Quality Egg** Ver. 2	$240	Electrochem	CO	0.0
				NO_2	0.0
	**Air Quality Egg** Ver. 2	$240	Electrochem	O_3	0.0 to 0.20
				SO_2	n/a
	**APIS**	$4,995	Electrochem	CO	0.87 to 0.90

				NO	0.87 to 0.97
				NO_2	0.30 to 0.44
				O_3	0.73 to 0.83
	**AQMesh** V4.0 Discontinued	$10,000	Electrochem	CO	0.42 to 0.80
				NO	0.0 to 0.44
				NO_2	0.0 to 0.46
				O_3	0.46 to 0.83
	**AQMesh** V5.1	$7,800	Electrochem	CO	0.90 to 0.94
				NO	0.67 to 0.76
				NO_2	0.49 to 0.54
				NO_x	0.73 to 0.84
				O_3	0.62 to 0.74

				SO_2	n/a
	**CairPol** Cairsens (CO)	$1,243	Electrochem	CO	0.93 to 0.94
	CairPol Cairsens (NO_2)	$1,198		NO_2	0.0 to 0.12
	**Igienair** (Zaack AQI)	$3,000	Electrochem	CO	0.84 to 0.87
				NO_2	0.53 to 0.58
				O_3	0.0
	**Kunak** (Air A10)	~$5,000	Electrochem	CO	0.55 to 0.60
				NO	0.78 to 0.93
				NO_2	0.24 to 0.32
				O_3	0.86 to 0.88
	**Magnasci SRL**	~$1,300	Electrochem	CO	0.00 to

	(uRADMonitor INDUSTRIAL HW103)				0.07
				NO_2	0.00 to 0.05
				O_3	0.00 to 0.08
	**Perkin Elmer** (ELM)	$5,200	Metal Oxide	NO	n/a
				NO_2	0.0
				O_3	0.89 to 0.96
	**Plume Labs** (Flow 2)	$199	Metal Oxide	NO_2	0.04 to 0.14
	**Smart Citizen Kit**	$200	Metal Oxide	CO	0.50 to 0.85
				NO_2	0.0
	**Spec Sensors**	$500	Electrochem	CO	0.84 to 0.90
				NO_2	0.0 to 0.16
				O_3	0.0 to 0.24
	**uHoo**	$300	Metal Oxide	CO	0.0

				O_3	0.43 to 0.72
	**UNITEC** SENS-IT (CO)	$2,200	Metal Oxide	CO	0.33 to 0.43
	UNITEC SENS-IT (NO_2)	$2,200		NO_2	0.57 to 0.62
	UNITEC SENS-IT (O_3)	$2,200		O_3	0.72 to 0.83
	**Vaisala** (AQT410) Ver. 1.11	$3,700	Electrochem	CO	0.28 to 0.31
				NO_2	0.0
				O_3	0.40 to 0.58
				SO_2	n/a
	**Vaisala** (AQT410)	$3,700	Electrochem	CO	0.80 to 0.83

	Ver. 1.15			NO_2	0.43 to 0.61
				O_3	0.66 to 0.82
				SO_2	n/a

2.3 Impacting Factor Effect on the Low-Cost Air Quality Sensors

When comparing the low-cost AQ sensors to the 'gold standard' AQM stations it is widely recognised that with calibration low cost sensors can repeat AQM station data in perfect conditions. However, when used in urban cities, the perfect conditions rarely exist and there are many aforementioned impacting factors that lower the reliability of the low cost sensors but not the AQM stations. The reliability of the low cost sensors could be described as being temporal and spatial with the location of the sensor and the nature of the impacting factors that it brings having an affect. Section 2.3 will seek to identify these factors and locations which heavily impact reliability and identify optimisation methods to nullify this.

2.3.1 AQ Sensor Analysis for Spatial Impacting Factors

A study by [21] analysed the performance of low cost AQ sensors (AQMesh) nodes compared to accepted AQM stations in a controlled lab and across three locations, with different settings, across Oslo Norway.

Testing in Perfect Conditions

To test the reliability and validity of the AQ sensors in 'perfect conditions' all 24 of the nodes being tested were set up in a lab with a constant temperature of 20 degrees and a pressure of 30%. Then finite amounts of pollutants were produced in the lab and the recordings from the nodes recorded. From this test [21] concluded that "all tested sensors have relatively good precision during the tests performed under stable laboratory conditions" with the modal average r-values for the correlation of the AQMesh nodes reaching 0.99. This test concurs the initial claim that low cost sensors work efficiently in perfect conditions.

Testing in Urban Locations

Although the low cost sensors work well in perfect conditions, the truest test of their reliability will occur when testing their performance in urban locations. [21] Placed motes in areas around three high quality AQM stations (two near busy traffic and one in a quiet area) and compared the results over three months.

Amount of NO_2 at Sensor Impacting Factor

A conclusion that could be drawn from the test is that there is potentially a link between the amount of NO_2 pollution and the performance of the AQ sensor, with the lesser the amount of NO_2 pollution the lesser the accuracy of the AQ sensor. This is because they observed that the performance for NO_2 worsened during the month of July and during July NO_2 levels were lower than other months because there is less traffic and therefore less pollution, as this is when people are typically on holiday. Therefore, it could be said that the amount of NO_2 pollutant at the sensor is a spatial impacting factor
for the sensor's reliability.

A further impacting factor is that AQ sensors measuring NO_2 performed better in the winter periods compared to summer. A study conducted by Zauli-Sajani et al measured the accuracy of low cost AQ sensors against reference instruments in summer compared to winter. The study gained an average R^2 value of 0.9 in the winter and 0.34 in the summer [22]. This demonstrates a huge effect of seasonality, and the meteorological factors that accompanies, on accuracy of AQ sensors analysing NO_2.

Amount of Particle Matter at Sensor Impacting Factor

A further potential impacting factor that could be drawn from the test is that the reliability in the measures of $PM_{2.5}$ and PM_{10} differed due to it's vicinity to the busier roads and therefore the amount of particle matter. The study suggests that for the PM_{10} the performance was lower during May and

July and for $PM_{2.5}$,the performance was lower during June and July which coincides with the months with the lowest ambient particle matter concentrations as May, June and July were the months with the lowest average concentrations. Therefore, it could be said that the amount of particle matter pollution at the sensor is a spatial impacting factor as the amount of particle matter and accuracy of the sensor are negative correlated.

Amount of O_3 at Sensor Impacting Factor

A similar study was conducted by [23] in which they measured the accuracy of low cost AQ sensors over a year. Their findings reinforced the converse of the previous claim that the lesser the NO_2 the lesser the accuracy by stating that at high concentrations the sensor's measurements were accurate [23]. Also, this study claimed that, similarly for NO_2, at high levels of O_3 concentration the sensor's measurements were also accurate. This suggests that placing the sensors in an area of low-concentration could be a spatial impacting factor.

Meteorological Impacting Factors on Sensor Accuracy

Both of the studies suggested that the meteorological factors (such as temperature and pressure) gave sporadic levels of accuracy with some motes being heavily affected and others not. However, it is clear that extreme meteorological factors do have an effect it is difficult to find specific meteorological factors that cause inaccuracy, other than the factors that will have an effect on the amount of pollutants and therefore in turn the accuracy of the sensors as discussed in section 2.1.

Conclusion

To conclude this analysis it can be noted that there is a positive correlation between the amount of pollutant at the sensor and the accuracy of the sensor for each of the NO_2, O_3, $PM_{2.5}$ and PM_{10} pollutants. Therefore more errors are to be expected at low concentrations of pollutants.

2.3.2 Optimising the Low-Cost AQ Sensors through Networking

Section 2.3.1 has outlined impacting factors that affect medium and low cost sensors but not high cost. However, the performance of the medium and low cost sensors can be optimised to reach levels closer to that of the high cost sensors. The main method of optimising the sensors is by using an ubiquitous sensoring network, which is when multiple sensors are used simultaneously around the same area. This dense array of sensors increases the spatial coverage and can improve air pollution exposure estimates [24]. It is stated in the EEA assessment of medium and low cost sensor that "Nevertheless, sensing techniques are rapidly evolving. This dynamic situation means that there also is currently no clear standard against which to evaluate performance. Despite ongoing efforts, including within the European standardisation system, a certification system will take some time to develop. Ensuring that a device is fit for purpose will continue to be important.At the same time, emerging evidence suggests that data from a large network of low-cost sensors, subject to statistical analysis or machine learning, could in the future provide information of a precision and accuracy that matches current quality criteria for official data. In the near future, a network of sensor systems could provide the kind of real-time information on air quality sought by the public." Therefor there is an opportunity to apply medium and lost cost without reducing accuracy of AQ measurement dataset repositories and increasing AQ measurements.

Some of the method to optimise are:

- a. Knowledge of the characteristics of the sensor, embodied in an observation model for the response, $y = f(x, \theta)$. A simple example is the linear model for the response: $y = a0 + a1x + e$ where e is a realization of the measurement error, usually assumed Gaussian with zero mean.

- b. Prior expectations on the parameters θ based on measurements performed some time previously, or on general knowledge of the sensor characteristics derived for example from a long-term body of observations.

- c. Known influences on the sensor.

- d. Known general characteristics of the measurement problem such as the general variation of the characteristics of the unknown x over a geographic region, expected diurnal variations associated with motor vehicles or sunlight, variations associated with different land-use (e.g., proximity of roads, industry or open country, high-rise buildings, waterways).

- e. Measurements with other techniques, such as reference instruments at particular locations, satellite observations, long-term average sample measurements.

- f. Correlations with meteorology and expected spatial patterns as a result rainfall, wind direction, and speed.

- g. Computational models, e.g.., dispersion models; landuse regression; interpolation models based on sparse reference data or on more densely distributed timeaveraged measurements made in specific campaigns using, for example, sample collection, sampling filters, or Palmes diffusion tubes.

2.3.2.1 Optimisation of network through statistical analysis

The AQ measurements can be statistically analyses to find anomalies, outliers, biases, irregular patterns and regular patterns.

2.3.2.1.1 Statistics

The statistics can be defined to find if anomalies go outside of trends or regular patterns. The statistic can be used to evaluate impact when remove potential anomalies to test irregular patterns.

2.3.2.1.1 Statistical Analysis

The AQ measurement can be calibrated further in the AQ dataset repository by statistical methods to remove anomalies, biases and outliers. The irregular pattern can be identified to assist AQ expert analyser to attribute causation to these irregular patterns of AQ measurements. Potential inaccurate or less precise measurement can be identified and aligned to more precise measurements.

2.3.2.1.2 Correlation of features

This is the correlations of the additional information and to other measured features at AQ sensor of temperature or humidity. It is known when these should be correlate and any anomalies can show anomalies, biases, outliers or irregular patterns. Many evaluation can be done including these: Pearson's coefficient of correlation, Relative Bias, normalized Mean Absolute Error, Normalized Mean Squared Error and Mean Absolute Percentage Error.

2.3.2.2 Optimisation of Networks by Using Machine Learning and Neural Network Methods

2.3.2.2.1 Machine Learning methods

There is increasingly more research in producing deep learning and neural networks for forecasting air pollution levels. Some of the most beneficial are LSTM. Huang et al [23] evaluated the performance of sensors measuring pollutants including NO_2 and O_3 in Beijing and sought to evaluate the measurements by using statistical, machine learning and neural network methods.

From the study, the most successful method of optimisation was the use of a long short term memory (LSTM) neural network model to correct errors caused by meteorological impacting factors that effect low cost AQ sensors. This method had a great effect on the reliability of the NO_2 pollutant, with the R^2 values for the sensors against the reference instruments increased rom 0.35 and 0.44 to 0.85 and 0.84 [23]. Although not perfect, this demonstrates that machine learning in the form of LSTM can be implemented to improve the low cost AQ sensors.

2.3.2.4 Geospatial Optimisation

2.3.2.3.1 Additional geospatial and other datasets

The use of additional dataset can be applied to make hypothesis of ranges and predictions of AQ measurement to compare to the AQ measurements. The variety of these are within the impacting factors identified earlier. The figure below shows the requirements for these additional dataset for various levels of AQ expertise and air quality analysis method

Table 1: SR assessment methods in different Tiers per assessment need (source: Literature Review (Maiheu and Janssen 2019))

	Estimation of surface area in exceedance	Estimation of total resident population in area of exceedance	Estimation of length of road in exceedance	Facilitation of configuration of representative network	Identify sampling points suitable for calibration and validation
Tier 1 Expert Opinion	Fixed radius e.g. (Castell-Balaguer and Denby, 2012)		Fixed length	Classification based on expert opinion and station classification	Expert assignment of station siting and type
Tier 2 Proxy Information	Methods relying on proxy data and distance relations to estimate source emissions and dispersion conditions. E.g. (Henne et al., 2010; Janssen et al., 2012; Righini et al., 2014; Spangl et al., 2007)			Objective station classification based on time series or GIS proxy data (Joly and Peuch, 2012; Nguyen et al., 2009)	
Tier 3 Geographically explicit, comprehensive fit-for-purpose modelling	Comprehensive and fit-for-purpose local scale modelling: line source modelling, parametric street box models (OSPM, CAR, ...), obstacle resolved modelling (CFD), (Rivas et al., 2019; Santiago et al., 2013)			Determine gaps in the network coverage taking into account the SR areas of the stations, e.g. (Soares et al., 2018)	Geographically explicit models applied for objective classification (typical SR length scale based on independent modelling)
	Comprehensive and fit-for-purpose regional scale modelling: regional scale Eulerian models e.g. (Martin et al., 2014)				
Tier 4 Modelling complemented with dedicated measurements	Modelling complemented with passive sampler campaigns, mobile monitoring, e.g. (Hagenbjörk et al., 2017; Li et al., 2019; Vardoulakis et al., 2011b, 2005). In the future sensor observations (Sadighi et al., 2018) might be used as well if sensor uncertainty is properly defined.				

2.3.2.3.2 Interpolation with a Network

One the large benefit of low cost and medium cost sensors is it is feasible to include sensors within a radius where interpolation can be used to compare AQ measurement. Some method used include Kriging and Voronoi interpolation. Further impacting factors that lessens the accuracy of AQ sensor networks are spatial errors that occur when analysing areas that are further away from a sensor in the network, and errors of this nature are increased by meteorological factors. A method that can be completed to lessen this effect, and thus improve the accuracy of the AQ sensors, is kriging the data to interpolate results for the entire area. Kriging was used by Ahangar et al in [25] in which they were improving the reliability of $PM_{2.5}$ sensors to map pollutants in Southern California. Their use of Residual kriging improved their model, with the R^2 of their interpolated results compared to the observed results reaching 0.92 in a certain area. Kriging was also used by Kassteele et al [26] as they used External drift Kriging of nitrous oxide concentrations to reduce uncertainties in the output of their model and gain accurate results in areas not covered by their network.

2.3.2.3.3 Compare to reference AQ sensors

The AQ measurements can be compared to reference sensor within 10 metres. The use of AQ forecasting and satellite sensing can be used to compared to the AQ measurements

2.3.2.4 Air Quality Modelling

The air quality modelling is modelling the factors that impact the air pollutants. It is done on many resolution from ECMWF long range AQ forecasts to ADMS urban street level AQ predictions.

2.3.2.5 Satellite Monitoring

There are many satellite measurements of NO2 and Ozone. These supplement region that don't have AQ sensors. The spatial distribution is large so it has limitations although is quite accurate, has a large coverage and is in real time.

2.3.2.6 Optimising location and framework of AQ network

The location of the AQ sensor allows the network have an optimal configuration when the sensors in the optimal location. This is mainly an optimisation problem. The features to optimise are distance between sensors, varying of complexity of urban density and other impacting factors on air pollutant near a sensor location and air flow between sensors. It is required that there aren't zones where the air pollution varies largely and there are no AQ sensors. A conclusive evaluation of air flows and impacting factors allows the estimation of variances of air pollution be determined over the geospatial domain. AQ sensor can then be optimised on the number and distance to nearest AQ sensor.

2.3.2.7 Existing Analysis Applications

Nebo — a system for identifying air pollution and the location of the pollution source based on measuring a marker substance PM2.5 https://ru.nebo.live/

Djinn Sensor — an AI expert system for human safety and productivity based on air quality data and physical parameters of the environment. http://djinn.one/

2.4 Regulations on AQ levels

The exposure to AQ levels is the largest health risk. Therefor there are specific limit values of air pollutants that regulatory authorities determine are not acceptable. These are often regulated by national government or intra governmental organisation similar to the European Union. These regulations therefor vary over authorities with international organisation providing recommendation based on research on exposure and health outcomes. The main recommendations are provided by the World Health Organisation. There is detrimental damage to vegetation through deposition although most regulations are for health protection.

2.4.1 Outdoor Ambient Regulations

2.4.1.1 EU Air Quality Directives

The EU Air Quality Directives require every Member State to establish a network of air quality monitoring stations in accordance with a set of criteria. These criteria specify both technical requirements for instruments and the types of locations where stations should be situated, including at traffic, industrial, urban, suburban and rural sites. These provisions aim to ensure that measurements are representative for a defined area and ensure the delivery of harmonised, comparable air quality data across Europe. The figure below shows the EU limit values for air pollutants.

Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedences each year
Fine particles (PM2.5)	25 µg/m3***	1 year	Target value to be met as of 1.1.2010 Limit value to be met as of 1.1.2015	n/a
Sulphur dioxide (SO2)	350 µg/m3	1 hour	Limit value to be met as of 1.1.2005	24
	125 µg/m3	24 hours	Limit value to be met as of 1.1.2005	3
Nitrogen dioxide (NO2)	200 µg/m3	1 hour	Limit value to be met as of 1.1.2010	18
	40 µg/m3	1 year	Limit value to be met as of 1.1.2010 *	n/a
PM10	50 µg/m3	24 hours	Limit value to be met as of 1.1.2005 **	35
	40 µg/m3	1 year	Limit value to be met as of 1.1.2005 **	n/a
Lead (Pb)	0.5 µg/m3	1 year	Limit value to be met as of 1.1.2005 (or 1.1.2010 in the immediate vicinity of specific, notified industrial sources; and a 1.0 µg/m3 limit value applied from 1.1.2005 to 31.12.2009)	n/a
Carbon monoxide (CO)	10 mg/m3	Maximum daily 8 hour mean	Limit value to be met as of 1.1.2005	n/a
Benzene	5 µg/m3	1 year	Limit value to be met as of 1.1.2010**	n/a
Ozone	120 µg/m3	Maximum daily 8 hour	Target value to be met as of 1.1.2010	25 days averaged over 3

The EU directives is stated by

Directive 2008/50/EC on ambient air quality and cleaner air for Europe including the following elements:

The merging of most of existing legislation into a single directive (except for the Fourth Daughter Directive) with no change to existing air quality objectives.

New air quality objectives for PM2.5 (fine particles) including the limit value and exposure related objectives.

The possibility to discount natural sources of pollution when assessing compliance against limit values.

The possibility for time extensions of three years (PM10) or up to five years (NO2, benzene) for complying with limit values.

Directive 2004/107/EC of the European Parliament and of the Council relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air *(Fourth Daughter Directive)*.

Directive 2015/1480/EC of 28 August 2015 amending several annexes to Directives 2004/107/EC and 2008/50/EC of the European Parliament and of the Council laying down the rules concerning reference methods, data validation and location of sampling points for the assessment of ambient air quality

Commission Implementing Decision 2011/850/EU: Commission Implementing Decision of 12 December 2011 laying down rules for Directives 2004/107/EC and 2008/50/EC of the European Parliament and of the Council as regards the reciprocal exchange of information and reporting on ambient air quality (notified under document C(2011) 9068)

2.4.1.1 UK Environmental Bill

The UK aims through the Environment Bill, which has not been passed by parliament, to keep the same limit values and reporting of the EU AQ directives yet have no authority to monitor it or issue fines. This is to allow authorities to reduce their focus, effort and responsibility on reducing air pollution so that the economy can grow and large corporation can earn more profits.

2.4.1.2 US Clean Air Act

Under the federal Clean Air Act, the Environmental Protection Agency (EPA) establishes health-based air quality standards that all states must achieve. The California Clean Air Act also establishes requirements for cities and counties to meet. South Coast AQMD was created by the state legislature to facilitate compliance with the federal Clean Air Act and to implement the state air quality program. Toward that end, South Coast AQMD develops regulations designed to achieve these public health standards by reducing emissions from business and industry.

2.4.2 Indoor AQ levels

The leading professional and standard-writing societies developed or expanded their IAQ-related work and released standards on minimum ventilation rates for providing acceptable IAQ. Currently standards by ISO, CIBSE and CEN are available for international use, with the most utilized one being the Standard 62 series by the American Society of Heating Refrigerating and Air Conditioning Engineers. The WHO has recommendation which can be seen in the figure below that some regulations apply. The Committee on the Medical Effects of Air Pollution COMEAP advises the UK government on air quality levels and has recommendations on IAQ. UK building regulation acceptable levels of NO2, CO and VOC's. The UK air quality strategy has management strategies for the main air pollutants. Health and Safety Executive have recommendations and restriction of exposure at work to some air pollutants.

Pollutant Averaging time (mean)	Interim target (μg/m3) 1	2	3	Air quality guideline μg/m3
PM2.5 Annual	35	25	15	10
PM2.5 24-hour	75	50	37.5	25
PM10 Annual	70	50	30	20
PM10 24-hour	150	100	75	50
Carbon monoxide 24-hour	–	–	–	7

The figure below shows the NO2 regulations and recommendations of IAQ. It shows that building regulations in the UK allow the peak NO2 to go 88 ugm 3 above two research expert groups on IAQ.

Table 4.5. Guideline concentrations for nitrogen dioxide, NO_2

	Nitrogen dioxide, NO_2 Guideline concentration μg m^{-3} (ppb)	Averaging time
World Health Organization (WHO)	200 (105)	1 hour mean
	40 (21)	Annual mean
COMEAP	200 (105)	1 hour mean
	40 (21)	Annual mean
UK Building Regulations, Approved Document F	288 (150)	1 hour mean
	40 (21)	Long-term
UK Air Quality Strategy	200 (105) with a maximum of 18 exceedances allowable within any 12 month period	1 hour mean
	40 (21)	Annual mean

The figure below shows the CO2 recommendations for IAQ for the UK from HSE and CIBSE building industry advisory group.

Table 4.4(a). Guideline concentrations for carbon dioxide, CO_2

	Carbon dioxide, CO_2	
	Guideline concentration mg m^{-3} (ppm)	Averaging time
UK HSE Workplace Exposure Limits	9,150 (5,000)	8 hour mean
	27,400 (15,000)	15 minute mean (short-term exposure limit, STEL)
CIBSE Guide A	~1,000 ppm	Performance standard to indicate 'adequate ventilation'

The figure below shows the VOC's recommended limit values.

Table 4.1. Guideline concentrations for Total Volatile Organic Compounds (TVOCs)

	Total Volatile Organic Compounds (TVOCs)	
	Guideline concentration μg m^{-3}	Averaging time
UK Building Regulations, Approved Document F	300	8 hours
European	200 to 500	
	Guideline concentration μg m$_{-3}$	Comment
Mølhave, L	<200	Comfort range
	200-3,000	Multifactorial exposure
	3,000-25,000	Discomfort
	>25,000	Toxic
Seifert, B	300	Target guideline value. No individual compound should exceed 10% of target value
Finnish Society of IAQ and Climate	<200	Target values of indoor climate; best air quality; 90% of occupants satisfied
	<300	Room may have a slight odour
	<600	Minimum requirement

The figure below shows the formaldehyde and benzopyrene

Table 4.2. Guideline concentrations for formaldehyde

	Formaldehyde	
	Guideline concentration μg m^{-3}	Averaging time
World Health Organization	100	30 minute mean based on effects other than cancer or odour/annoyance
COMEAP	100	30 minutes
UK HSE Workplace Exposure Limits	2,500	8 hour mean
	2,500	15 minute mean (short-term exposure limit, STEL)
INDEX	30	Non-carcinogenic no-effect level

Table 4.3. COMEAP guideline concentrations for benzene and benzo[α]pyrene

Pollutant	Guideline concentration	Averaging time
Benzene	5.0 μg m^{-3} (1.6 ppb)	Annual mean
Benzo[α]pyrene	0.25 ng m^{-3}	Annual mean

The figure below shows the CO authorities limit levels.

Table 4.6. Guideline concentrations for carbon monoxide, CO

	Carbon monoxide, CO	
	Guideline concentration mg m^{-3} (ppm)	Averaging time
World Health Organization (WHO)	100 (85)	15 minute mean*
	35 (30)	1 hour
	10 (9)	8 hours
	7 (6)	24 hours**
COMEAP	100 (90)	15 minutes
	60 (50)	30 minutes
	30 (25)	1 hour
	10 (10)	8 hours
UK Building Regulations, Approved Document F	100 (90)	15 minutes
	60 (50)	30 minutes
	30 (25)	1 hour
	10 (10)	8 hours
UK Building Regulations, Approved Document F	35 (30)	8 hour occupational exposure
UK Air Quality Strategy	10 (10)	8 hours
UK HSE Workplace Exposure Limits	35 (30)	8 hour mean
	232 (200)	15 minute mean (short-term exposure limit, STEL)

The figure below shows the SO2 and PM Limit levels of authorities.

Table 4.8. Guideline concentrations for sulphur dioxide, SO_2

	Sulphur dioxide, SO_2	
	Guideline concentration $\mu g\ m^{-3}$ (ppb)	Averaging time
World Health Organization (WHO)	20 (8)	24 hour
	500 (188)	10 minute
UK Air Quality Strategy	350 (130)	1 hour mean concentration not to be exceeded more than 24 times a year
	125 (47)	24 hour mean concentration not to be exceeded more than 3 times a year
	266 (100)	15 minute mean concentration not to be exceeded more than 35 times a year

Table 4.9. Guideline concentrations for particles

	Particles		
	PM_{10} $\mu g\ m^{-3}$	$PM_{2.5}$ $\mu g\ m^{-3}$	Averaging time
World Health Organization (WHO)	20	10	Annual mean
EU Ambient Air Quality Directive and current UK Air Quality Standard	50	25	24 hour mean
	50		24 hour mean

The figure below shows the O3 limit values of authorities.

Table 4.7. Guideline concentrations for ozone, O_3

	Ozone	
	Guideline concentration $\mu g\ m^{-3}$ (ppb)	Averaging time
World Health Organization (WHO)	100 (50)	8 hour mean
UK Building Regulations, Approved Document F	100 (50)	Performance criteria – buildings other than dwellings
UK Air Quality Strategy	100 (50)	8 hour mean concentration not to be exceeded more than 10 times a year
UK HSE Workplace Exposure Limits	400 (200)	15 minute short-term exposure limit (STEL)

Buildings can gain certification certificates through these assessments:

BREEAM (Building Research Establishment's Environmental Assessment Method)

WELL Building Standard

LEED (Leadership in Energy and Environmental Design)

These assessments are often measured by mitigation of:

Outdoor air pollution source control

Reducing ingress of outdoor pollutants

Building airtightness

Ventilation air intake position

Ventilation air intake control

Filtration Medium ('M' type filters) – Fine ('F' type filters) – Efficient Particulate Air (EPA or 'E' type filters) – High Efficiency Particulate Air (HEPA or 'H' type filters) – Ultra-Low Penetration Air (ULPA or 'U' type filters)

Control of ground pollutants

Ventilation

Recirculation

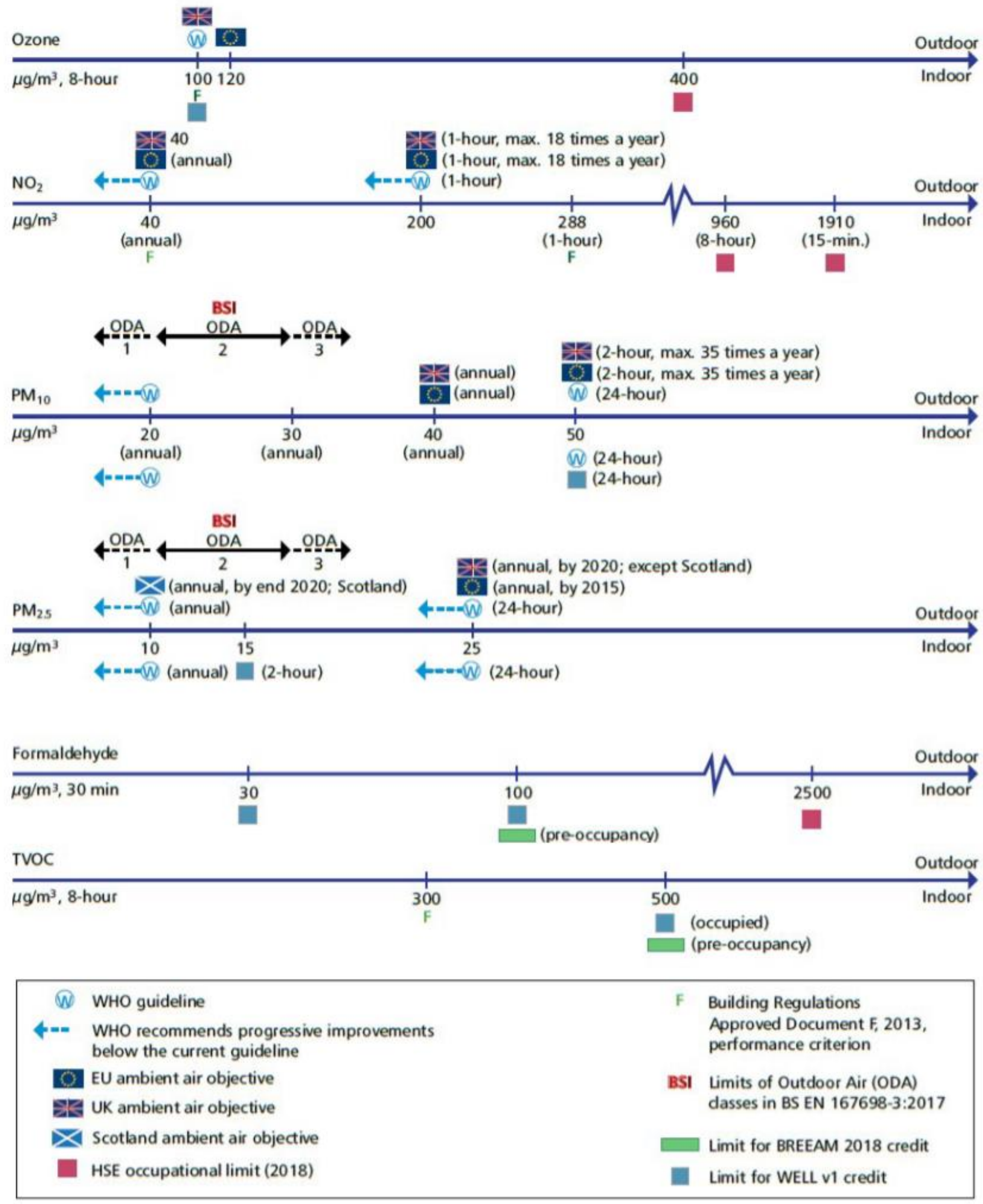
2.4.3 WHO, EPA's, COMEAP and other advisors

COMEAP in the UK provides independent advice to government departments and agencies on how air pollution impacts on health. Its members come from a range of specialist fields such as air quality science, atmospheric chemistry, toxicology, physiology, epidemiology, statistics, paediatrics and cardiology. There is also a lay member, who helps ensure that the general public can access and understand the committee's work. It is produced overviews on research from ultra fine particulars to climate change or net zero carbon policies to impact on Covid-19 to impacts on dementia. Air pollution kills an estimated seven million people worldwide every year. WHO data shows that almost all of the global population (99%) breathe air that exceeds WHO guideline limits containing high levels of pollutants, with low- and middle-income countries suffering from the highest exposures. WHO supports countries to address air pollution. The EPA's have a responsibility to meet national and international regulations. They have an aim to provide regulators and managers with recommendations on analysis and mitigation. They have a role to advise government of additions to act of parliament to regulate air pollution levels and emission levels. Often it is the local authorities responsibility to manage air pollution levels, to gain funding for innovate mitigation and report AQ levels. This is the case in the EU which requires authorities to report a mitigation plan and improvements when limit value are not met. The emission are mainly regulated on manufacture of vehicles or products. The vehicles emissions are regulated on manufacture which cause large problem that these emission levels increase when vehicles age. It is also a problem that many manufacture have lied to regulatory authorities. The usage of vehicles is not regulated and often not advised on even when style of driving has been shown impact air pollution levels and emission levels. Factories, energy suppliers or larger emitters are largely regulated although they are still a large cause of air pollution.

2.4.4 Overview of Regulations

The figure below show the overview of regulations on air pollutant in the UK and EU with WHO recommendations.

Figure 3.1: Summary of Selected Air Quality Criteria



2.5 Health impact of AQ levels

There are variety of health impacts from exposure to low air quality levels. The AQ exposure differs in long term or short, specific levels and either indoor or outdoor. The differing air pollutant have differing health impacts with PM be able to be of microscopic size of many varying materials they can cause further fully unrealised health impacts. The figure below shows the WHO's links of air pollution exposure to health outcomes.

Disease or injury	WASH	Indoor fuel combustion	Second-hand tobacco smoke	Ambient air pollution	Noise	Chemicals[b]	Other housing risks	Recreational environment	Water resources management	Land use and built environment	Other community risks	Radiation	Occupation	Climate change[c]
Infectious and parasitic diseases														
Respiratory infections		●	●	●			●							
Diarrhoeal diseases	●							●						●
Intestinal nematode infections	●												●	○
Malaria									●		●		●	●
Trachoma	●													○
Schistosomiasis	●							●					●	○
Chagas disease							●							○
Lymphatic filariasis	●								●				●	○
Onchocerciasis									●				●	○
Leishmaniasis							●						●	○
Dengue							●						●	●
Japanese encephalitis									●				●	○
HIV/AIDS													●	
STDs													●	
Hepatitis B and C													●	
Tuberculosis		●					●						●	
Other infectious diseases	●						●		●				●	
Neonatal and nutritional diseases														
Neonatal conditions	●	●	●	●		●							●	○
Protein–energy malnutrition[d]	●										●			●
Noncommunicable diseases														
Cancers		●	●	●		●					●	●	●	
Neuropsychiatric disorders					●	●	●						●	●
Cataracts		●										●	●	
Hearing loss					●	●							●	
Cardiovascular diseases		●	●	●	●	●				●			●	●
COPD		●	●	●									●	
Diabetes		●	●	●										
Asthma		●	●	●		●	●						●	○
Other respiratory diseases													●	○
Chronic kidney diseases						●							●	○
Skin diseases	●					●							●	
Musculoskeletal diseases	●												●	
Congenital anomalies			●	●		●						●	●	

Figure WHO Health outcome link to emission and other sources

The figure below show the health impact of the indoor air pollutants.

Table 3. Typical health impacts of some common pollutants found indoors

Pollutant	Impact on health
Carbon monoxide (CO)	Carbon monoxide can cause headaches, dizziness, nausea and at very high levels, death. Elderly people, pregnant women, young children and people with heart disease and lung disease are more sensitive to the adverse effects of carbon monoxide.
Formaldehyde	Formaldehyde can cause eye, nose and throat irritation and is considered a potential human carcinogen.
Nitrogen dioxide (NO_2)	Exposure to nitrogen dioxide can cause inflammation of the airways, respiratory illnesses and possibly increases the risk of lung infections. Young children and people with asthma are the most sensitive to NO_2. It plays a major role in the development of chronic obstructive pulmonary disease in adults which will affect more people than heart disease by 2020 (Environmentalist 2012). Long-term exposure may also affect lung function and can enhance responses to allergens in sensitised individuals.
Odour	Odorous discharges are subjective and cause nausea and irritation for some people.
Ozone (O_3)	Ozone exposure can cause asthma, irritation and damage to the eyes, nose and airways. Prolonged exposure to high levels may result in damage to the lungs and airway linings.
Particulate matter	Inhalable particles have been linked with a number of respiratory illnesses, including asthma and chronic bronchitis. Long-term exposure to fine particles can cause premature death from heart disease and lung disease including cancer. Short-term exposure to higher levels of fine particle concentrations have also been linked with cardio-vascular problems and increased death rates. Exposure to fine particles has also been linked to prevalent anxiety and hypertensive disorders.
Volatile organic compounds (VOCs)	Key symptoms associated with exposure to VOCs include eye irritation, nose and throat discomfort, headache and allergic skin reaction.

Figure Indoor air pollutant health impacts from BRE Group https://www.bregroup.com/bretrust/wp-content/uploads/sites/12/2019/03/Ensuring-Good-IAQ-in-Buildings-Trust-report_compressed-2.pdf

Some of variances health and productivity impacts in the US can be seen in the figure below for many Air pollutants that is known.

Health Effect Reductions (PM2.5 & Ozone Only)	Pollutant(s)	Year 2010	Year 2020
PM2.5 Adult Mortality	PM	160,000	230,000
PM2.5 Infant Mortality	PM	230	280
Ozone Mortality	Ozone	4,300	7,100
Chronic Bronchitis	PM	54,000	75,000
Acute Bronchitis	PM	130,000	180,000
Acute Myocardial Infarction	PM	130,000	200,000
Asthma Excaberation	PM	1,700,000	2,400,000
Hospital Admissions	PM, Ozone	86,000	135,000
Emergency Room Visits	PM, Ozone	86,000	120,000
Restricted Activity Days	PM, Ozone	84,000,000	110,000,000
School Loss Days	Ozone	3,200,000	5,400,000
Lost Work Days	PM	13,000,000	17,000,000

2.6 Other Impacts

One of the main other impact is a reduction in productivity. This can be for office workers and farm or factory workers. There are main reasons for reduced productivity being work absents, long term health impact i.e. asthma or others, early retirement, air pollution affecting cognition. It was found that “men exposed to high levels of black carbon had reduced cognitive performance, equivalent to aging by about two years, as compared with men who'd had less black carbon exposure.”[37] The black carbon is a form of PM found in diesel plumes. This can affect productivity in offices, schools or factories through ventilation systems and construction, farm or transport workers.

Another impact is desirability of offices, shops and sites in regions along with commuting routes. This can cause massive reduction in local economic value and social degradation.

2.7 Existing Networks

There are main existing networks along with dataset repositories from the AQ sensors. Many national EPA's manage high cost regulatory sensors similar to the UK's AURN and the European Environmental Agency report on 4000 AQ sensors. These are of high quality, high calibration and have been installed for a long time although design for an earlier air quality domain problem and only in the low hundreds of AQ sensors in the UK. Many local councils, states and regions are installing innovative networks of medium cost AQ sensors. These are often highly calibrated and acceptable quality yet haven't been installed for a long time, are installed just for one purpose to protect the authorities responsibilities and have problems due to being early prototypes. Some commercial companies are partnering with AQ sensor manufactures like Google and Aclima to produce AQ dataset repositories fully open to further analysis. These are often medium quality or cost AQ sensors, are more conclusive in coverage with aim to be used commercially for multiple purposed although use innovative techniques like mobile AQ sensors which are difficult to calibrate so have some extreme occurrence of inaccuracy which is difficult to detect. Some AQ sensor manufacturers are producing AQ dataset repositories from their sold sensors to individual enthusiasts, researchers and innovative organisations like PurpleAir's repository. These are independent of large managerial biases yet are difficult to clarify calibration and management accuracy. Some researchers and enthusiast are producing their own AQ sensor and producing AQ dataset repositories similar to HackAir. These are often of various quality with some analyses stating they skew the accurate measurement because of their inaccuracy although comparing to accurate measurement can allow usage of these 'hacked' AQ sensors. The main advantage is the education domain of these to allow many users to understand and interact with measuring AQ in their situations. Some organisations, researchers, EPA's and citizen scientists are producing AQ dataset repositories through research and other means. These are of use to supplement accurate AQ measurements and can often include other measurements of traffic, green space, urban density, lichen levels and exposure experience.

2.7.1 OpenAQ

OpenAQ is one of the largest AQ dataset repositories being with the national AQ sensor networks. It is increasingly including medium cost and low cost sensors datasets.

2.7.2 Luftdaten or Sensor Community

This is another AQ dataset repository with 13,604 AQ sensors and 14bn measurements. This more of an independent AQ sensor owner's repository allow 'hacked sensors' or their own 50 Euro sensor be applied. https://sensor.community/en/

2.7.3 AirQo

AirQo is Africa's leading air quality monitoring, research and analytics network. We use low cost technologies and AI to close the gaps in air quality data across the continent. Work with us to find data-driven solutions to your air quality challenges.

2.8 Limitations of existing Networks

The existing sensors main limitation is the lack of AQ sensors. This is a problem in all nations with extreme examples in Africa, South America and regions in Asia where some of highest air pollution levels are often measured.

Another main limitation is accountability because these sensor's management are done by those with a responsibility for high air quality and with a risk of fines. In many cases in China AQ measurements have been falsified, measurements edited and lies been reported externally. From 2015 to 2017 China under reported many air quality levels.[38] In other countries AQ sensor are strategically located near spatial optimal locations that don't represent the regions air quality levels.

The networks have a limitation in the radius from every AQ sensor and that is impossible or not feasibility to put sensor in a dense formation to resolve this.

Chapter 3

Analysing Trends in AQ Data and their Causes

As mentioned throughout this paper, there are many factors which have an effect on the amount of pollutants in cities and lots of these impacting factors are predictable and happen routinely. Therefore, most of these 'spikes' and short increases in air pollutants can be predicted. Therefore would be of great importance if a system could use machine learning through knowledge of the pollutant trends and impacting factors to predict future AQ levels using real time, or near to real time, data. If refined to a high standard these predictions have many applications in the built environment, most notably in ventilation systems, and this section will explore them.

3.1 Seasonality and Trends of AQ Pollutants in Urban Locations

Existing data from AQMS' can be accessed through OpenAQ [27] and this section has analysed data from various time points at the DEFRA AQMS in Newcastle city centre. This section shall use the existing data from that sensor to analyse trends and seasonality to draw any notable conclusions.

3.1.1 Weekly Data

Conclusive data from a DEFRA AQMS located in Newcastle's city centre (N54.97825, E-1.610528) was collected between 05/07/21 and 10/07/21 in an attempt to see trends in day to day AQ measurements. Figure 3 below graphs the results for the NO_2, O_3, $PM_{2.5}$ and PM_{10} pollutants.

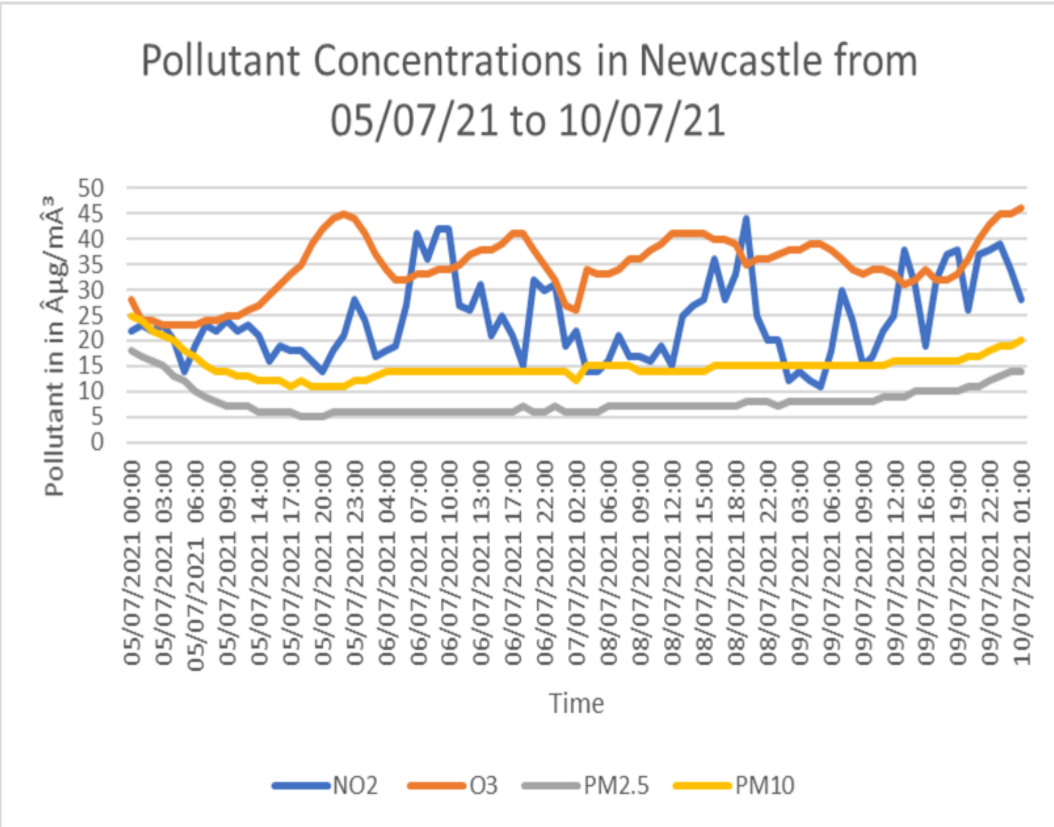


Figure 3.1: Pollutant Concentrations Over Short Time Period [27]

From figure 2.1 the daily trends can be observed.

For the NO_2 pollutant levels, a clear correlation between peak traffic times and pollutant level can be observed as the large spikes always occur between 7am and 9am and 4pm and 7pm. These times are 'rush hour' times in which the vast majority of commuters travel to and from work. Therefore, the amount of traffic as an impacting factor for NO_2 emission is reinforced by this data.

The O_3 pollutant level is interesting as it shows a negative correlation with the NO_2 pollutant, as the peaks in the O_3 line tend to be when the NO_2 levels are low. Obviously, this isn't a perfect fit due to the multifactorial causes of pollution but however, it is clear to observe a link between the two pollutants. Therefore, it can be reaffirmed that a lack of NO_2 in an area could cause an increase in O_3 pollution.

There was little fluctuation in both of the PM pollution levels with both lines having a very small gradient which suggests that there aren't any clear daily trends for those pollutants. However, it interesting to note that both lines had an almost identical gradient at all times suggesting that the factors that impact the levels of $PM_{2.5}$ and PM_{10} are the same.

3.1.2 Annual Seasonality

To analyse an annual seasonality I plotted the levels of each pollutant from the same sensor in Newcastle from 01/01/19 to 01/01/20. The reasoning behind using data from 2019 was to avoid using anomalous data from the COVID-19 pandemic, in which Government 'lockdowns' had a huge effect on pollution levels. Therefore data from 2019 better represents seasonality in a typical urban setting.

N02 Annual Seasonality

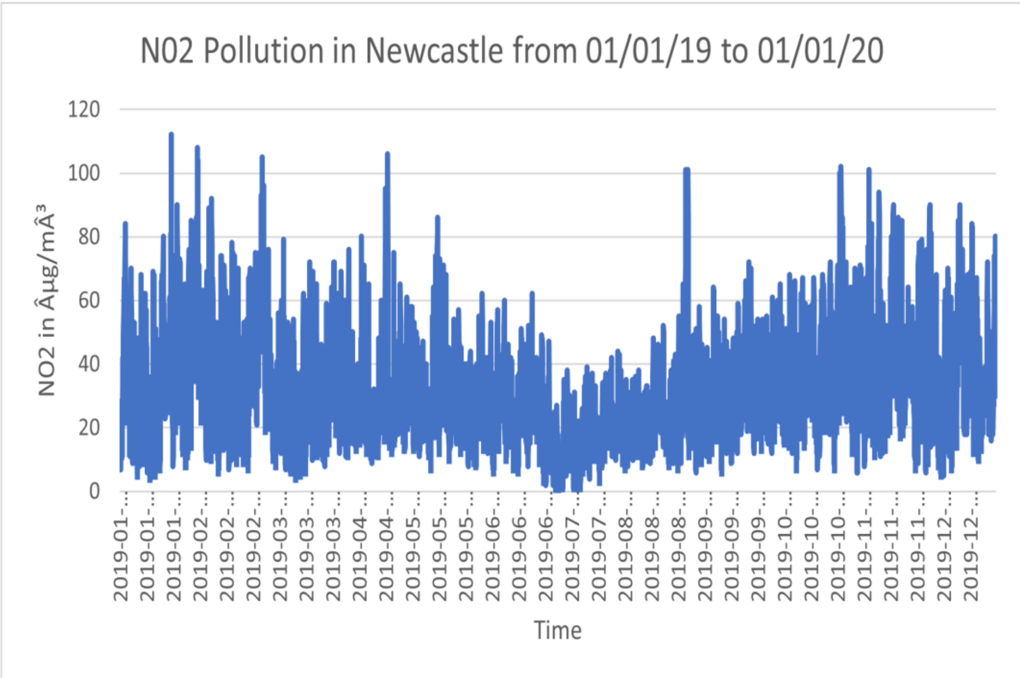


Figure 3.2: NO2 Concentrations Over a Year [27]

From figure 2.2 the seasonality of NO_2 pollution can be observed. This data reinforces claims from section 2.3.1 that there is less NO_2 in warmer summer months as from the graph it can be noted that the levels of pollution is much lower in June, July and August, which are the warmest months in the UK. Also, the converse of this claim can also be observed as there is more NO_2 pollution in winter, with the levels of pollution being highest in January, February, March, November and December.

There is a uncharacteristically large spike on 25/08/2019 from 7pm to 10pm and from investigation I believe that this large spike may have been caused by an increase in people and traffic in the area. This increase in people was due to the 25th being the crux of a bank holiday weekend with multiple different events taking place in Newcastle that evening.

Ozone Pollution Annual Seasonality

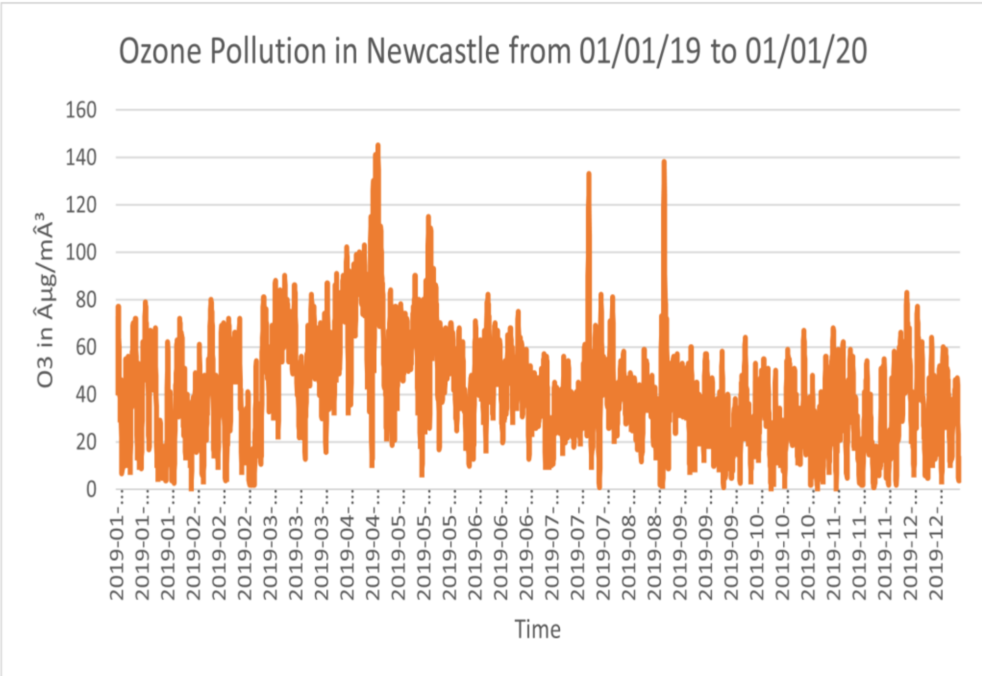


Figure 3.3: 03 Concentrations Over a Year [27]

Figure 3.3 demonstrates the ozone pollution levels over a year. Initially it can be noted that ozone levels are not as volatile as the NO_2 pollution, as although there is evidence of some seasonality, it doesn't have as great an effect as NO_2 pollution.

However, this graph demonstrates that ozone levels are higher in the warmer summer months than winter months with April, May, June and July being the months with the highest levels of ozone.

There were two great spikes on 25/07/2019 and 25/08/2019 and I believe these were due to a great increase in temperature with the temperature on 25/07/2019 setting a record for the warmest day in July and 25/08/2019 also setting a record for the warmest bank holiday in the UK. This therefore suggests that sharp increases in warm weather can cause sharp ozone spikes. Also, as the ozone spike occurred on the same day as the NO_2 spike, it could be noted that high temperature for Ozone and increased amount of traffic for NO_2 is greater than the link between the two pollutants.

PM2.5 Pollution Annual Seasonality

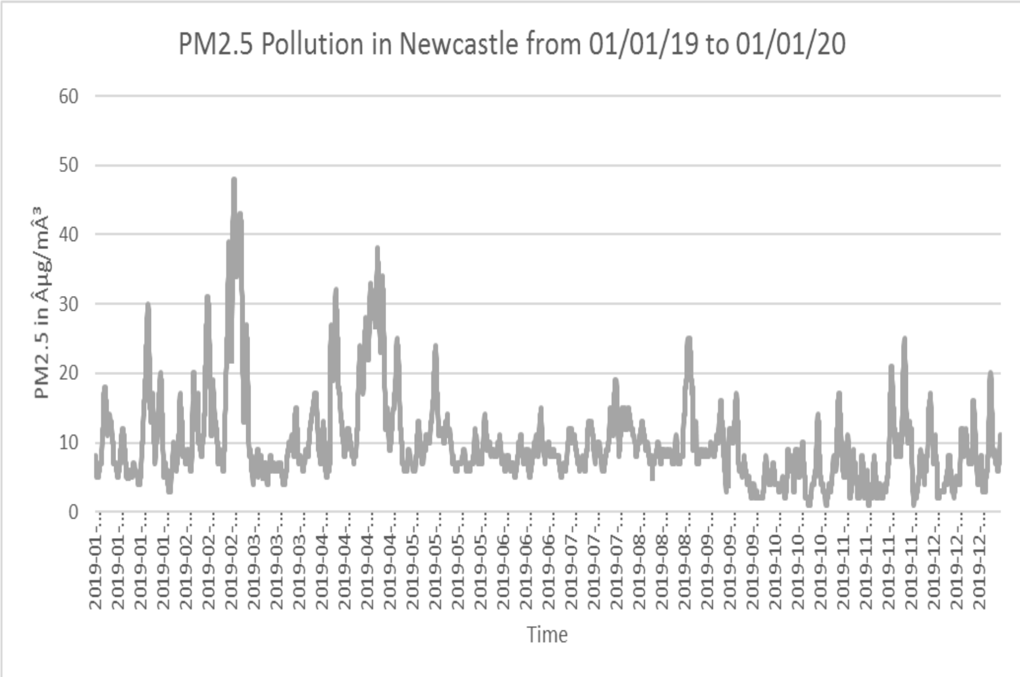


Figure 3.4: PM2.5 Concentrations Over a Year [27]

From figure 3.4 it can be observed that PM2.5 pollutant levels were slightly higher and more volatile in winter and spring months and lower in autumn and summer months, which is similar to what was noted from section 2.3.1. There are a few large spikes which are typically in February and March. This could be due to an increase in traffic and construction in the vicinity of the sensor as roadworks were taking place during those months on St Mary's

Place (the location of the sensor).

PM10 Pollution Annual Seasonality

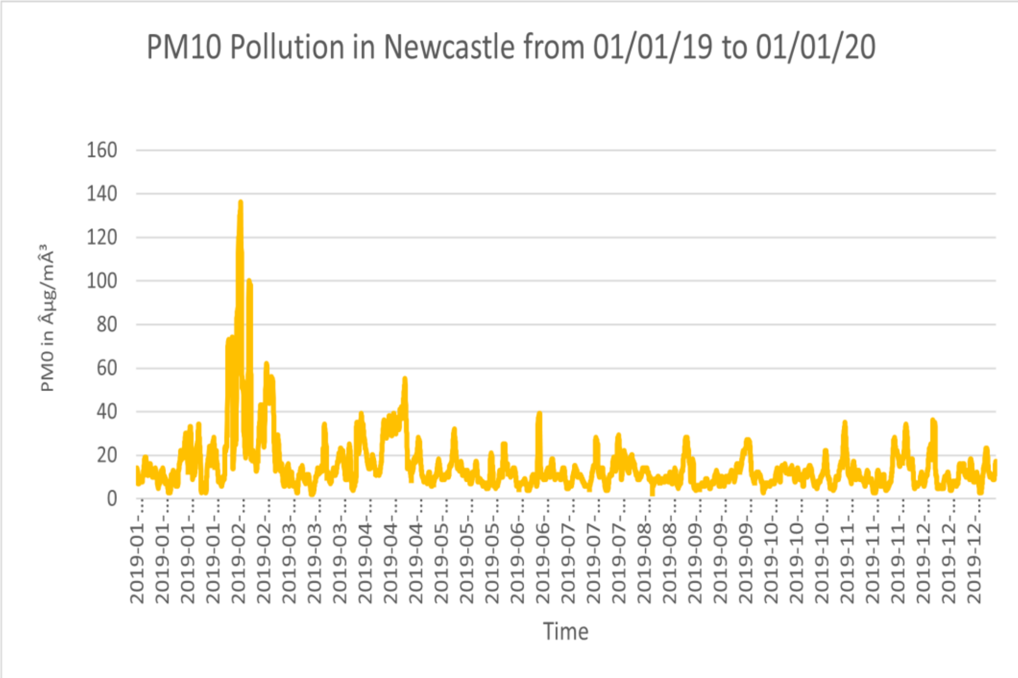


Figure 3.5: PM10 Concentrations Over a Year [27]

From figure 3.5, it can be noted that for 11 months of the year the levels of PM10 pollution was very consistent and stable. This would suggest that there isn't a link between the season and the amount of PM10 pollution. However there is a major spike in the amounts of PM10 pollution around the 15/02/19, which is similar to the increase that occurred for the PM2.5. This reinforces the findings from section 3.1.1 that both PM2.5 and PM10 follow very similar trends.

3.2 Identifying Impacting Factors

Throughout this paper it has been discussed that there are several impacting factors which affect both the levels of pollutants produced and the ability of the AQ sensor networks to detect the pollutants. Therefore, if AQ levels are to be modelled it would be desirable to also measure the levels of these impacting factors to identify the sources to then decrease the uncertainties formed by these factors [28].

This section will seek to find methods to identify the levels of these impacting factors from available data sets. By utilising GitHub many open codes could be utilised to measure the impacting factors on AQ levels, which in turn could be used to predict and extrapolate the air quality in an area.

3.2.1 Traffic and Road Vehicle Emissions

One of the main impacting factors for NO_2, $PM_{2.5}$ and PM_{10} is the amount of traffic in the area. Chen et al [29] have created an open software code which computes the emission levels due to road vehicles and maps the level of emission for a given area. This software could be implemented into a model for emission levels as the traffic related sources of emission could be identified for the desired area. The volume traffic has the largest correlation to air pollution levels although many other features impact air pollution levels. The type of vehicle is a large feature along with its speed and style of driving. These are difficult to gain dataset of but with the usage of traffic cameras and computer vision technique these can be extracted. This is further to added to if ANPR camera are allowed to be applied to determine vehicle license plates. The additional usage of road structure of sharp corners, traffic lights, braking zone and accelerating zones these can be attributed to causing emissions. Another feature is the age of the vehicle and type that determines the emission levels. Large amount research has been done on this and a commercial option is provided by emission analytics of a database of vehicles, ages and emission levels.

https://www.emissionsanalytics.com/about

There are many methods to model traffic emission levels from individual vehicles to plume from many vehicles. Whether the analysis that is done on the plume is to model the expected traffic flow on transport networks or to identify individual vehicles motion from traffic cameras a large amount of high resolution, real time and accurate features about traffic is beginning to become available.

There is unfortunately a large difference in regions from the most innovate and often most congested have large amount of dataset to rural or less innovative regions have to apply limited data to modelling to gain uncertain results. The figure below identifies the feature of interest of this factor and possible method of extraction with accuracy levels.

Feature	Dataset	Extractio	Uncertaint y or	Real time	Resolutio

		n Method	accuracy	ability	n factors
Traffic Volume	Google Maps	API	Medium	Yes	Low
Traffic Density	Traffic cameras	Computer vision	High	Yes	Spatial resolution
Vehicle type	Traffic cameras	Vivastreet and computer vision	High	Yes	Individual vehicle or ratio of volume
Vehicle emission levels	Traffic cameras	Vivastreet and emission analytics computer vision	High	Yes	Exact or estimate
Vehicle speed	Traffic cameras	Computer vision	High	Yes	At location or on average over route

Vehicle acceleration	Traffic Cameras	Computer vision	Medium	Yes	At location or on average over route
Vehicle Age	ANPR	National Authority or DVLA API	Medium	No	Exact or estimation
Vehicle braking	Traffic cameras	Computer Vision	Medium	Yes	At location or on average over route
Vehicle load weight	Traffic cameras	Computer Vision	Low	Yes	Individual vehicle or estimate
Vehicle mileage	ANPR	National Authority or DVLA	Medium	Yes	Exact or estimate

Vehicle modifications	ANPR	National Authority or DVLA	Medium	Yes	Exact or estimate
Vehicle braking	Traffic cameras	Computer Vision	Medium	Yes	At location or on average over route
Vehicle Cold starts	Traffic cameras	Computer Vision	Medium	Yes	At location or on average over route
Vehicle parked	Traffic cameras	Computer Vision	Medium	Yes	At location or on average over route
Vehicle	Traffic	Compute	Medium	Yes	At location

idling	cameras	r Vision			or on average over route
Vehicle waiting in congestion	Traffic cameras	Compute r Vision	Medium	Yes	At location or on average over route
Road structure	openstreetma p	API and machine learning	Medium	Yes	At location or on average over route
Vehicle obstruction and accident	Traffic cameras, WAZE	API and Compute r Vision	Medium	Yes	At location or on average over route

Road furniture	Satellite imagery , street imagery	Computer Vision	Medium	Yes	At location or on average over route
Road Signage	Street imagery	Computer Vision	Medium	Yes	At location or on average over route

Some the features used in air quality modelling and analysis can been in the figure below.

Table 3.1: Metadata information selected with focus on sampling point location and classification. References to the EU AQ legislation which requires the metadata to be reported are given in parentheses.

Mandatory - All	Mandatory - Traffic	Mandatory, where available	Voluntary
Inlet height (AAQD, Annex III. C.and 2011/850/EC II. D ii.19)	**Building distance** (AAQD, Annex III.C and 2011/850/EC, II. D.ii.20) .	**Station information** (2011/850/EC, II. D.ii.27)	**Dispersion local** (IPR Guidance, XML user guide D5.2.11.1 pp 199)
Altitude (2011/850/EC,II.D.ii.26)	**Kerb distance** (AAQD Annex III.C and 2011/850/EC, II.D.ii.21)	**Main sources** (2011/850/EC,II.D.ii.23)	**Dispersion regional** (IPR Guidance, XML user guide D5.2.11.8 pp 203)
Latitude, Longitude (2011/850/EC,II.D.ii.26)	**Distance to major junction** (AAQD Annex III.C and 2011/850/EC, II.D.ii.29),	**Spatial extent of representative area** (2011/850/EC,II.D.ii.16).	**Traffic emissions** (IPR Guidance, XML user guide D5.1.5.3. pp 127)
Classification of the area (2011/850/EC,II.D.ii.28)	**Traffic volume** (2011/850/EC,II.D.ii.30)	**Mandatory, where available - Traffic**	
Station classification (2011/850/EC,II.D.ii.22) .	**Mandatory - Industrial**	**Heavy duty fraction** (2011/850/EC, II.D.ii.31)	
	Distance from source (AAQD, Annex III.B.1.b and 2011/850/EC, II.D.ii.24)	**Traffic speed** (2011/850/EC, II.D.ii.32)	
	Industrial emissions (IPR Guidance, XML user guide D5.1.5.5. pp 128)	**Street-canyon - Width of street** (2011/850/EC,II.D.ii.33)	
		Street canyon - Height of building facades (2011/850/EC, II.D.ii.34)	

The availability of these features can be seen for the EU from 2018 in the figure below that were reported.

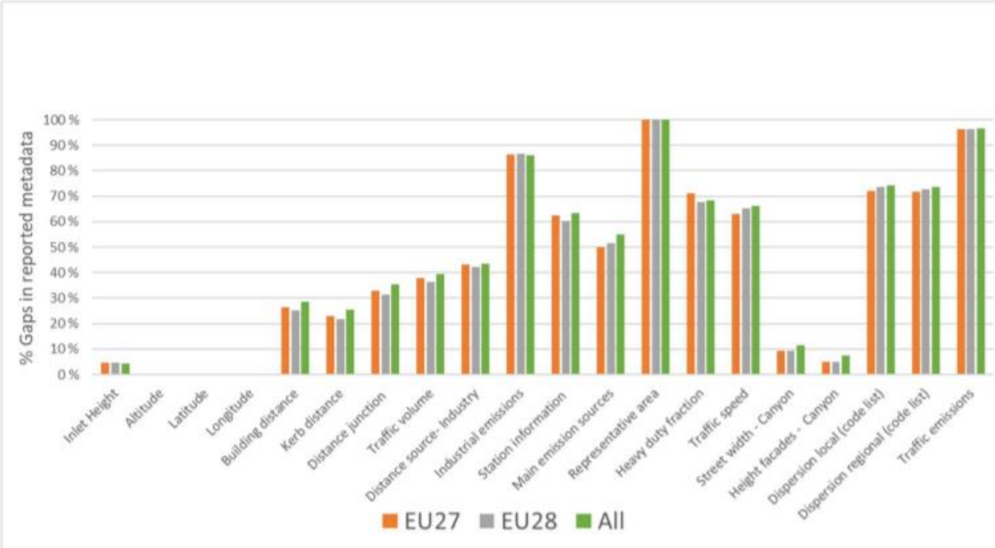


Figure 6.1. Summary of the metadata analysis showing the percentage of missing or not reported metadata

3.2.2 Wind, Relative Humidity, Precipitation, Air Pressure, Solar Radiation and Other Meteorological Factors

Another key factor on the emissions in an area is wind and humidity. This especially impacts particle matter pollution with PM and wind being negatively correlated and PM and humidity being positively correlated. Kulshresth has created a code [30] which predicts the levels of $PM_{2.5}$ in a city due to the wind and humidity at that time, which has been tested in Dehli with relative accuracy as the predicted versus the actual $PM_{2.5}$ values having an R^2 value of 0.80 [30]. This software could be implemented into a model for emission levels as wind and humidity are both already calculated by almost all low cost sensors, as mentioned in section 2.2, and therefore the levels of $PM_{2.5}$ could be predicted. Similar to most meteorological features there are accurate predictions at sparse spatial domain.

The most severe pollution episodes are usually associated with calm or very low wind speed conditions. Vignati et al. [41] have shown that differences in prevailing wind speed conditions seem to explain much of the differences in urban pollution concentrations.

In urban areas, the wind direction is rarely constant over short periods of an hour or less. This is particularly true for low wind speeds, less than 1 m s−1. The dependence of concentration on fluctuations, when averaged over a period of an hour, is smoothed significantly. In order to account for this effect an averaging interval with respect to the wind direction is often applied Berkowicz and Hertel [42].

There is a lack of knowledge, analysis and prediction of wind or other meteorological prediction at the street level. One option is to just use machine learning method to predict from meteorological stations and interpolate the measurements although this has large inaccuracies. This is because of the complexity of the meteorological features. Another option is wind or meteorological modelling techniques either using gaussian methods or computational fluid dynamics methods. This can only be done for small zone and has its own sensitivities or uncertainties. There is still a lack of meteorological prediction at the street levels that can only be solved modelling.

Feature	Dataset	Extraction Method	Uncertainty or accuracy	Real time ability	Resolution factors	
Wind Speed	ECMWF	API	High	Yes	Metres	

at top of canyon or building rooftop						
Wind Speed at street level						
Wind Direction at top of canyon or building rooftop	ECMWF	API	High	Yes	Metres	
Wind Direction at street level						
Wind acceleration at top of canyon or building rooftop	ECMWF	API	High	Yes	Metres	
Wind acceleration						

at street level						
Wind turbulence at top of canyon or building rooftop	ECMWF	API	High	Yes	Metres	
Wind turbulence at street level						
Air pressure	ECMWF	API	High	Yes	Metres	
Wind temperature	ECMWF	API	High	Yes	Metres	
Solar Radiation	ECMWF	API	High	Yes	Metres	
Cloud cover	ECMWF	API	High	Yes	Metres	
Precipitation	ECMWF	API	High	Yes	Metres	
Relative Humidity	ECMWF	API	High	Yes	Metres	
Due	ECMWF	API	High	Yes	Metres	
Snow	ECMWF	API	High	Yes	Metres	

	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	
	ECMWF	API	High	Yes	Metres	

3.2.3 Atmospheric Turbulence

At very low wind speeds, the wind vortex in the canyon vanishes and turbulence created by the traffic flow will become significant in determining the highest pollution levels in a street canyon. In a street canyon, the flow of vehicles is generally dense and thus the turbulence field cannot be considered as a simple superposition of non-interacting vehicle wakes. For this reason, the vehicles in a canyon are considered as moving roughness elements. In Berkowicz et al.[39] it is shown that traffic-induced turbulence increases with the square root of the traffic flow and decreases with increasing canyon width. Apart from these parameters, knowledge of the number of vehicles passing the street per unit time and the average driving speeds of cars and heavy vehicles are needed. The flow regime within a street canyon is primarily determined by its geometry (e.g. height-to-width, (H/W), and length-to-height, (L/H) ratios). For wind flow across the street axis, Oke (1988)[40] distinguishes between 'skimming flow' with a characteristic vortex occurring for a relatively large H/W, 'wake intermediate flow' for intermediate H/W, and 'isolated roughness flow' for smaller H/W. As OSPM is a model designed for street canyons of aspect ratio close to 1.0 the model assumes an isolated roughness flow regime. As already explained, the Gaussian plume from local traffic within a street canyon of an aspect ratio of 1.0 is directly advected to the leeward side while on the windward side the impact is only from the air that has recirculated in the street for wind speeds greater than 2 $m\ s^{-1}$.

3.2.4 Temperature Prediction.

As previously mentioned, temperature is the key impacting factor on the levels of ozone O_3 with the ozone pollution levels showing great seasonality due to temperature. This code by Handford [31] uses historical data to predict the temperature for a specific location in the UK. This code could be implemented to predict general seasonality in temperature and therefore be utilised to predict any potential ozone spikes due to high temperatures. This a highly advanced domain with many accurate predictions produced in real time by European Centre for Medium Range Weather Forecasting, Met Office and other over a large area and within urban domains. The highly resolution prediction to street level are highly uncertain. There is a lack of measurement of temperature in a dense spatial domain. One option is to apply costly temperature modelling techniques either using gaussian methods or computational fluid dynamics methods. This can only be done for small zone and has its own sensitivities or uncertainties. This makes the heat island affect in urban zones difficult to analyse and therefor is lack of understanding and predictions of temperature at street levels in most cases.

3.2.5 Urban density

This is large impacting factor in how the air flows through an urban domain and how air pollution disperses. This is often why complex air quality modelling is required when urban density is complex and there is no available AQ sensors measurements to calibrate against. It is quite basic to measure with advent of GIS techniques and openstreetmap.org availability of urban density. There are still features about urban density that are of interest. Some of these are façade material of buildings, obstructions in transport routes, attachment to buildings, telephone cables, transport route signage and furniture. Many of these features are possible to extract through streetmap images and satellite imagery with computer vision techniques. The only limitation is the real time requirement from the analysis and sometimes the lack of high resolution imagery in real time.

Urban density						

Building heights	https://www.wudapt.org/, google, openstreetmap					
Aspect ratio of urban canyons						
Width of urban canyons						
Height of urban canyons						
Façade of buildings						
Pavement width						
Attachments to buildings	Street imagery	Computer Vision			Yes	
Road width						
Building morphology						

Road morphology						

3.2.6 Green Spaces

The green spaces have large benefits and impact on those in urban domain and the urban domain itself. There is large impact of green space on air pollution levels. Initially they reduce the emission because they limit traffic usage and promote non emission sources. They can also add chemical, biological and physical impacts on air pollution. The dynamics of the green space impact on air pollution is highly uncertain although it has been shown to be an overall positive to reduction in air pollution. In the majority the amount of green space needed to mitigation is often much larger than expected and feasible to implement. It main benefits and impact are to encourage reduction in emission. This is more affective as the main air quality experts state that the most effect reduction in air pollution is to erase the emission source not to mitigated air pollution. The majority of research is to identify the type of vegetation that positively impacts reduction in air pollution. Some sparse vegetation like some types of individual trees have been shown to allow air pollutant like PM to depose on the leave meaning it restricts the flow of the air pollution out of the urban zone. This then allow the air pollutant to recirculate and cause increased air pollution levels. So the main limitation is to determine the vegetation that benefits reduction in air pollution. The majority of these are hedges, parks and gardens.

3.2.7 Population usage

The usage of the domain impacts the exposure levels but can hinder air flows, increase CO2 emissions and cause more air pollution. It is often an indicator to more urbanisation which increases air pollution levels.

3.2.8 Land usage

The land usage is a factor in the type of emission and amount of emission along with potential for other impacting factors or green space, urban density etc… It is also the occupancy, social level and type of usage.

Social levels	https://data.unhabitat.org/pages/datasets, https://ghsl.jrc.ec.europa.eu/ucdb2018Overview.php				
Zone type	https://ourworldindata.org/urbanization				
Permanent or temporary residents					

3.2.9 Long range air pollutants

There are longer range air pollutants which occasionally can have a significant impact. These are dust storms, sand storm from sahara or desert regions. There are forest fires which have PM, NOx and Ozone impacts.

3.3 Application in Ventilation Systems

Though it may be difficult to refine the low cost AQ networks to be used in building legislation, there are many uses and applications for a low cost but accurate AQ network. One of these such applications is the use in ventilation systems for both citizen awareness and commercial efficiency. The general idea is that a ventilation system could link with a sensor network which interpolates and predicts duration of low and high air quality. This is done so the ventilation system can turn on and off to avoid venting in low quality air and also save money when opening windows can be used as a cheaper alternative.

3.3.1 Air Ventilation in City Units

Air ventilation units are common in urban buildings, such as offices and shopping centres, where the temperature, comfort and health of workers and clients is important. However, as previously mentioned, urban areas tend to have poor ambient air quality which would potentially be filtered into the inside spaces through the ventilation system. Therefore, a ventilation system only works at an optimum level when ambient air quality is good and a fully refined AQ sensing network could be utilised to monitor that [32].

An example of a company already implementing this is through the form of RESET created by ebm-papst neo. RESET offers a sensor based system which monitors and then communicates the levels of air quality around commercial buildings. This is done by implementing AQ sensors around the primary air units to asses the ambient air quality, which then sends data to the ebm-papst Building Connect Platform to be analysed. To analyse the AQ levels a few steps are taken which involves the air being pre-treated and sent to an air handling unit which mixes the air with the return air from the indoor space. The indoor air quality is then measured again using indoor AQ sensors and algorithms from the Connect Platform are implemented to learn from user behaviour and find general trends to optimise the indoor AQ levels whilst saving energy [33]. This technology clearly shares the aims of the potential application of the AQ sensor network. However it is too soon to judge the technology's use as it is still in its early days, with limited facilities, and hopefully in the future more AQ sensing ventilation systems can be configured which will give a clearer indication into its usability.

3.3.2 Domestic Ventilation Use

An application of the AQ sensing 'smart' ventilation system is for use in homes, both urban and suburban, to improve health. [34] has designed a system in which air quality sensors evaluate the, indoor and ambient, air quality around a home and feed real time information to a central computer system and then a mobile device, which controls the heating and cooling, ventilation system and windows. This is an example of another application for this system, which although would not be used in many homes due to its cost, could be an interesting evolvable system.

3.4 Application in Awareness

3.4.1 Applications in citizen science

The citizen science domain includes allowing citizen's to measure environmental factors, analysed and visualise these. It allows citizen to better understand environment or other scientific factors, the measurement and analysis of these. In air quality analysis it allows citizens to understand better:

- producing information on local air quality and the exposure of the population to air pollution;
- raising awareness of a local air quality problem to attract the attention of local or national authorities;
- complementing measurements taken by official air quality monitoring networks and helping improve air quality models; and/or
- generating experience of the use of low-cost measuring devices and networks of such devices

It also allows them to relate air pollution levels to their situations, exposures and to their impact. It further educates citizen and leads to citizen having a large role in environmental science and potentially doing further analysis.

3.4.1.1 Citizen science organisations

3.4.1.1.1 HackAir

hackAIR is an open technology platform that you can use to access, collect and improve air quality information in Europe. It was created by six European organisations as part of an EU-funded project on 'Collective Awareness Platforms for Sustainability and Social Innovation' (2016-2018). It includes an open app, web platform, mobile sensor and repository management. **https://www.hackair.eu/open-air-quality-datasets/**

3.4.1.1.2 AirSensEUR

AirSensEUR is an open framework focused on air quality monitoring using low cost sensors. The project started on 2014 from a group of passionate researchers and engineers. The framework is composed by a set of electronic boards, firmware, and several software applications. AirSensEUR aims to implement a low cost, battery operating, accurate air quality monitoring system to: Sample a set of chemical sensors like, for example, O3, NO, NO2, CO and SO2 from several manufacturers including AlphaSense, City technology, Membrapor and SGX SensorTech; Sample a set of auxiliary sensors for temperature, pressure and relative humidity; Aggregate samples with optional GPS localized information; Store aggregated samples in a local database; Periodically update an external server through WiFi or GPRS channels.

3.4.1.1.2 senseBox

The three different modular senseBox kits are ideal for use in digital education, citizen science and for professional environmental data collection. An easy-to-program microcontroller forms the basis and many different sensors can be connected directly to create an individual environmental measuring station. Versatile modules enable data transmission to an Internet platform from almost any location. The product can sense CO2, PM with temperature and humidity.

The senseBox: edu is designed for use in schools to bring students closer to the world of microcontrollers and programming through examples from the field of the environment. It offers the largest range of hardware and thus enables a huge selection of projects and experiments . All components are in a robust plastic case with a foam insert. The senseBox: edu is therefore perfectly equipped for use in school.

Pollution Explorers Toolkit

Pollution Explorers Toolkit (PET) is a toolset and community engagement methodology designed for people to act collectively on air quality issues.

The community is activated through a series of workshops in which participants explore their collective responsibility and agency in tackling air pollution and environmental issues, using wearable devices along a series of specific routes around their neighbourhoods. Participants make sense of the impact they have on the environment, share experiences and motivate each other in committing to tackling air quality issues through their own actions. https://umbrellium.co.uk/projects/pollution-explorers-toolkit/

Clean Air for Schools Framework

The Clean Air for Schools Framework is a free, online tool to help every school create a tailored clean air action plan to tackle air pollution in and around the school.

The framework is designed to help your school to:

- Reduce air pollution from your own operations
- Tackle air pollution at the school gate, including the school run
- Educate the next generation to help them and their families make cleaner air choices.

  Become a local leader on air pollution, working with local partners to improve air quality in the local are

https://www.transform-our-world.org/clean-air-for-schools

3.4.1.1 Citizen science experiments in Schools

St Annes Lambeth London UK

Our project is now nicely up and running. Our 7 Air Ambassadors are enjoying their role working alongside Holly from Sustrans.

They have:

- Situated diffusion tubes around the school to measure air quality

- Led an assembly to share with the children what has been happening
- Put up a display to advertise the project

https://st-annes.lambeth.sch.uk/air-quality-project/

Mapping for Change

Mapping for Change is working with pupils and teachers to monitor nitrogen dioxide levels around each school using citizen science. https://communitymaps.org.uk/project/air-quality-monitoring/contribution/41230?center=55.8670:-4.2652:17&tab=1

GLOBE Ireland Air Quality Campaign 2020/21

The GLOBE Ireland Air Quality Campaign is a citizen science project to measure and assess nitrogen dioxide (NO2) air pollution at schools in Ireland. This is an educational project designed to raise awareness about traffic-related air pollution and showcase the potential of citizen science to gather unique datasets and insights into our environment. There have been 5 Air Quality campaigns since 2019, overall participation in the campaigns has increased year-on-year, from 31 schools taking part in the inaugural campaign in February 2019, to 112 schools in April 2021.

There was a total of 165 schools participating in the Air Quality campaign this 2020/21 academic year, compared to 103 in the previous 2019/2020 academic year. 53 schools took part in the October 2020 campaign and 112 schools participated in the April 2021 campaign

The April campaign saw a 100% increase in registrations compared to the October campaign, this included a large increase in primary school participation, from 11% of schools in October to 33% of schools in April. Twenty-four counties of Ireland were represented by participating schools in this campaign, an increase from previous campaigns and highlighting the level of interest in air pollution at a national level.

The campaign focuses on the measurement of nitrogen dioxide (NO2) outdoors at three locations on school grounds. A total of 412 valid NO2 (µg/m3) measurements were recorded for the October 2020 and April 2021 Air Quality campaigns.

https://www.globe.gov/web/ireland/home/overview-of-air-quality-campaign/about

LetSchoolbreathe

Airly, we provide air quality monitoring solutions for schools and local governments around the world. We do this through networks of affordable outdoor air quality sensors that we display for anyone in the world to view for free through our online map and mobile application. We currently operate in over 30 countries and deliver real-time air quality data to millions of people worldwide. https://airly.org/en/let-schools-breathe/

3.5 Advocacy

3.5.1 Influencers

3.5.1.1 General Influencers

Extinction Rebellion UK 75.4K Twitter Followers

Slogan: HE CRISIS IS HAPPENING NOW, THE GOVERNMENT IS FAILING TO and COME TO THE TABLE: LET'S PULL TOGETHER https://twitter.com/XRebellionUK

UK100 4,674 Twitter Followers 2 daily tweets

The only network for highly ambitious UK locally elected leaders committed to cleaner, more powerful communities. UK100.org

3.5.1.2 Air Quality Advocacy

Little Ninja UK 4,559 Twitter Followers 4 daily Tweets

Children are exposed to five times more #airpollution during the #schoolrun. Highest level on main roads & near #idling vehicles = stunted lung & brain growth https://www.littleninja.co.uk/

Dr Claire Holman (Air Pollution Services)

See AQ consultants

Air Quality News

The leading AQ news media with weekly publications for free and premium publications along with two annual awards conferences. https://airqualitynews.com/

UK Clean Air Champion Dr Gary Fuller (Imperial College London)

Clean Air in London 41.4K Twitter Followers 2 Daily Tweets Simon Birkett as Founder and Director of Clean Air in London cleanair.london

Clean Air 2 Breathe 3,799 Twitter Followers 4 daily Tweets

SREnvironment 5,731 Twitter Followers 1 daily Tweets UN Special Rapporteur on human rights and the environment, UBC professor, and environmental optimist

Dr Maria Neira 19K Twitter Followers 3 Daily Tweets WHO Director, Public Health, Environmental and Social Determinants of Health.

3.5.1.3 Air Quality Measurements

3.5.1.4 Air Quality Exposure

3.5.1.5 Air Quality Impact

3.5.1.6 Air Quality Mitigations

3.6 Air Quality Consultancy

This is mostly within the domain of completing Air Quality modelling assessment at specific sites for regulators, advocates, constructors or managers.

3.6.1 Project Based Outdoor AQ Consultancy

3.6.1.1 Air Pollution Services Dr Claire Holman

The services are Air Quality Assessments, Odour Assessments, Climate Change Assessments, Indoor AQ Assessments, Ecosystem Assessments. Air Pollution Services (APS) is an independent Bristol UK based professional environmental consultancy, specialising in air quality, odour, meteorology and climate change. We have a proven track record of providing unique solutions to support clients with complex projects and lead the way professionally, maximising technical knowledge with efficiencies to ensure clients timescales are achieved. https://www.airpollutionservices.co.uk/about-aps/

3.6.1.2 Air Quality Assessments Ltd

Air Quality Consultant providing Dust, Odour & Air Quality Assessments established in 2014, is based in the South West, and provides specialist ambient air quality advice and services to clients across the UK. The services are Planning Application Support, Environmental Permit Support, Air Quality Modelling, Air Quality Monitoring, Dust Assessment, Odour Assessment. https://aqassessments.co.uk/services

Chapter 4

Impact of Research

4.1 Similar Research

There is a large amount of research in air quality dataset and analysis. From the cause to impact of air pollution there are many domains. Additionally mitigations are research domain to reduce air pollution. Much of the cause research is in emission sources of vehicles and static emitters. The impacting factors research is in atmospheric sciences along with social sciences. The large majority of research on impact is in the health sciences from exposure studies to epidemiology to health impacts studies. There is further research in the urban system, mitigations and built environment on impact of air quality levels. There is further research in air quality measurement from high quality devices to citizen science and awareness initiatives.

4.1.1 Air Quality Experts

Professor William Bloss (University of Birmingham)
UK Clean Air Champion Dr Gary Fuller (Imperial College London)
David Milner (Create Streets)
Prof Sir Stephen Holgate SPF Clean Air Champion
Dr Jenny Baverstock University of Southampton SPF Clean Air Champion
Dr Noel Nelson The Met Office
Professor Gavin Shaddick, University of Exeter
Dr Ian Mudway Imperial College London
Professor Marta Blangiardo Imperial College London
Professor Catherine Noakes University of Leeds
Dr Bethan Davies – Imperial College London
Dr Matthew Hort – The Met Office
Professor Anna Hansell - University of Leicester
Professor Aziz Sheikh – University of Edinburgh
Dr Paul Young – Lancaster University
Kieran Laxen (Air Pollution Services)

Oliver Puddle (DustScanAQ)
Chris Rush (Hoare Lea)
Peter Walsh (WSP)
Roger Barrowcliffe (Clear Air Thinking)
Ethny Childs (Secretary, IES)
Emma Gibbons (UCL)
Dr Hywel Davies (CIBSE)
Dr Sani Dimitroulopoulou (Public Health England)
Dr Vina Kukadia (University of Surrey)
Dr Gráinne McGill (University of Strathclyde)
Dzhordzhio Naldzhiev (University College London)
Dr Clive Shrubsole (University College London)
Dr Marcella Ucci (University College London)
Stuart Upton (Building Research Establishment)
Edwin Wealend (Cundall)
Carl Hawkings (ADM Ltd)
Dr Christine McHugh (Keane & Gray)

4.1.2 Emission sources

4.1.2.1 TRANSITION Clean Air Network

Interdisciplinary network undertaking innovative research to address emerging indoor/outdoor air quality challenges across UK surface transport. It is led by the University of Birmingham in collaboration with nine universities and over 20 cross-sector partners, which seeks to deliver air quality and health benefits associated with the UK transition to a low-emission transport economy. The academic investigators and policy, public, commercial and not-for-profit sector partners will undertake joint research, to co-define indoor and outdoor air quality challenges and co-deliver innovative, evidence-based solutions. The programme is funded through a £0.5 million UKRI (UK Research & Innovation) investment administered by the Natural Environment Research Council (NERC). The funding is part of the Clean Air Strategic Priorities Fund (SPF) Clean Air Programme which supports high quality multi- and interdisciplinary research and innovation linked effectively with government research priorities and opportunities.transition-air.org.uk

Atmospheric science

4.1.3 Social Science

4.1.4 Exposure Studies

Airless

AIRLESS project which aims to draw more reliable associations between personal exposure to air pollutants and adverse changes in cardiopulmonary responses and health outcomes during the heating and non-heating seasons in urban and rural settings in Beijing. Three main methodological novelties are employed in the project:

- the detailed assessment of personal exposure to air pollution in diverse indoor and outdoor environments
- the integration of time-activity profiles and activity-dependent inhalation rates to derive precise dose estimations
- a comprehensive collection of medical biomarkers to understand the underlying mechanisms of health responses to air pollution exposure.

BioAirNet

Taking a transdisciplinary approach to understand the complexity and connectivity among people, biological particulate matter (BioPM) exposure and health impacts across the indoor/outdoor continuum to inform interventions development, prioritisation and assessment of environmental and health interventions. www.bioairnet.co.uk

https://www.aeroqual.com/case-studies/university-of-birmingham

4.1.5 Epidemiology studies

4.1.6 Health Impact studies

4.1.7 Urban Systems

4.1.8 Mitigation of air pollution

4.1.8.1 Schools

Tackling Air Pollution at School

TAPAS is a multidisciplinary network designed to bring stakeholders together from across society to develop the research base to design and operate healthy schools now and in the future. Our aim is to build collaboration and discussion via our events programme, our working groups, our research fund, and by engaging directly with children, schools and parents. www.tapasnetwork.co.uk

4.1.8.2 Vulnerable Groups

Cleanair4V

Identifying, developing, and evaluating robust solutions that reduce the impact of indoor air pollution on two vulnerable groups: children, and those with pre-existing conditions such as COPD. A multidisciplinary approach is taken focusing technological and behavioural intervention. www.birmingham.ac.uk/cleanair4v

4.1.9 Built Environment

Breathing City

Coupling indoor and outdoor air flows to enable a new integrated health evidenced approach to urban building design and technology innovation. Bringing together researchers, practitioners and policy makers to develop a programme of research and impact activities. www.breathingcity.org

4.1.10 AQ Measurement

4.1.11 Awareness initiatives

STFC Air Quality Network

Bringing together research, industry and policy to address air quality challenges using the untapped potential of the Science & Technology Facilities Council. www.saqn.org

4.2 Trajectory of Research

4.2.1 Health impact

4.2.2 Economic impacts

4.2.3 Social impacts

4.2.4 Mitigation impacts

4.2.5 Re design impacts

4.3 Impact on commercial Products and Services

4.3.1 AQ measurement

4.3.2 AQ Modelling

4.3.3 AQ Awareness

4.3.4 Individual's exposure

4.3.5 Individual's impact

4.3.6 Regulations

4.3.7 Health impacts

4.3.8 Causation correlation impacts

4.3.9 Insurance impacts

4.3.10 Product re designs

Chapter 5

Air Quality Analysis

5.1 Statistical Analysis

5.2 Prediction Analysis

5.3 Geospatial Analysis

Chapter 6

Analysis of Causation

6.1 Method to evaluate causations

6.2 Causations from impacting factors

6.3 Trajectory to reduce uncertainty of causations

Chapter 7

Review of Mitigations

7.1 Overview of Mitigations

7.1.1 Economic incentives

Some possible mitigations are:

- **financial incentives** for implementing cleaner technologies from non-toxic dry cleaning machines to new or retrofit engines for heavy-duty on-road trucks,
- **emission reduction** through innovative regulations,
- **raising the profile of clean products** such as solvents and commercial products through certification,
- **identification of other clean air products** and equipment that can be used by businesses large and small to help improve air quality,
- **compliance assistance** through South Coast AQMD-sponsored training
- **small business assistance** to help those businesses with regulatory requirements

RECLAIM South Coast AQ US

RECLAIM uses the power of the marketplace to reduce air pollutants from stationary sources, an approach to air quality regulation that has the potential to clean up our air more effectively than traditional regulations. For businesses, RECLAIM means greater flexibility and a financial incentive to reduce air pollution beyond what clean air laws and traditional command-and-control rules require. For the public, RECLAIM means guaranteed annual reductions in air pollution until public health standards are achieved.

Each firm participating in RECLAIM receives RECLAIM trading credits (RTCs) equal to its annual emissions limit. Facilities must hold credits equal to their actual emissions, but they can sell excess credits to firms that cannot or choose not to meet their limits. Because businesses are different, some can reduce emissions more easily and at less cost than others. Credits are assigned each year and can be bought or sold for use within that year. No matter who buys or sells credits, RECLAIM requires that total emissions from all participating companies be reduced each year.

http://www.aqmd.gov/home/programs/business/business-detail?title=reclaim

7.1.2 Driver behaviour change

7.1.2.1 Reduce Idling of vehicles

7.1.2.1.1 NYC Complaint and Bounty Reward Scheme

Idling emissions from gasoline and diesel motor vehicle engines are known contributors to health related impacts, including asthma, respiratory and cardiovascular harm. Idling for longer than three minutes or more than one minute while adjacent to a school is illegal in the US. Idling complaint can be issued for trucks that are used or maintained primarily for the transportation of property and buses that have seating capacity of 15 or more passengers in addition to the driver and used for the transportation of persons. However, there are exceptions for when a citizen can file a complaint against a truck and bus.

https://www1.nyc.gov/site/dep/environment/idling-citizens-air-complaint-program.page?question=faq11

7.1.3.1 Installations

7.1.3.1.1 Road installations

GRAMM is the UK leading specialist in the design, supply & installation of environmental acoustic barriers with over 20 years of experience. We have constructed literally 1,000's of Km's of acoustic barriers of all types of materials throughout the UK and Europe. SmogStop Barrier reduces air and noise pollution levels in surrounding neighbourhoods, and takes a two-pronged approach to reducing air pollution from major roads, highways and railways. https://www.smogstop.co.uk/

7.1.4.1 Clean air Zones

There are several initiatives already in place to help tackle many of the sources of air pollution - for example, London's Ultra Low Emission Zone (ULEZ). A further five councils across the UK are also set to introduce Clean Air Zones (CAZs) having been identified by a DEFRA study to identify cities in the UK which were likely to miss EU air quality targets by 2020. Such schemes are highly effective in targeted locations to incentivize and/or regulate driver behaviour. Clean Air Zones are part of a broader strategy to improve the air we breathe but also improves the way we move around our cities.

Yunex Siemens

Yunex Traffic provided the TfL ULEZ enforcement system in London on a Design, Build, Operate and Maintain basis, covering both the roadside equipment and central IT instation. A central IT instation service management centre is operated on a 24/7, 365 days a year basis by a dedicated Yunex Traffic team with our maintenance engineers providing local 1st and 2nd line support. 3rd line support is provided by technical experts at Siemens Mobility in Poole, UK.

The system is integrated with the roadside sensors and ANPR cameras which form part of TfL's existing Congestion Charging scheme. ANPR cameras identify and register every vehicle that enters the ULEZ - 24 hours a day, 365 days a year. This information is then transmitted to a dedicated and secure Yunex Traffic data centre, where our ULEZ instation software determines the compliance of the vehicle. https://www.yunextraffic.com/uk/en/portfolio/clean-air-zones

7.1.5.1 Traffic Management

7.1.5.1.1 Traffic light optimisation

Yunex Siemens Stratos Traffic Management

Make meaningful and timely interventions through our Stratos traffic management system to implement strategies based on reliable pollution data and prevailing air quality levels.

Yunex Siemens SLD4 single loop classification in Nottingham

This detects lorries or LGV or buses and gives priority in traffic lights or junctions to reduce stop start in traffic flow and therefor reducing air pollution. We have worked with Highways England on an advanced trial for large vehicle classification enabled by a single in-road loop using the SLD4 detector. The trial successfully reduced the number of large vehicles stopping, ultimately leading to potential air quality improvements.

7.1.6.1 Clean Air Day

7.1.6.1.1 International Clean Air Day

ICADis recognized by the United Nations (UN) as a part of their UN Environment Program initiative. The day is observed on September 7 every year, and this year will be the 2nd year of the event.

The general theme of the event is “Clean Air for All,” which is also a sustainable development goal. The event brings together various countries, governments, and nonprofits to increase awareness of air pollution and discuss actionable steps to reduce it.

7.2 Framework to analyse mitigations

7.3 Trajectory of mitigations

7.3.1 EU to 2050

7.3.1 Overall in EU to 2050

7.3.1.1 Overview

As mentioned in the European Green Deal , creating a toxic-free environment requires more action to prevent pollution from being generated as well as measures to clean and remedy it. To protect Europe's citizens and natural ecosystems, the EU needs to better monitor, report, prevent and remedy pollution in the air, water, soil and consumer products. This will also contribute to achieving the Sustainable Development Goals. The EEA 'Air quality in Europe - 2020 report' published in November 2020 shows that, although emissions of most air pollutants have declined in the EU in recent decades (see figure 1), air pollution continues to be a significant problem. Air pollution overall is responsible for about 400 000 premature deaths in the EU every year and for about two-thirds of ecosystem area in the EU being exposed to eutrophication 2 . Air pollution also entails considerable economic costs by inducing increased medical expenses, reduced productivity, for example through lost working days, and reduced agricultural yields.

7.3.1.2 EU enforcement

The EU's approach to improving air quality rests on three pillars. The first pillar comprises the ambient air quality standards set out in the Ambient Air Quality Directives for ground-level ozone, particulate matter, nitrogen oxides, dangerous heavy metals and a number of other pollutants 3 . If the set limit values are exceeded, Member States are required to adopt air quality plans detailing measures to keep the exceedance period as short as possible.

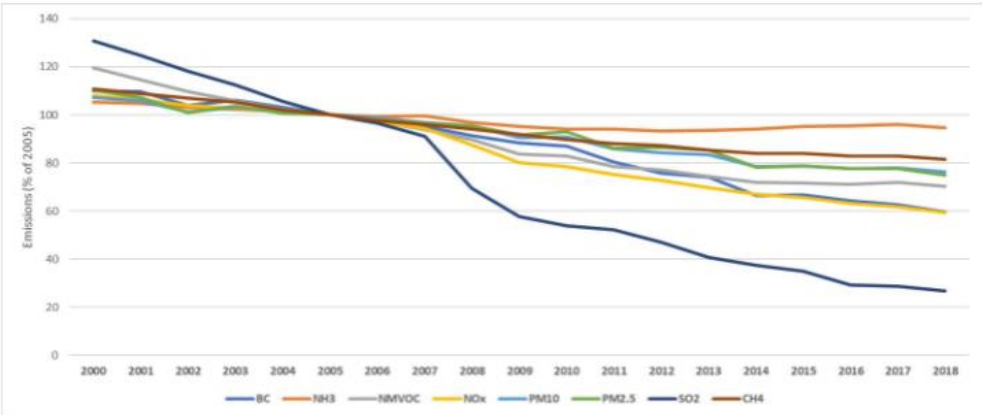
The second pillar consists of national emission reduction obligations set by the National Emission reduction Commitments Directive (NEC Directive) 4 for the most important transboundary air pollutants: sulphur dioxides, nitrogen oxides, ammonia, non-methane volatile organic compounds and particulate matter. Member States had to develop national air pollution control programmes (NAPCPs) by 2019 presenting the measures they will put in place to comply with their emission reduction commitments.

The third pillar comprises emission standards for key sources of pollution, from vehicle and ship emissions to energy and industry. These standards are set out at EU level in dedicated legislation.

7.3.1.3 EU AQ Since 2005

Since 2005 (the base year for emission reductions under the NEC Directive) and even before, emissions of air pollutants in the EU have decreased significantly thanks to EU and national legislation 12 . In fact, since 2000 the EU's GDP has grown by about 30% while emissions of the main air pollutants have decreased by 10% to 70%, depending on the pollutant. The figure below show the EU28 emissions reduction from 2000 to 2018 that is reported.

Figure 1: Development of EU-28 emissions, 2000-2018 (% of 2005 levels) (Source: EEA)



When it comes to air quality, there have been significant improvements over the past decade, yet there are still major problems with exceedances of the EU's air quality limit values under the Ambient Air Quality Directives. For 2019, 23 Member States reported exceedances above at least one air quality standard, for at least one pollutant, in at least one location – this includes 17 Member States with exceedances of EU air quality standards for NO2, 14 with exceedances for PM10, four with exceedances for PM2.5 and one for SO2.

As of 1 December 2020, a total of 31 infringement cases against 18 Member States are ongoing for exceedances of PM10, PM2.5, NO2 or SO2 concentration levels or flawed monitoring. Ten of these cases have been referred to the Court of Justice of the European Union, of which five cases have received a ruling. In its Communication on 'Cleaner Air For All' in May 2018, the Commission underlined the importance of continued enforcement

7.3.1.4 Most effective Mitigations

The modelling exercise under this Clean Air Outlook has identified the most cost-effective air pollution control measures that would allow all Member States to fulfil their commitments under the NEC Directive, even without taking into account possible synergies with climate measures. For SO2, PM2.5 and NOx, they mostly relate to measures in industrial processes and industrial combustion. To reduce NMVOC, the large majority of the cost-efficient measures would tackle emissions from the burning of biomass for domestic heating and, to a lesser extent, from the use of solvents. The measures that would cut ammonia emissions in the most cost-efficient manner all relate to agriculture and are, to a large extent, related to animal feeding practices, manure management and use of fertilisers. Member States committed in December 2018 to climate and energy targets for 2030 34 , which require appropriate policies and measures to be put in place. With those measures and the application of existing legislation tackling air pollution at its source, the reductions in all air pollutant emissions required by the NEC Directive across the EU would be fulfilled for the period from 2030 onwards, except for ammonia. This hides, however, differences between Member States in achieving their national commitments.

7.3.2 UK to 2050

7.3.2.1 UK Decarbonisation strategy report

An academic review stated it “promotes technological innovation to reduce emissions per vehicle but does not substantively address the social, behavioural and planning changes needed to reduce total vehicle use in both urban and rural areas. Whilst seeking to reduce carbon emissions in response to legally binding net zero commitments, the Plan fails to fully capitalise on the opportunities – via modal shift – to improve air quality and deliver wider societal public health benefits. The fundamental shortcoming of this approach for improving air quality (i.e., achieving cleaner, healthier places to live, work and visit) is two-fold: vehicle electrification only removes exhaust emissions, and it risks displacing pollutant emissions elsewhere, for example in the supply and energy distribution chain (if all of our electricity demands are not met by clean, renewable sources). Despite being misleadingly dubbed ‘zero emission vehicles’ (as they do not themselves emit tailpipe CO2 and NO2 pollutants), electric vehicles (EVs) continue to emit harmful, fine particulate matter (PM2.5) from tyre, brake and road wear, and dust resuspension. PM2.5 is recognised to be the air pollutant of greatest harm to human health, responsible for approximately 1 in 20 premature deaths in England, equivalent to an average reduction in life expectancy of up to 6 months. Unless action is taken, the contribution of non-exhaust emissions (NEEs) to total PM2.5 is expected to increase over the next decade, in part due to the increased weight of EVs (laden with heavy batteries). To build on recent, hard-won reductions in PM2.5 emissions arising from cleaner vehicle fleets, attention must be paid to reducing NEEs – in addition to exhaust emissions for carbon mitigation."

Chapter 8

Management of Air Quality

7.1 Overview of Management

7.1.1 Requirements

7.1.2 Feasibility

7.1.3 Existing management

7.2 Setup of Monitoring and reporting

7.2.1 Setup of monitoring network

7.2.2 Reporting of AQ measurements

7.3 Framework to manage air quality

7.3.2 Managing network of AQ sensors

7.3.2 Awareness of air quality levels

7.3.2 Installing mitigations

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