What Lurks Below: Air Pollution on the London Underground

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Hereby declare (a) that this dissertation is my own original work and that all source material used is acknowledged therein; (b) that it has been specially prepared for a degree of King's College London; and (c) that it does not contain any material that has been or will be submitted to the Examiners of this or any other university, or any material that has been or will be submitted for any other examination.

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Date: March 29th 2016

Abstract

Air pollution on belowground sections of the London Underground was investigated using a portable sensor rig. Particulate matter below 10 um (PM_{10}), Ozone, Nitric Oxide, Nitrogen Dioxide and Carbon Monoxide were sampled across the entirety of the belowground sections of the London Underground in order to determine spatial trends and assess public health risk. A variety of weak spatial trends were identified. Additionally, levels of $PM_{2.5}$ found exceeded WHO recommendations by 25 times on average across deep tunnels, showing the need for a thorough investigation into what is clearly a potential health hazard.

Acknowledgements

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Abbreviations

CAL- Cleaner Air in London

COMEAP- Committee on Medical Effects of Air Pollution

HSE- Health and Safety Executive

IOM- Institute of Occupational Medicine

ISB- Individual Sensor Boards

LAQN- London Air Quality Network

PM- Particulate Matter (Aerosols)

PM_x- x represents particle diameter in um

TfL- Transport for London

WHO- World Health Organisation

Introduction

Air pollution is an insidious and underreported public health threat. The World Health Organisation estimates that tropospheric air pollution is responsible for 3.7 million premature deaths annually worldwide (WHO, 2014), with alternative estimates placing the annual death toll at 1.6-4.3 million (Lelieveld, *et al.,* 2015) Research conducted in the USA estimates air pollution is responsible for 134,700 premature deaths annually, with the risk substantially higher in large urban areas such as Los Angeles, where 10% of deaths can be attributed to air pollution (Fann *et al.,* 2011), while other regions fare much worse, such as China where an estimated 1.6 million annual deaths are directly caused by contaminated air, primarily in the urban corridor between Beijing and Shanghai, representing 17% of total deaths in the country (Rohde & Muller, 2015). As the global population becomes increasingly urbanised, the number of people exposed to dangerous air pollution will only increase. According to the UN, in 2014 54% of the global population resided in urban areas; by 2050 this proportion is expected to increase to 67% (UN Department of Economic and Social Affairs, 2014). Compounding this increase in exposure, is the expectation that business as usual emissions scenarios will increase air pollution mortality worldwide by a factor of two by 2050 (Lelieveld, *et al.,* 2015). However, air pollution exhibits great spatial variation both on regional and city-wide scales (London Air, 2016). It is crucial to understand this variation in order to identify and mitigate hotspots of particularly high exposure rather than simply looking at global or regional trends. Within the UK specifically, approximately 29,000 annual deaths can be attributed in part to air pollution (COMEAP, 2009). An area of particular concern in the UK is London, the capital and by far largest population centre. Previously nicknamed the “Big Smoke” due to abysmal air quality, London has seen significant progress in reducing air pollution in recent decades; the 1993 Clean Air Act was crucial in eliminating “dark smoke” by regulating fuel composition, chimney height and furnace construction and vesting enforcement powers in local authorities (The National Archive, 1993)(Cleaner Air for London, 2016). However, while major progress has been made in improving air quality in general, London’s iconic Underground Network may represent a significant pollution sink and source, with little public or scientific understanding of the risk posed. Transport for London and the London Mayor’s Office have made repeated assurances that air quality on the Tube is safe (Greater London Authority, 2013) (Transport for London, 2007,2005,2013). However, there is reason to question the veracity of this assertion based on both conflict of interest and interpretation of findings from previous investigations.

Background

Air Pollution

Air pollution can be roughly divided into gaseous pollution -such as NO_2 from exhaust- and aerosolised particulate matter that can form from sources such as combustion reactions and (specifically in regards to this investigation) the brake systems of underground trains.

- Particulate Matter/Aerosols

Particulate matter (PM) is classified by the diameter of particles, with particles below a diameter of 2.5 um ($PM_{2.5}$) considered dangerous to respiratory health. There is broad scientific consensus that particles below 2.5 um in diameter, particularly "ultra-fine" particles below 1 um diameter pose a threat to public health. Chronic exposure to PM2.5 has a myriad of negative effects on the respiratory system, including cytotoxia, inflammation of bronchioles, increased stroke risk, increased risk of emphysema, increased risk of lung cancer and increased all-cause mortality (WHO, 2013). No lower threshold has been identified for health impacts from chronic exposure, with health risk simply increasing linearly with exposure (WHO, 2013). A number of studies point to a 6-9% increase in all-cause mortality per 10 um/m^3 increase in $PM_{2.5}$ (Shi *et al.,* 2016)(COMEAP, 2009,2010).

The health impact of larger particles in the 2.5-10 um range is less clear. Particles below 2.5 um can penetrate to the gas exchange surfaces within alveoli, preventing them from being easily expelled, while inhaled particles above 10 um are typically captured and expelled by cilia and mucus before reaching the lungs. (Nieuwenhuijsen, 2003) However, particles in the intermediate range, "thoracic particles" are able to enter the bronchi and may still have negative consequences for respiratory health (Nieuwenhuijsen, 2003). Researchers are divided on the question of whether $PM_{2.5.-10}$ pose a public health risk; Peng *et al.* (2008) found no statistically significant link between deaths or hospitalisations and $PM_{2.5-10}$ after correcting for $PM_{2.5}$, while Beelen *et al.* (2008), Krewski *et al.* (2009), and Pope *et al.* (2002) found statistically significant mortality increases with higher $PM_{2.5-10}$ concentrations, although these effects were minor compared to the impact of $PM_{2.5}$; Loxham *et al.* (2015) determined that while $PM_{2.5-10}$ is somewhat protected against by the body's natural defences, coarser particulates may still be absorbed into cells with oxidative effects. Both the UK and EU government have concluded that $PM_{2.5\text{-}10}$ do pose public health risks (COMEAP, 2010)(European Commission, 2015).

Both $PM_{2.5}$ and PM_{10} are largely caused by combustion reactions and are strongly associated with road traffic. In London, and many other major cities, this leads to a spatial distribution of generally higher aerosol concentrations in central areas, as well as localised high readings along major transport arteries (London Air, 2016).

- Gaseous

Direct health impacts of gaseous pollution are often ignored due to the focus on greenhouse gas emissions and climate change when considering emissions standards. However, a number of gaseous pollutants have been identified as directly harmful to human health.

a. Ozone

Tropospheric ozone (O_3) is linked to increased mortality, with a number of time-series studies demonstrating that exposure aggravates underlying respiratory illnesses such as asthma and chronic obstructive pulmonary disease (Weinhold, 2008)(Lelieveld *et al.,* 2013)(Fann *et al.,* 2011). Thus, O_3 has a disproportionate effect on the elderly (Fann *et al.,* 2011). Some studies have linked O_3 to additional cardiovascular diseases, but there is a lack of consensus on this conclusion (Weinhold, 2008). O_3 is rarely produced directly by human activities, and is instead formed by the interaction of NO_2 and other emitted gasses reacting with sunlight. According to the London Air research group, the southeast of England has the highest baseline levels of O_3 in the UK due to proximity to continental pollution sources. However, Central London has lower levels, as other exhaust products react with O_3 and degrade it (London Air, 2016). Additionally, O_3 can form from breakdown of molecular oxygen (O_2) by electrical discharges; it is possible that the electric rails on the underground network facilitate this process and act as a production source (Arc Suppression Technologies, 2011).

b. Nitrogen Oxides

Nitrogen oxides (NO, NO_2) have similar health effects to O_3, irritating airways and reducing immunity to respiratory infections, and similarly disproportionately affect those with underlying respiratory health conditions and the elderly (Weinhold, 2008). However, about half of nitrogen oxides are produced by automotive transportation, meaning that levels are much higher in the centres of urban areas and near roads (London Air, 2016). This association is potentially concerning for the Tube, as ventilation shafts are often located along major roads. Typically, surface levels of NO_2 vary inversely with O_3 due to the fact that NO_2 is an O_3 precursor; NO_2 breaks down into an NO molecule and a free oxygen atom in the presence of sunlight. This free O combines with molecular oxygen (O_2) to form O_3 (Han *et al.,* 2010). There is no existing literature on how this relationship may change in underground systems that are unaffected by sunlight. NO_2 and O_3 have also been shown to have a co-interactive effect on human health; that is people exposed to O_3 and NO_2 simultaneously suffer health impacts greater than the expected sum of the typical effects of the two gasses. Current medical theory explaining this effect is that the two gasses react in the body to form N_2O_5 and HNO_3, both of which are cytotoxic (Gamon *et al.,* 2014).

c. Carbon Monoxide

Carbon monoxide (CO) is an extremely dangerous gas that is produced by combustion reactions. CO has a much higher affinity for haemoglobin than O_2, bonding permanently to the molecule's active sites and preventing its use in O_2 exchange, with obvious negative health effects (Kao and Nañagas, 2006). Acute CO exposure of 5000 ppm can be lethal to humans in as little as 5 minutes, however chronic exposure of 10 ppm can cause neurological problems in otherwise healthy individuals as well as aggravating underlying respiratory illnesses (Goldfrank, 2002). The introduction of catalytic converters in automobiles has significantly reduced CO levels in London, and London Air no longer considers chronic exposure a health risk in London (2016).

- Regulatory Standards

At the time of writing, there are no published air quality guidelines for underground subway systems such as the London Underground. However, many countries and organisations have published recommended aboveground air pollutant exposure guidelines for both acute and chronic exposures to specific pollutants, as well as daily air quality indices combining multiple factors.

Great Britain's Health and Safety Executive (HSE) is responsible for both setting and enforcing regulation on workplace exposure to toxins, carcinogens and other threats to worker safety, including various forms of aerosol and gaseous health threats. However, in regards to both $PM_{2.5}$ and PM_{10}, HSE have declined to set limits on chronic exposure levels, instead setting only an acute limit of 4,000 ug/m^3 for $PM_{2.5}$ and 10,000 ug/m^3 for PM_{10} for a single 8-hour shift, set in 1998 (HSE, 2005). These levels are both extremely high, and are designed for industrial processes where breathing protection is common, such as welding, milling and smelting. However, the HSE guideline is the only legally binding regulation that TfL is subject to, as more stringent EU limits on surface air quality are not applied underground and there is no day-to-day monitoring. The Institute for Occupational Medicine (IOM) has recently revised its opinion on the HSE limits, concluding that British regulations for dust are unsafe and should be reduced by at least 75% for acute 8-hour limits (Institute of Occupational Medicine, 2011). The WATCH committee of the HSE was instrumental in the revision of the IOM opinion; however, the UK's national regulations have not been updated to reflect modern medical opinion as of 2016.

EU air quality regulations address ground-level pollutant exposure, given in daily exposure averaged over a year. These limits are largely line with the WHO recommendations for minimising exposure. $PM_{2.5}$ was targeted to be below 25 ug/m^3 in 2010, becoming a binding limit in 2015; PM_{10} was limited to 40 ug/m^3 in 2005; NO_2 was limited to 40 ug/m^3 in 2010; O_3 does not yet have an annual average in EU regulations, instead being limited to an 8-hour average of 120 ug/m^3, however, the WHO recommends a threshold of 108 ug/m^3(European Commission, 2015)(WHO, 2014). However, the WHO advocate a lower limit of 10 ug/m^3 for $PM_{2.5}$ as annual average based on the preventative principle and a lack of an identified lower threshold for health impacts (WHO, 2014).

However, for particulates specifically, EU/WHO guidelines simply do not correspond to the HSE limits; a worker operating at the HSE $PM_{2.5}$ limit would exceed the exposure allowance proscribed by the EU/WHO limits in a mere 7 8-hour shifts. Despite this, TfL treat the HSE guideline as a daily limit, noting in a press release on underground dust levels, "levels are consistently below the HSE workplace exposure limits for general dust (4 mg/m3)" (TfL, 2013:1). Beyond this disparity, however, the London Underground shouldn't be regulated simply as a workspace, as members of the public, not just TfL workers, are exposed to pollutants in tunnels, therefore, the air quality should be monitored as a public space and subject to EU regulations for surface air quality. However, it is worth noting that these annual limits do not differentiate PM based on composition, which Franklin *et al.* (2006,2008) have determined is a major factor in the health risk posed by particulates, stating, “mass alone is not a sufficient metric when evaluating health effects of PM exposure” (2008:680). Determining the magnitude of effects from composition is difficult however, real-time monitoring of aerosol composition is difficult and effects from correlation with other pollution sources such as sulphates are difficult to correct for.

<u>The London Tube Network</u>

- Background and Infrastructure

London’s underground network is the oldest metro system in the world, dating back to 1863, when the Metropolitan Railway began serving 8 stations between Farringdon and Paddington. The London Underground, known informally as the Tube, now consists of 11 lines, totalling 270 stations and 402km of track and serves 1.3 passengers annually (TfL, 2016). It is currently operated by Transport for London, formerly London Underground Ltd.

The lines of the Underground are divided into two main types, subsurface lines such as the District and deep lines such as the Jubilee. Subsurface lines are effectively at ground level, while deep lines can be more than 50m below ground. Stations on the deep tube are typically higher than the connecting tunnels, as the slope assists with decelerating and accelerating at stations, potentially creating a further sink for heavier-than-air pollution. (TfL, 2016)

Air can flow through the Tube in three ways: through tunnel mouths, stations or ventilation shafts. Air is drawn into tunnels through the movement of trains, which effectively act as a piston that creates suction (Gilbey *et al.,* 2011). This effect has primarily been investigated in regards to heat regulation on the Tube, as the network has a tendency to act as a sink for excess heat generated by train friction and passengers. TfL has refused to publish details of air intakes, citing the threat of terrorists exploiting airflow access as an exemption to freedom of information requests. Some ventilation shafts, which are often disguised by false facades, have been mapped by urban explorers, however, without an accurate inventory it is impossible to determine the relative magnitudes of airflow from stations, tunnel mouths and ventilation shafts.

An investigation into air quality on the Barcelona Metro demonstrated that the piston effect was not sufficient to maintain adequate air quality for aerosols for single-carriage tunnels (similar to London's deep tube), which require additional powered ventilation (Moreno *et al.,* 2014). The Tube's ventilation shafts do have powered fans, but without access to official inventories and specifications it is difficult to gain an accurate understanding of where air on the tube actually originates and what the overturning rate for each line may be.

- Pollution on the Tube

a. Sources

Pollution on the Tube has two potential sources; pollutants may be created through the operation of trains themselves or they may be draw into the tunnel from external surface sources. Aerosol pollution, the most concerning aspect from a public health standpoint is highly likely to be produced by friction between rails and carriage wheels. Previous investigations have reported conflicting findings about the composition of dust on the tube. TfL in 2013 determined that the composition of particulate matter on the tube is ~90% iron, consistent with this theory of formation (TfL, 2013), while an earlier IOM report found that the dust was only 67% iron, suggesting much of the particles are drawn into the tunnels from external sources (Seaton *et al.,* 2005).

b. Previous Investigations

Air quality on the London Tube has been subject to shockingly little public scrutiny, particularly in recent years, with very little scientific work published. However, in 2001, in the context of a broader survey of dust exposure across London transport modes, Adams *et al.* reported mean $PM_{2.5}$ levels on modelled journeys on the tube as 247 ug/m^3. Additionally, a survey of metro commuting adolescents in inner-city New York discovered elevated personal exposure to steel dust attributed to the NYC metro (Chillrud *et al.,* 2004). Directly in response to these findings, as well as unpublished dust counts by Nick Priest of University of Middlesex and a subsequent investigation by the Evening Standard newspaper (Hunter, 2002), in 2004

London Underground Ltd. commissioned a report by the Institute of Operational Medicine at University of Edinburgh (TfL, 2013)(Seaton *et al,* 2005).

This final report by Seaton *et al.* investigated the concentration, composition and toxicology of London Underground $PM_{2.5}$ at selected sites, concluding, "those principally at risk from dust inhalation by working or travelling in the London Underground should not be seriously concerned" (2005:362). However, a close reading reveals critical methodological failings in this study. Chronic exposure is not considered by the authors; instead dust measurements are incorrectly compared to the acute 8-hour HSE regulation, which does not assess chronic health effects. Furthermore, the toxicology analysis undertaken simply assessed the cytotoxic effect of dust on cultured alveolar epithelial cells over 8 hours. This simply does not model chronic exposure to $PM_{2.5}$, the effects of which are well documented in a multitude of studies. The results of these toxicology assays led the authors to conclude that the primarily iron dust posed minimal risk to the public. A 2013 summary report by TfL cites this study and "ongoing research" in stating, "The results have provided sufficient reassurance that the dust on the Underground does not pose a risk to the health of our customers or employees" (TfL, 2013:1). However, the report inexplicably states the composition of the dust is 90% iron rather than the 67% determined in the 2005 study and makes further reference to the HSE regulations, which the IOM, who undertook the original 2005 study, described in 2011 as unsafe and in need of at least 75% reduction (IOM, 2011). The self-reported dust range on trains is 80-560 ug/m^3, with no data on spatial distribution, particle size or descriptive statistics published (TfL, 2013).

Worldwide, a number of air quality surveys have been undertaken on various metro systems, finding significantly elevated PM counts in many cases, although rarely measuring other pollutants such as NO_2. Investigations in Mexico City (Mugica-Alvarez, *et al.,* 2012), Barcelona (Moreno *et al.,* 2014), New York (Vilcassim *et al.,* 2014), Taipei (Cheng & Lin, 2010), Seol (Kwon *et al.,* 2015), and Stockholm (Johansson & Johansson, 2003) have all detected $PM_{2.5}$ in concentrations significantly higher than the WHO guideline of 10 ug/m^3, universally flagging these elevated concentrations as a potential health risk. The fact that UK-based investigations have seemingly downplayed a risk that is recognised worldwide is particularly concerning.

Knowledge Gaps

There are a number of gaps and inconsistencies in the scientific literature about air quality on the London Underground through either a lack of research or outdated findings. It does not appear that any study has been undertaken measuring atmospheric pollutants other than PM on the Underground in London. Following on from this fact, it is unknown if there is any correlation between any gaseous pollutants and PM. Additionally, no publically available data contains spatial information on pollutants such as differences between lines, intra-line variation with proximity to tunnel mouths or particular trouble spots, or investigates differences between the shallow subsurface lines and the deep lines.

Motivations for this Research

In addition to blue-sky research motivations in understanding how air pollution behaves in underground metros, there is a clear public interest in assessing the risk that air pollution may pose to passengers on public transport and publicly employed staff exposed from either platform postings or driving trains. This study aims to answer two primary questions: What is the spatial distribution of air pollution on the London Underground network? And are pollution levels high enough to pose a risk to either passengers or TfL staff?

Methodology

Target Area

In order to both assess the health risks to passengers and staff and understand the spatial distribution of pollution on the tube a study was launched. The London Underground network is comprised of 11 different lines running for a total track length of 402 kilometres. According to Transport for London (TfL), the underground handles 1.3 billion passengers annually. Approximately 45% of the network is contained within tunnels (10% subsurface and 35% deep tunnel), with the remaining 55% running aboveground (TfL, 2016)(Figure 1). This investigation focuses on the sections of the tube wholly contained within tunnels, which are likely to act as pollutant sinks due to reduced airflow. This subset of the network is located almost entirely within the central two zones, with only one branch of the Northern line extending out of this peak fare zone. Underground sections of the network account for a disproportionate amount of the total journeys made, further increasing the exposure of the population as a whole to potential pollution (O'Brien, 2014).

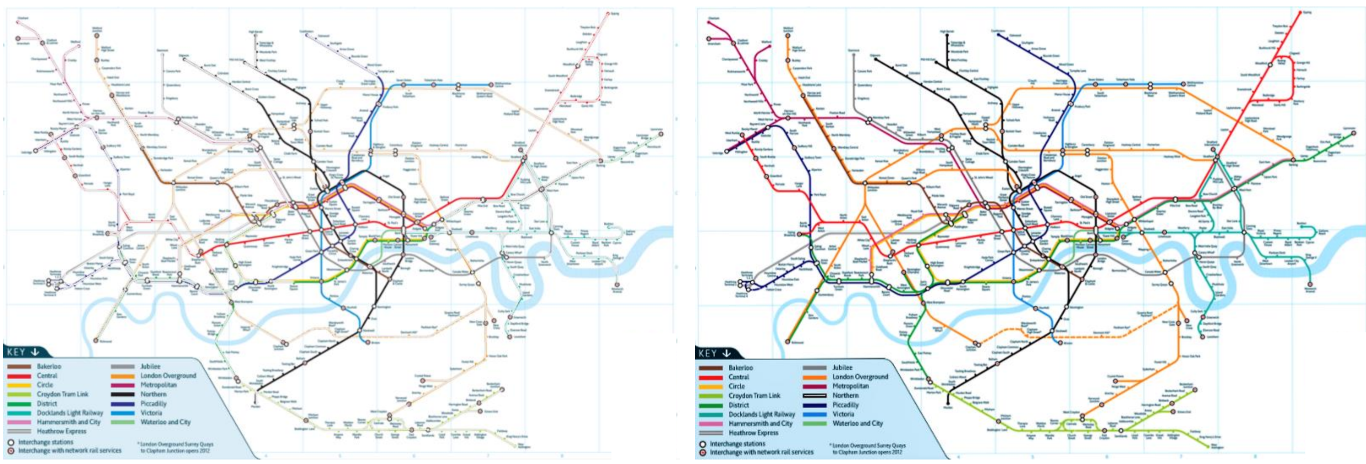


Figure 1. Underground sections of the London Underground (left) compared to entire network (right). Adapted from Noad, 2011.

Test Variables

Both aerosols and gasses, the two main components of air pollution, were analysed. Aerosol dust up to $PM_{2.5}$ has well-documented negative health effects and forms the basis for most air quality indices, while dust up to PM_{10} has potential but unknown health effects. TfL analysis shows that dust in the tube is primarily iron, attributing the high levels to particles formed from friction between rails and carriage wheels (Transport for London, 2013). Aerosols were sampled by size categories based on their health impacts: PM_1 (ultrafine), $PM_{1-2.5}$ (fine), $PM_{2.5}$ (respirable, <2.5 um), $PM_{2.5-10}$ (coarse inhalable) and PM_{10} (total inhalable, <10.0 um). The gasses selected for analysis were NO, NO_2, O_3 and CO, based on their potential sources and adverse health effects. All four gasses can be produced aboveground and could potentially be drawn into the underground network due to the placement of ventilation shafts along major roads. O_3 could also be produced through a proposed mechanism within the tube system; it is possible that electrical discharges from the electrified rail can produce O_3 through the breakdown of O_2 into oxygen free radicals which then recombine with O_2 to form O_3 molecules. As the tube network is electrified with no combustion sources, any NO, NO_2 or CO will have been drawn in from the surface through either stations, tunnel mouths or ventilation shafts. It was also intended to analyse both volatile organic concentrations and sulphur dioxide (SO_2) within the Tube, however it was impossible to obtain appropriate sensors for these variables in the timeframe required.

Equipment

A portable sampling rig that simultaneously measured gas and particulate concentrations was assembled for this investigation. The sampling rig was composed of a DustTrak DRX 8533 aerosol monitor that both took measurements of aerosol concentrations and drew air through a series of four Alphasense 4-electrode individual sensor boards (ISB), which fed into a pair of HOBO dataloggers. The ISBs are known to be prone to external electrical interference, and were therefore insulated with a charged Faraday cage outside the sensor casing. Each ISB corresponded to one of the four sample gasses (CO, NO, NO_2 and O_3). Additionally, a filter preventing aerosols above PM_{10} (which have no known health effects) was placed over the air intake to prevent choking the airflow with accumulated matter. The entire sensor rig was enclosed within a backpack that allowed easy portability while within train carriages. Outputs from the sensors were in mg/m^3 for aerosols detected by the DustTrak and parts-per-billion (ppb) for the gas ISBs. The DustTrak has a detection range of 0.001-150.000 mg/m^3, accurate to .0001 mg/m^3. Ranges for the ISBs vary by gas, but all are accurate to approximately 1ppb with the shielding in place. Initial tests additionally included a thermometer to detect potential overheating of the rig, which ultimately did not materialise.

Sampling Strategy

The primary objective of this investigation was to shed light on the spatial distribution of particulate and gaseous pollution on the London Tube Network. During January 2016, over 20,000 readings were collected with the portable sensor rig. Preliminary investigations, along with analysis of previous work informed the sampling strategy. Initially, readings were taken on station platforms in order to allow like-to-like comparisons with published TfL data. However, preliminary investigations showed that pollution counts were higher within carriages compared to station platforms. Additionally, the internal carriage air is much more representative of the environment commuters and drivers face; therefore, the decision was made to focus on internal carriage conditions. Segments are uneven in both transit time and actual distance, therefore certain segments have significantly more readings than others. However, as exposure to pollutants is measured primarily on an exposure over time basis this was not a concern for data analysis.

The entirety of the underground portions of the tube network was sampled, with additional readings taken at selected aboveground sections for comparison with London Air Quality Network data in preliminary tests.

All eleven tube lines were sampled, although in the belowground sections of the tube network, the subsurface Circle, District, Hammersmith & City and Metropolitan lines utilise the same tunnels and are effectively a single line, bringing the actual effective number of lines analysed to eight. TfL's self-reported infrastructural data reports line segments that are partially covered as underground, therefore it was necessary to manually identify which segments were actually exposed with the initial survey.

Readings were taken between the hours of 11:00 and 16:00 to avoid peak busy periods for a number of reasons; The air intake for the DustTrak becoming blocked was a major concern in an underground carriage filled to capacity, as was the transport of complex sensors during peak travel periods in the immediate aftermath of the Paris terror attacks. Additionally, off-peak sampling allowed more efficient data collection due to reduced travel time and a larger daily sampling window. Preliminary tests showed no significant temporal variation at initial test sites within the off-peak window and any variance from this source is likely to be minor compared to other variables such as depth, ventilation and line. Investigating whether significant temporal differences exist, for example, on a seasonal or peak versus off-peak basis was deemed impractical for the scope of this investigation but remains an avenue for further research.

Secondary Data

In addition to primary data collection in the London Underground, secondary data was taken from the London Air Quality Network (LAQN). This dataset consists of spatially modelled concentrations of NO_2, O_3, $PM_{2.5}$ and PM_{10} created from measurements in 2010 and provides baseline measurements across London as an annual average for a given location.

Calculation of Exposure

Exposure levels were estimated using shift data from TSSA (the largest London Underground Union), infrastructure data from both TfL and preliminary investigations in this study and background pollutant levels from the LAQN. Across the entirety of the London Underground, which is 35% deep tube lines (TfL, 2016), assuming uniform train frequency (which is not actually the case, but is a sufficient heuristic for these purposes) it was determined that drivers would face an average of 555 hours each year of deep tube exposure, which could potentially increase to 1679 hours if exclusively working within fully enclosed lines such as the Victoria. Exposure for passengers was calculated for a one-hour daily commute through deep lines, which is high, but not uncommon (O’Brien, 2014).

Data Processing and Analysis

Data from the ISB sensors had to be processed before input into a statistics package; concentrations are calculated from the difference between two currents, with zero values and sensitivity factors unique to each sensor (Appendix 4). Once ppb concentrations were calculated from each sensor, the datasets were time-synchronised, combined into a single spreadsheet and trimmed from ~20,000 total datapoints (including aboveground travel, direction changes and extra travel time) to 1600 relevant test values. Data was excluded from the final analysis for a number of potential reasons. Most of the excluded data collected was either from outside the specific sample area, such as overground sections of the Tube, or represented inapplicable data such as line changes or time spent on platforms rather than within carriages. A small number of datapoints were excluded due to what appeared to be a temporary fault in the ISB gas sensors showing negative values for NO_2, O_3 and NO; these datapoints were wholly excluded and the section of line re-sampled. The exact cause of this anomaly is unknown but was likely due to either a loose connection in the sensor rig or outside electromagnetic interference.

Once all primary data was collected, additional information was entered manually into the dataset. Line segment, labelled as a four letter designation, was manually coded for each of the relevant datapoints from the logs taken during transits, as well as the distance (in number of stations) from a tunnel mouth, calculated from maps annotated with the previously identified tunnel mouths (hereafter reported as "proximity"). This final collated dataset was then analysed using IBM Statistics 22 and Microsoft Excel.

In the final analysis findings were compared to surface measurements provided by the secondary LAQN data in order to provide contextual data, explain spatial trends and estimate total exposure levels of Tube staff and passengers living in the London area.

<u>Methodological Limitations of the Research</u>

One of the largest limitations of this investigation was the scale of the survey. Only having one sensor rig rather than several limited both the amount of data that could be collected in the timeframe of an undergraduate dissertation, as well as the ability to take simultaneous measurements that could better account for temporal variation. Certain variables are likely to vary on a seasonal basis, such as O_3, which is known to be found in generally higher concentrations during summer months. Further complicating investigations of day-to-day temporal variation was the requirement that the sensors be returned to the lab daily, limiting the amount of time available to collect data on any given day, especially as the ISB sensors require 90 minutes in order to begin collecting accurate readings. Additionally, measurements were taken without the knowledge of TfL, who have a vested interest in avoiding research that could reflect badly on the underground network. Ideally, for further, funded investigations TfL's cooperation could be secured in placing a network of sensors on platforms and in carriages for a longer-term survey, which would provide a far better dataset. There is reason to believe that higher train frequency during peak periods could increase particulate counts, and that the well-documented increase in surface exhaust products during peak periods could correspond to similar increases belowground. Another research avenue would be investigating the composition of aerosols, as previous literature has obtained conflicting results regarding composition, which is now known to have a major effect on health risk (Franklin *et al.,* 2008).

Results

Primary Data

- Particulate Aerosols (PM)

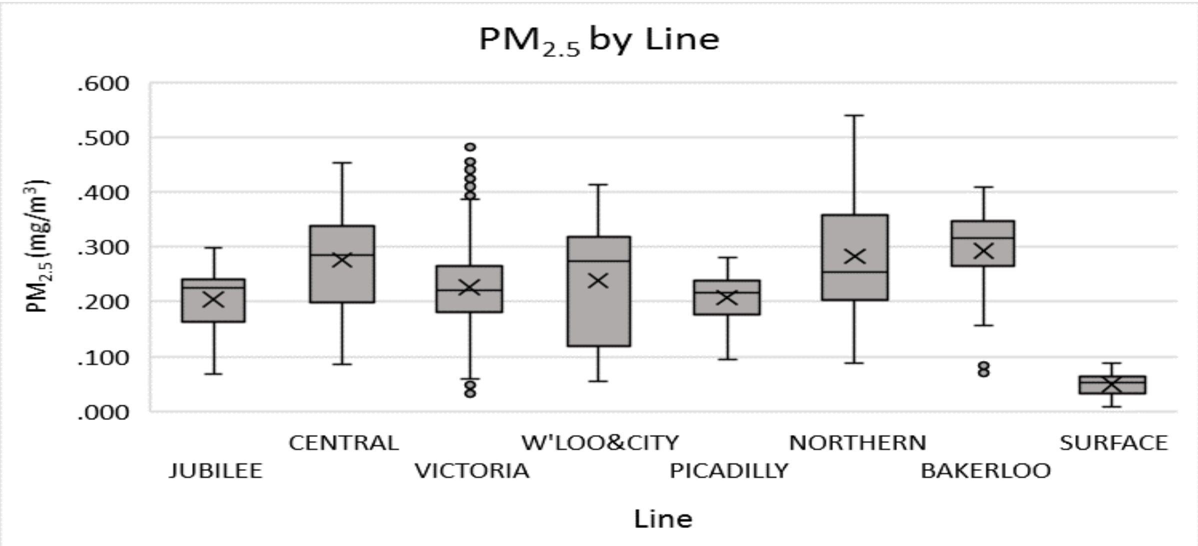
Aerosol levels were much higher on the deep tube lines than on the subsurface lines; the mean $PM_{2.5}$ for subsurface lines was 50 ug/m3, compared to 252 ug/m^3 across the deep lines. The WHO recommendation and EU limits on annual PM exposure are 10 and 25 ug/m^3 respectively (WHO, 2013) (European Commission, 2015), while background levels in central London are 15-20 ug/m^3 (London Air, 2016). The implications of this finding are discussed later in this report. Some correlation existed between PM concentrations and the number of stations between the sample location and a tunnel mouth, a proxy for both depth (in deep lines) and absolute distance (in both deep and subsurface lines), hereafter referred to as "proximity". For subsurface lines only, this correlation was not always significant at a two-tailed 99% or 95% confidence interval (insignificant at 95% for $PM_{1.0\text{-}2.5}$ and $PM_{2.5}$, significant at 95% but not 99% confidence for all other categories) and was much weaker than on the deep lines only (r=0.162-0.243 compared to r=0.335-0.358). Correlations with proximity were more positive with greater particle diameter; r=0.335 for $PM_{1.0}$ compared to r=0.358 for PM_{10} when considering deep lines. Despite this spatial pattern, as expected, PM values of all categories (1.0, 1.0-2.5, RESP, 2.5-10.0 and Total) were extremely strongly correlated with each other (Pearson's r=0.962-0.990).

Particulate Aerosols in Deep Tunnels					
Particle Size	N	Minimum (ug/m^3)	Maximum (ug/m3)	Mean (ug/m^3)	Std. Deviation (ug/m^3)
PM_1	1350	26	360	172.5	63.6
$PM_{1\text{-}2.5}$	1350	31	483	230.1	83.2
$PM_{2.5}$	1350	33	540	252.1	90.9
$PM_{2.5\text{-}10}$	1350	36	596	275.3	98.7
PM_{10}	1350	36	605	280.0	99.7

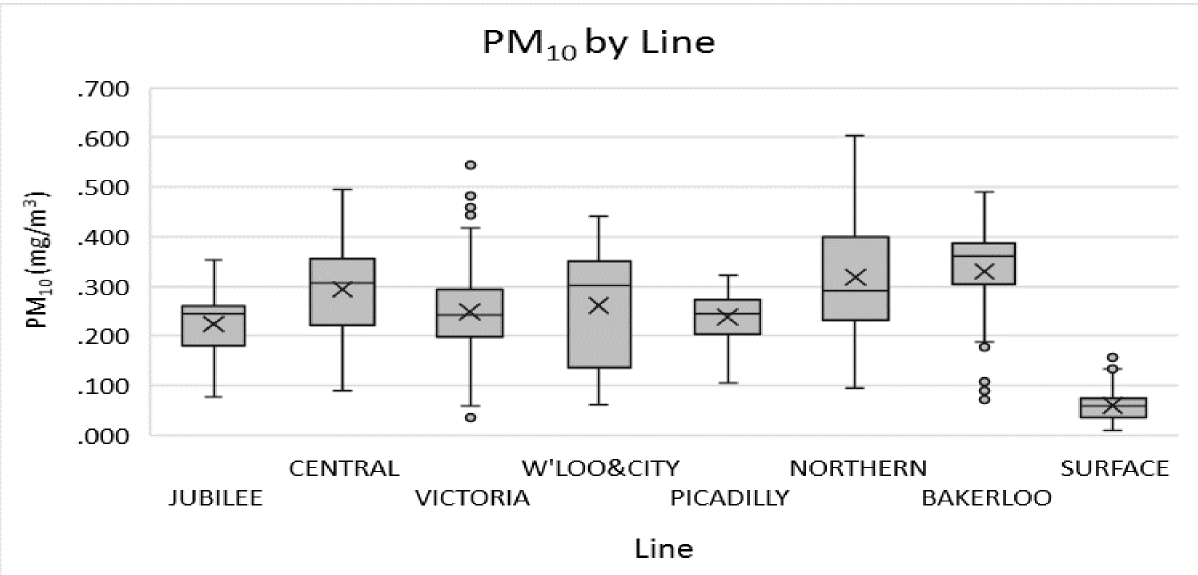
(Table 1. Summary of Aerosol Data for Deep Tunnels)

Particulate Aerosols in Susbsurface Tunnels					
Particle Size	N	Minimum (ug/m^3)	Maximum (ug/m3)	Mean (ug/m^3)	Std. Deviation (ug/m^3)
PM_1	155	8	73	39.9	16.3
$PM_{1-2.5}$	155	9	86	47.0	19.1
$PM_{2.5}$	155	9	89	49.2	20.0
$PM_{2.5-10}$	155	9	110	54.1	23.1
PM_{10}	155	9	161	60.1	30.4

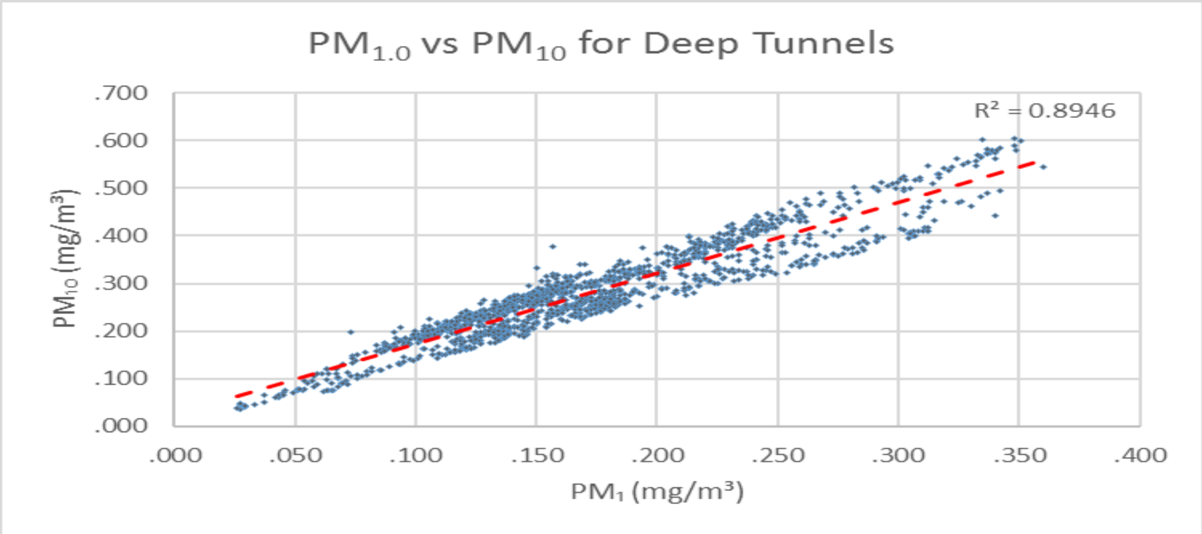
(Table 2. Summary of Aerosol Data for Subsurface Tunnels)



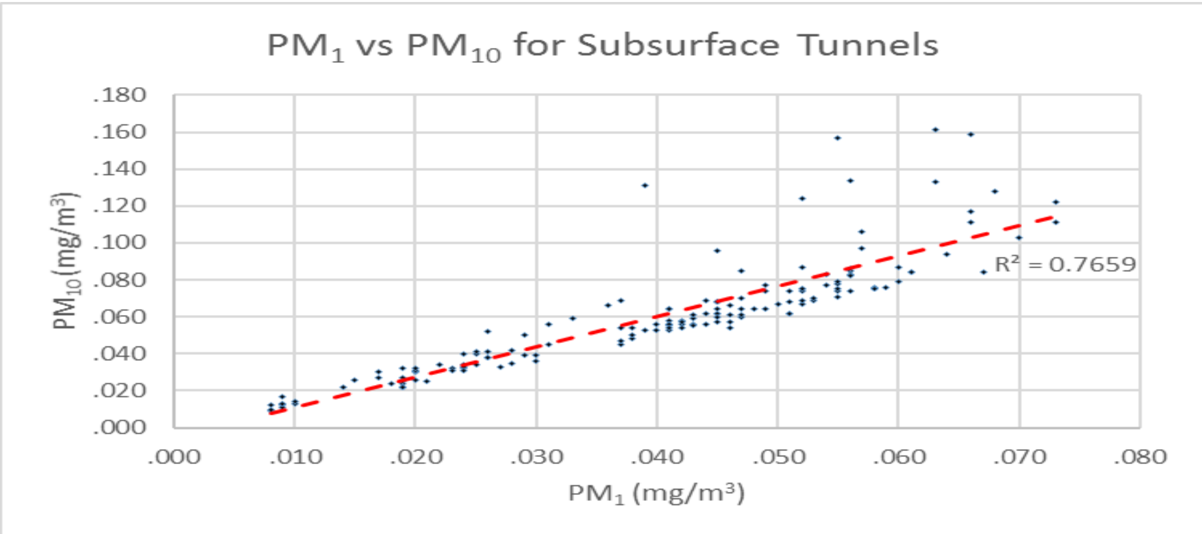
(Figure 2. $PM_{2.5}$ Concentrations by Line)



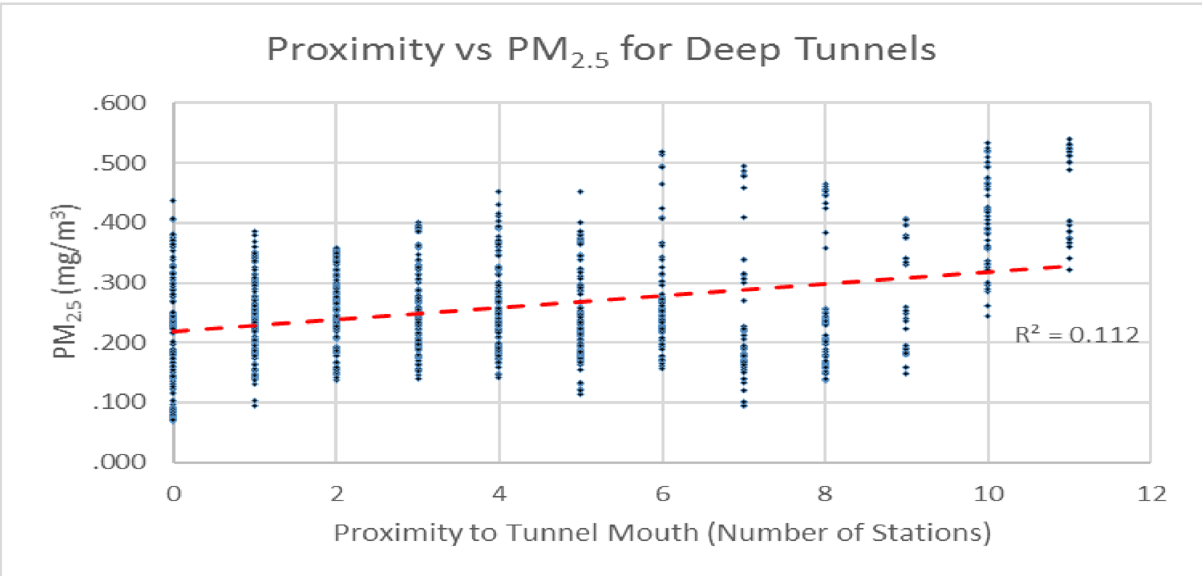
(Figure 3. PM_{10} Concentrations by Line)



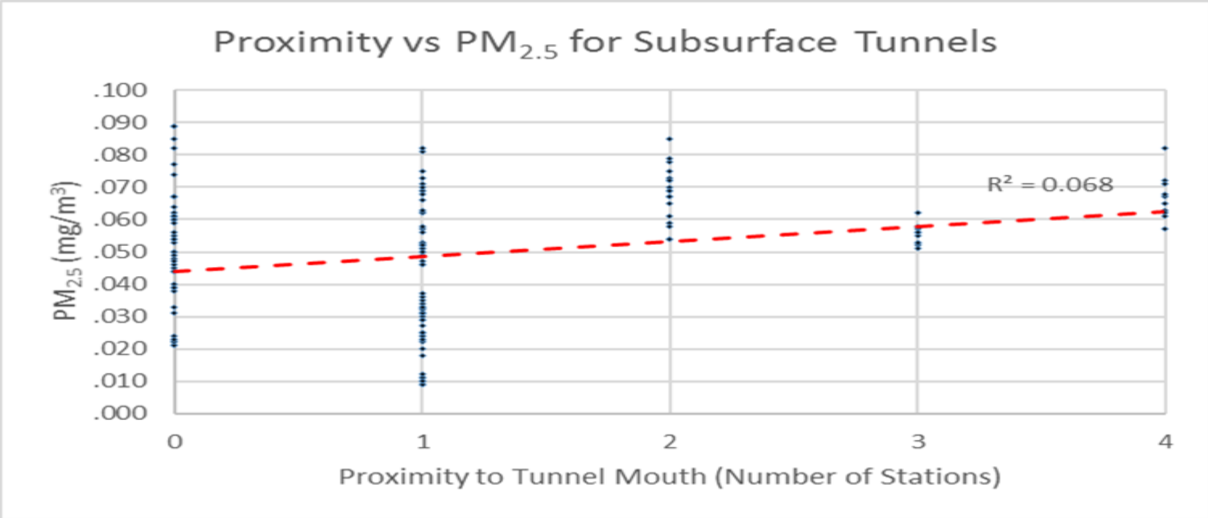
(Figure 4. Correlation Between PM_1 and PM_{10} for Deep Tunnels)



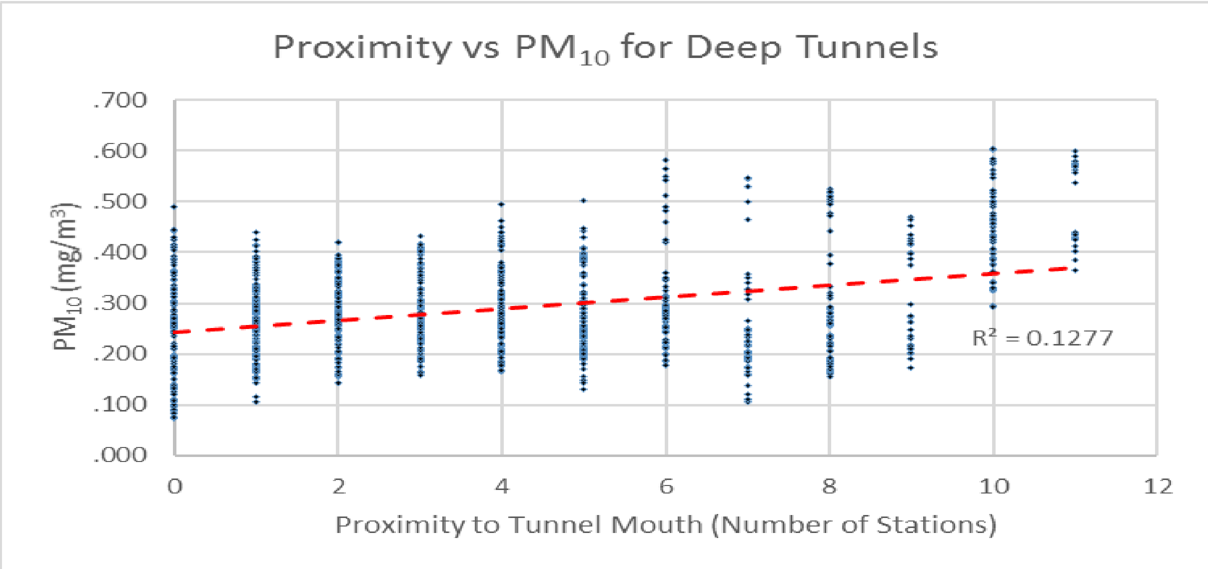
(Figure 5. Correlation Between PM_1 and PM_{10} for Subsurface Tunnels)



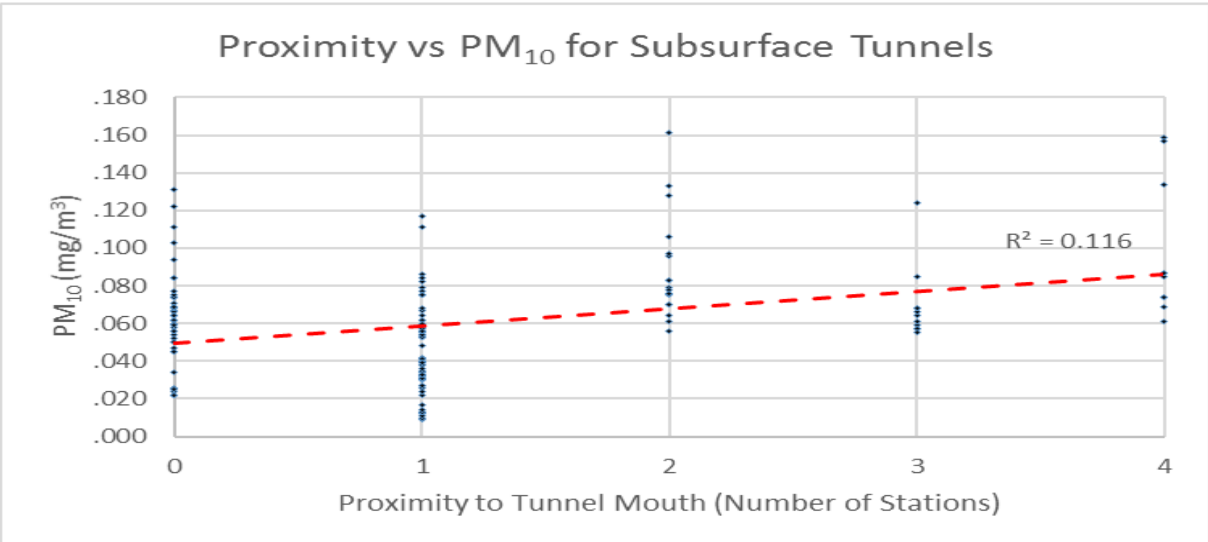
(Figure 6. Correlation Between Proximity and $PM_{2.5}$ for Deep Tunnels)



(Figure 7. Correlation Between Proximity and $PM_{2.5}$ for Subsurface Tunnels)



(Figure 8. Correlation Between Proximity and PM_{10} for Deep Tunnels)



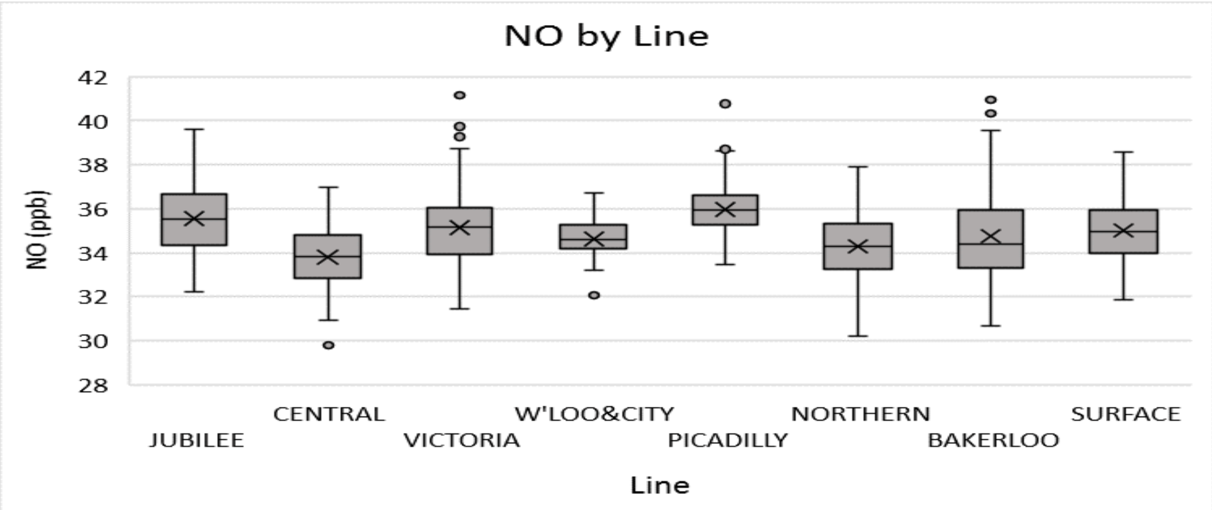
(Figure 9. Correlation Between Proximity and PM_{10} for Subsurface Tunnels)

- Carbon Monoxide (CO)

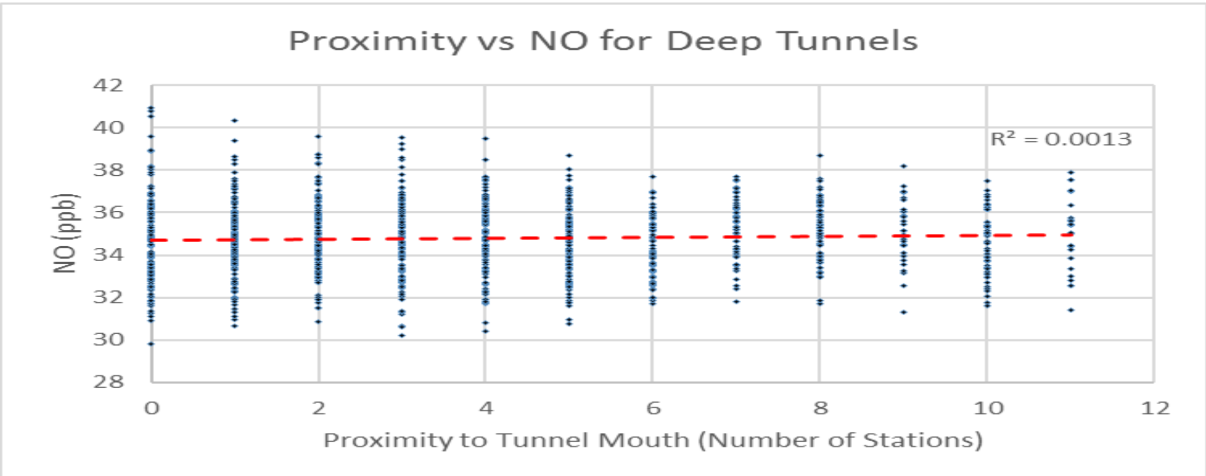
Only a single non-zero CO reading was obtained in the entirety of the surveys, including excluded extraneous data, meaning that the level was below the detection threshold of the portable monitor. Therefore, no meaningful statistical analysis could be undertaken with respect to CO.

- Nitric Oxide (NO)

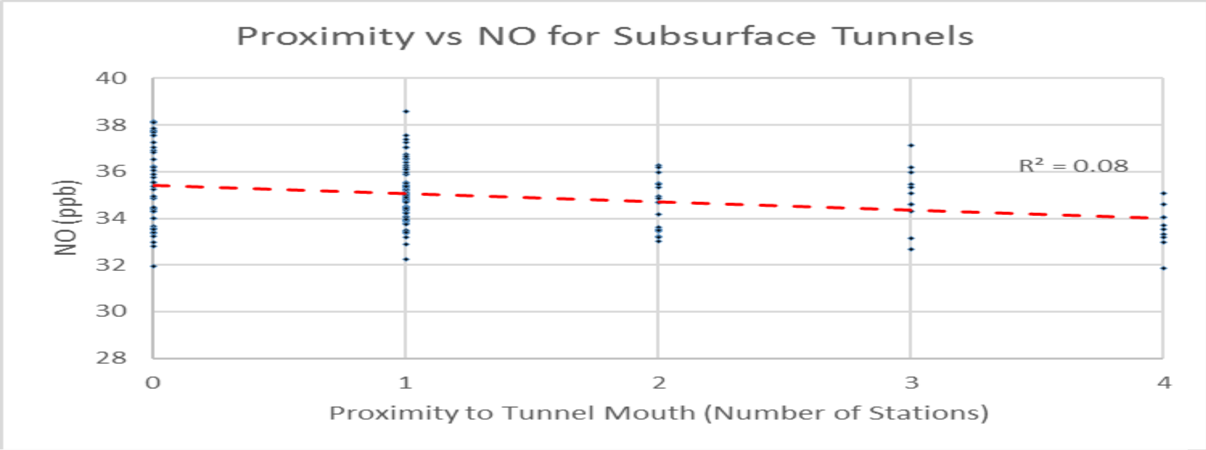
NO levels were generally low, ranging between 29 and 41 ppb, far below typical exposure guidelines of 25 ppm (WHO, 2014). NO concentrations exhibited differing spatial behaviour between deep and subsurface lines. When considering deep lines, there was no significant correlation with proximity to tunnel mouths, while when considering subsurface lines, a weak negative correlation occurred (r=0.259).



(Figure 10. NO Concentrations by Line)



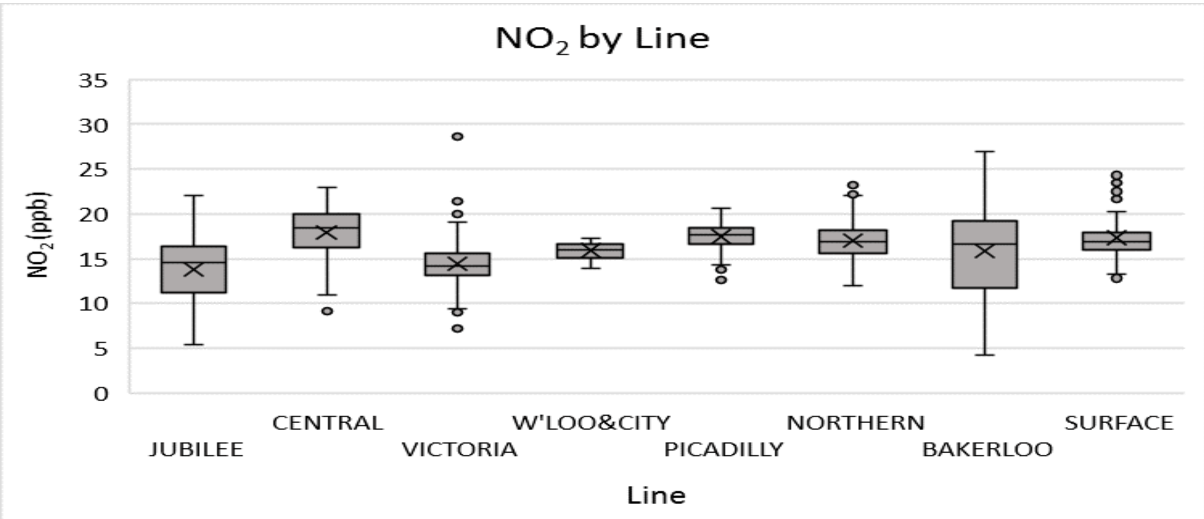
(Figure 11. Correlation Between Proximity and NO for Deep Tunnels. Note that correlation is insignificant at 95% confidence)



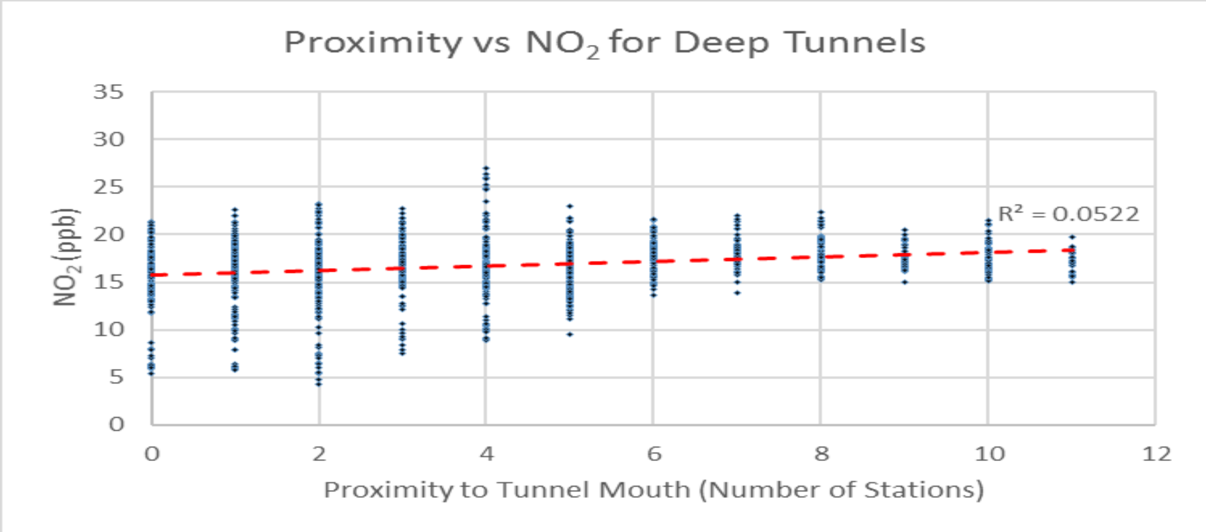
(Figure 12. Correlation Between Proximity and NO for Subsurface Tunnels)

- Nitrogen Dioxide

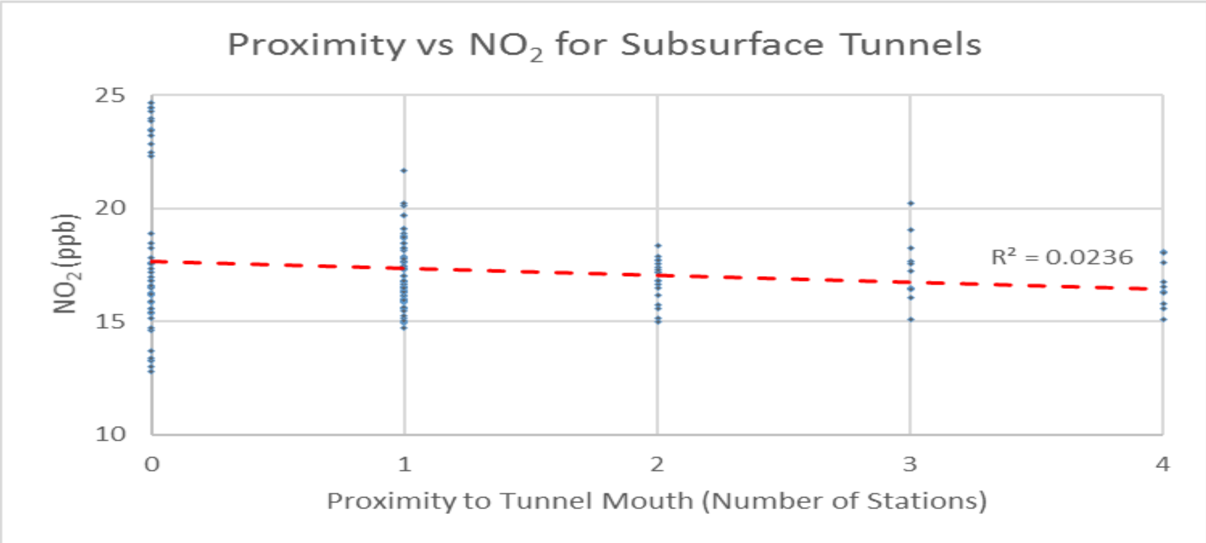
NO_2 showed a weak positive correlation with proximity (r=0.228) when only considering deep lines, and reversing to a very weak negative correlation or r=-0.157 when considering only subsurface lines. NO_2 levels varied across health guideline thresholds, ranging between 4 and 29 ppb with a mean of 16.4 ppb, compared to recommended annual limits of 20 ppb (WHO, 2014). However, this represents a reduction compared to baseline levels of ~21 ppb in central London generally and ~44 ppb along major roads.



(Figure 13. NO_2 Concentrations by Line)



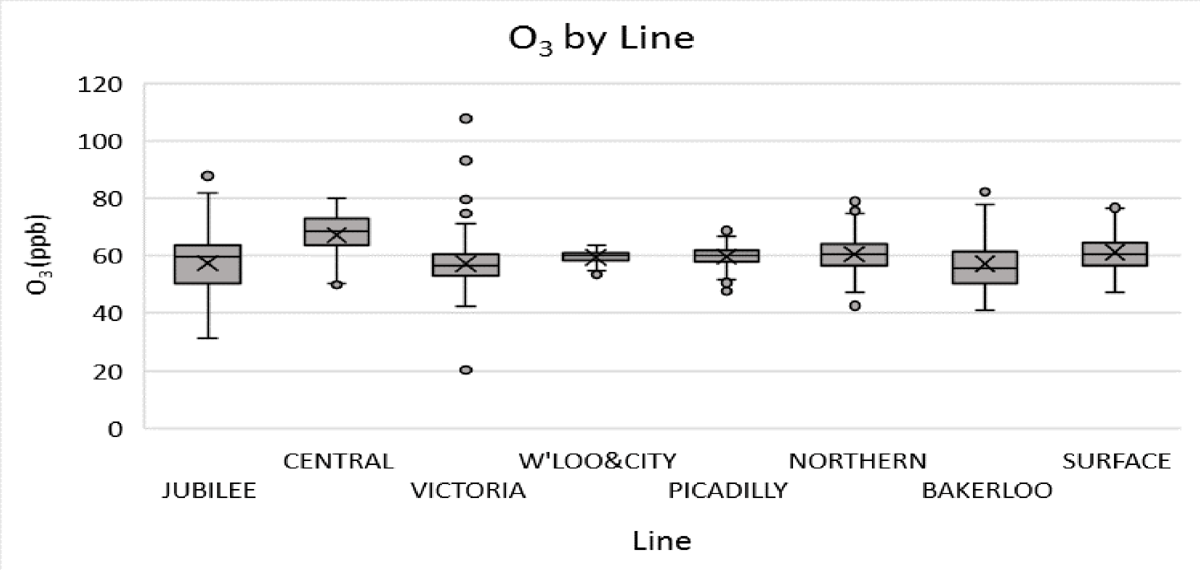
(Figure 14. Correlation Between Proximity and NO_2 for Deep Tunnels)



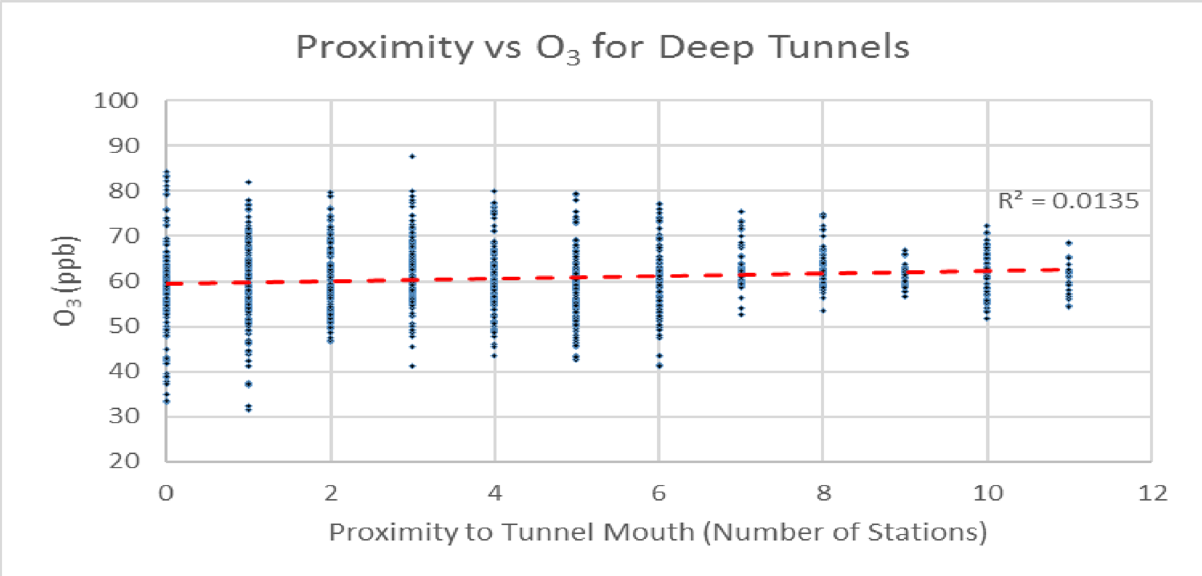
(Figure 15. Correlation Between Proximity and NO_2 for Subsurface Tunnels. Note that correlation is insignificant at 95% confidence level)

- Ozone (O_3)

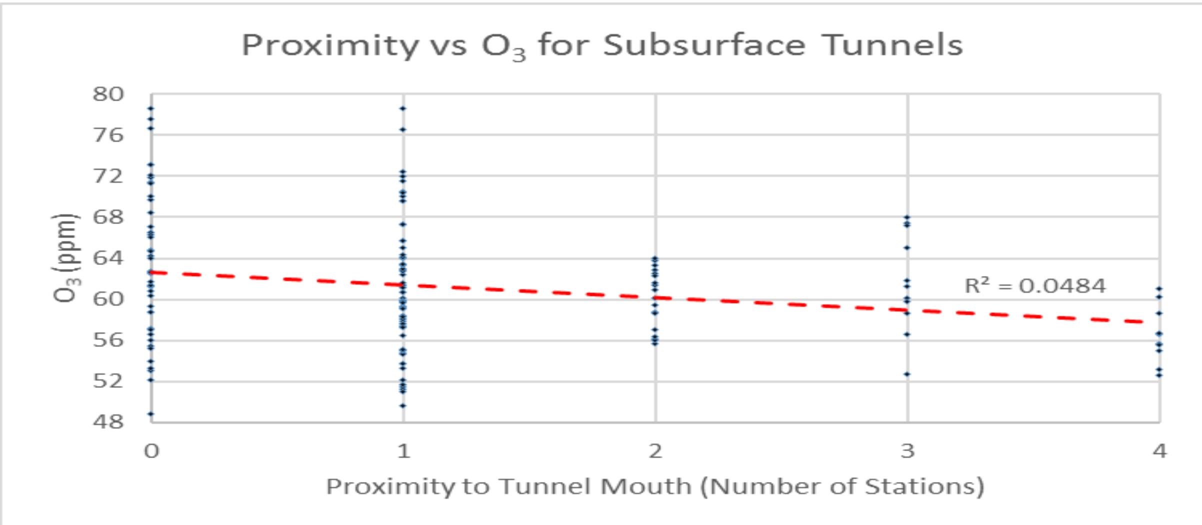
O_3 shows a similar spatial distribution to NO_2; very weakly positively correlated with line proximity across deep lines (r=0.116) and weakly negatively correlated with proximity in surface lines only (r=-0.210). Concentrations were moderately high compared to health guidelines; values ranged between 20 and 108 ppb, with a mean of 60.1 ppb, compared to annual health guidelines of 47.3 ppb (100 um/m^3) (WHO, 2014) and represents an increase over baseline London levels of ~16 ppb (London Air, 2016).



(Figure 16. O_3 Concentrations by Line)



(Figure 17. Correlation Between Proximity and O_3 for Deep Tunnels)



(Figure 18. Correlation Between Proximity and O_3 for Subsurface Tunnels)

Gasses on Deep Tunnels					
Gas	N	Minimum (ppb)	Maximum (ppb)	Mean (ppb)	Std. Deviation (ppb)
NO	1350	30	41	34.8	1.7
O_3	1350	20	108	60.0	7.8
NO_2	1350	4	29	16.3	3.2

(Table 3. Summary of Gas Data for Deep Tunnels)

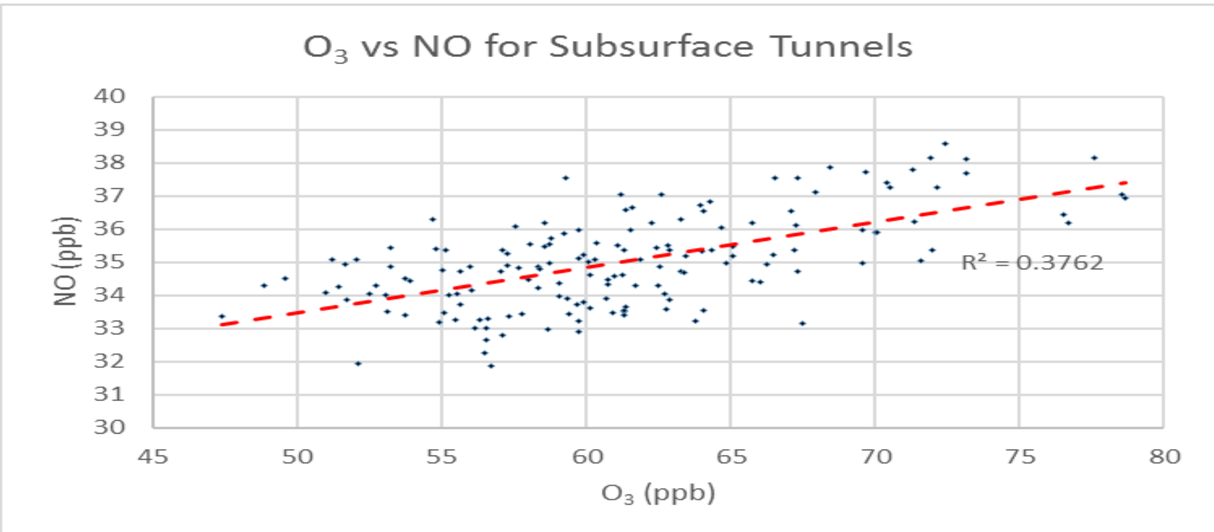
Gasses on Subsurface Tunnels					
Gas	N	Minimum (ppb)	Maximum (ppb)	Mean (ppb)	Std. Deviation (ppb)
NO	155	32	39	35.0	1.4
O_3	155	47	79	61.2	6.3
NO_2	155	13	25	17.3	2.3

(Table 4. Summary of Gas Data for Subsurface Tunnels)

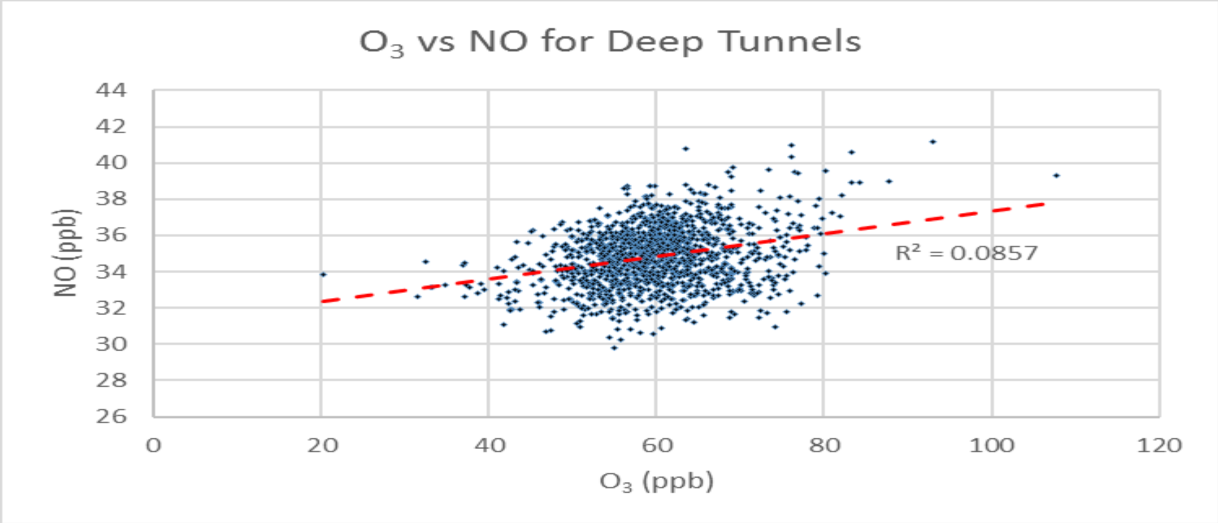
Correlations

A number of correlations existed between the test variables, which varied greatly depending whether subsurface, deep or both line categories were considered.

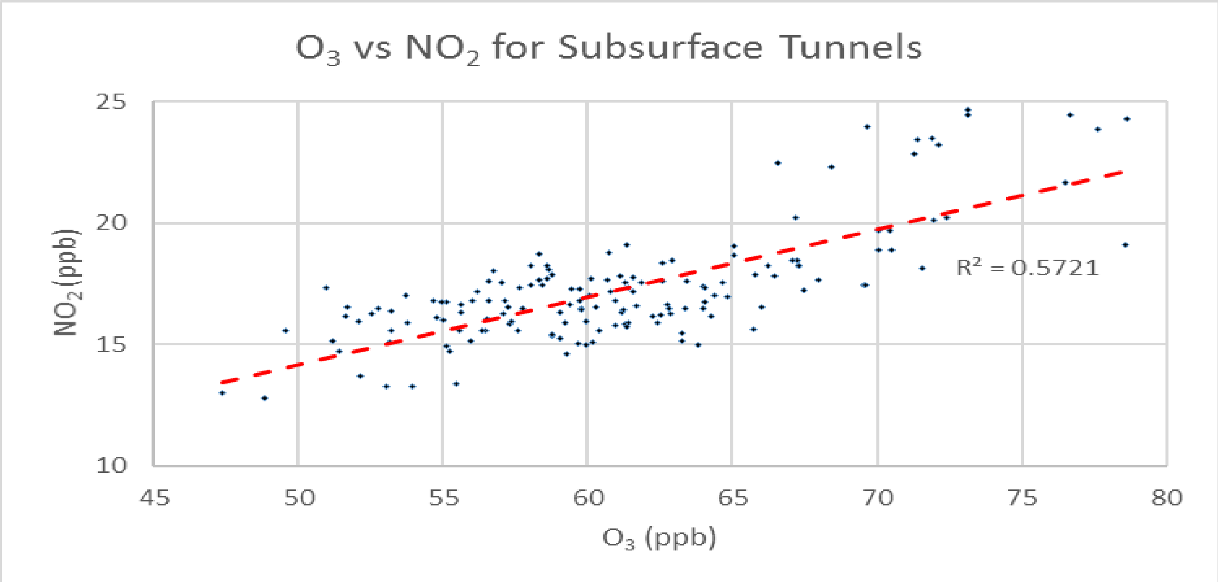
Gas concentrations in the subsurface tunnels were clearly linked. O_3 had strong positive correlations with both NO (r=0.618) and NO_2 (r=0.746), while NO and NO_2 exhibited a moderate positive correlation with each other (r=0.570). For the deep tunnels, this trend was less clear, with NO and NO_2 exhibiting no significant correlation and the correlations between O_3 and NO, and O_3 and NO_2 becoming weak and moderate respectively (r=0.293 and r=0.480).



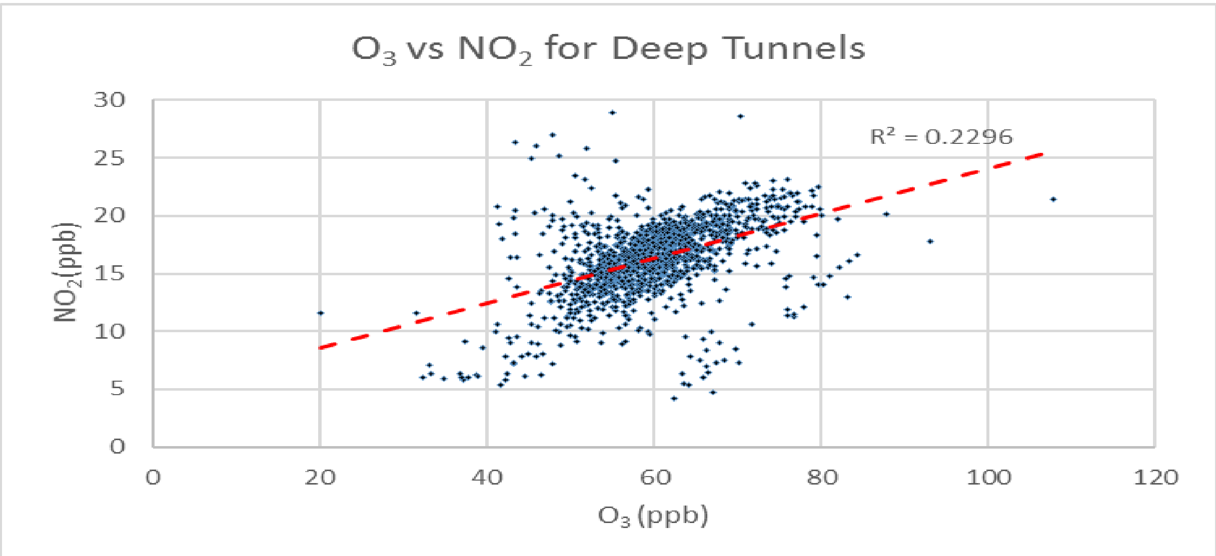
(Figure 19. Correlation Between O_3 and NO for Subsurface Tunnels)



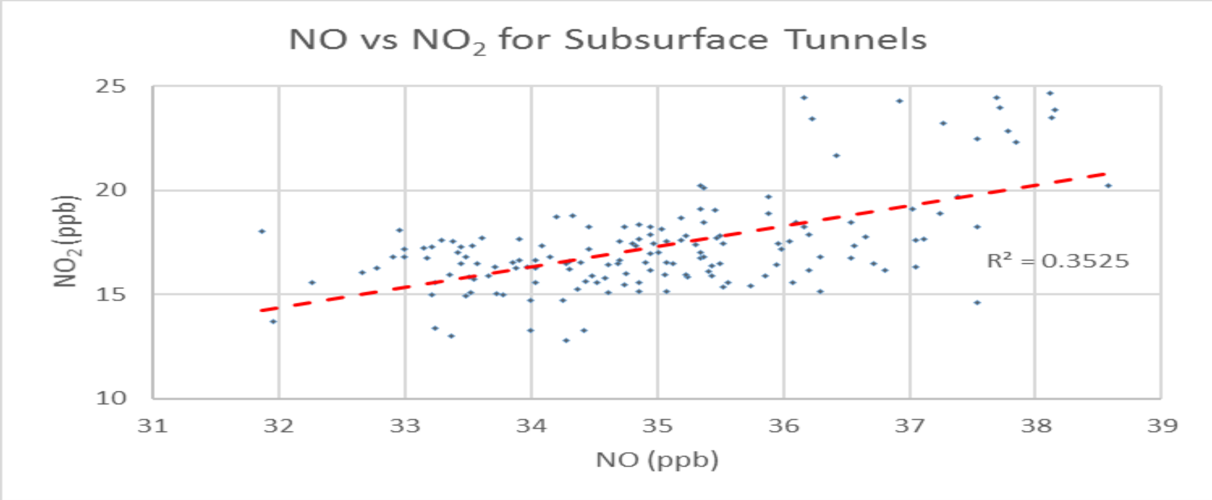
(Figure 20. Correlation Between O_3 and NO for Deep Tunnels)



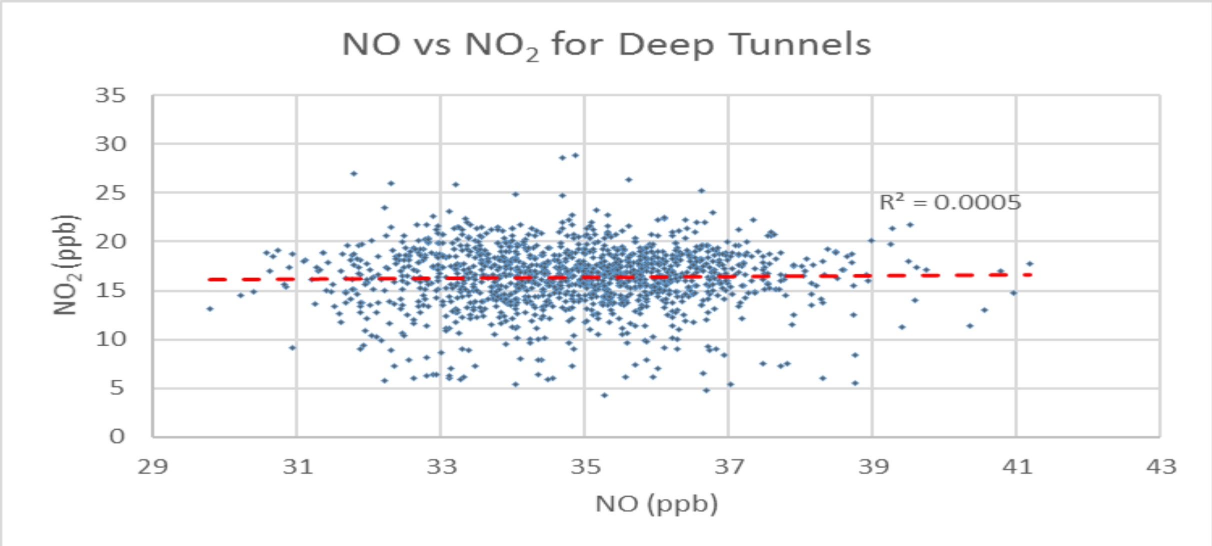
(Figure 21. Correlation Between O_3 and NO_2 for Subsurface Tunnels)



(Figure 22. Correlation Between O_3 and NO_2 for Deep Tunnels)

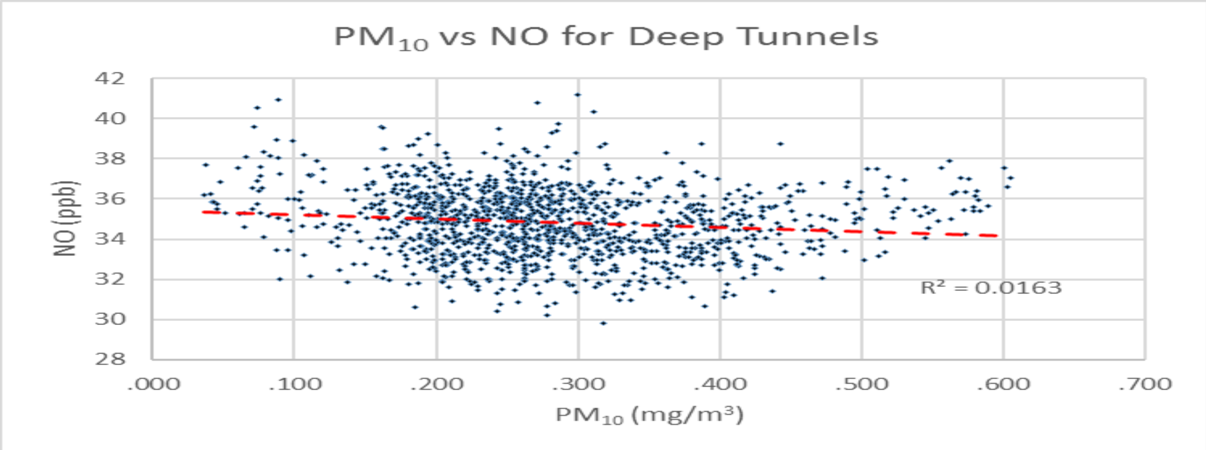


(Figure 23. Correlation Between NO and NO_2 for Subsurface Tunnels)

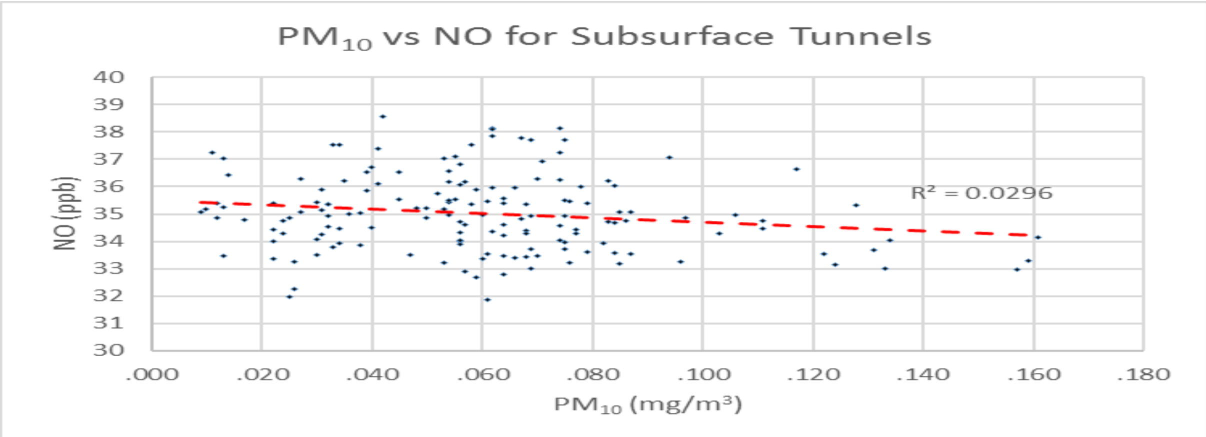


(Figure 24. Correlation Between NO and NO_2 for Deep Tunnels)

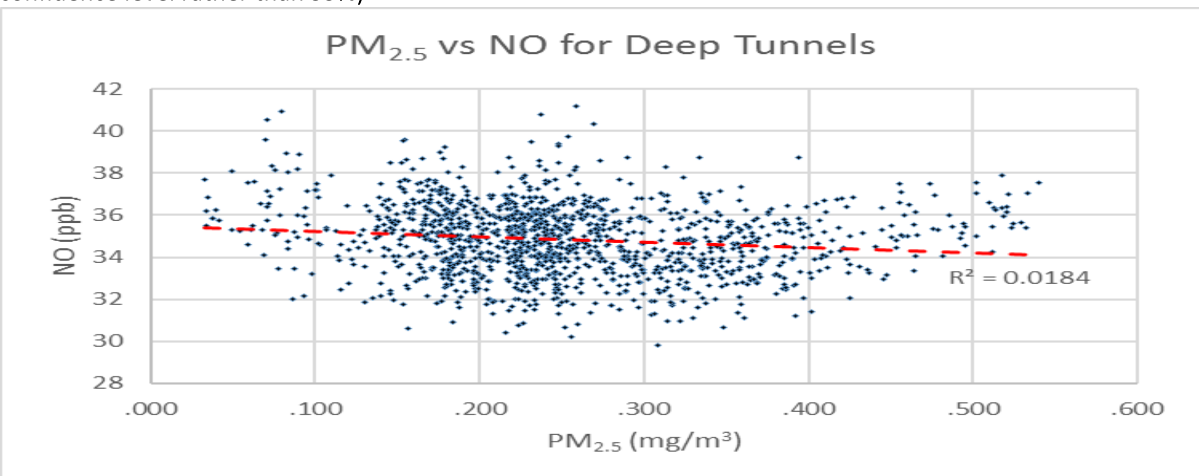
Correlations between PM and gasses ranged from weak to insignificant and, similarly to inter-gas correlations, had differing trends when considering deep and subsurface lines separately. When considering subsurface lines, NO exhibited very weak negative correlations significant at the 95% confidence level with $PM_{2.5}$ and below. For $PM_{2.5\text{-}10}$ and PM_{10}, the trend increased to weak negative correlations significant at the 99% confidence level. When considering deep lines rather than subsurface, the trend was consistently a very weak negative correlation across all particle sizes, significant at the 99% confidence level. For subsurface lines, NO_2 exhibited very weak positive correlation with $PM_{2.5}$ and below, significant at 95% confidence, becoming insignificant at larger particle sizes. However, for deep lines this trend reversed, becoming very weakly negatively correlated with $PM_{2.5}$ and below (95% confidence) and exhibiting no significant trend for larger particle sizes. O_3 exhibited no significant trends with PM for subsurface lines and consistently very weak negative correlations for deep lines only. Even when controlling for other variables using partial correlation tests, these trends retained their respective statistical significance or insignificance.



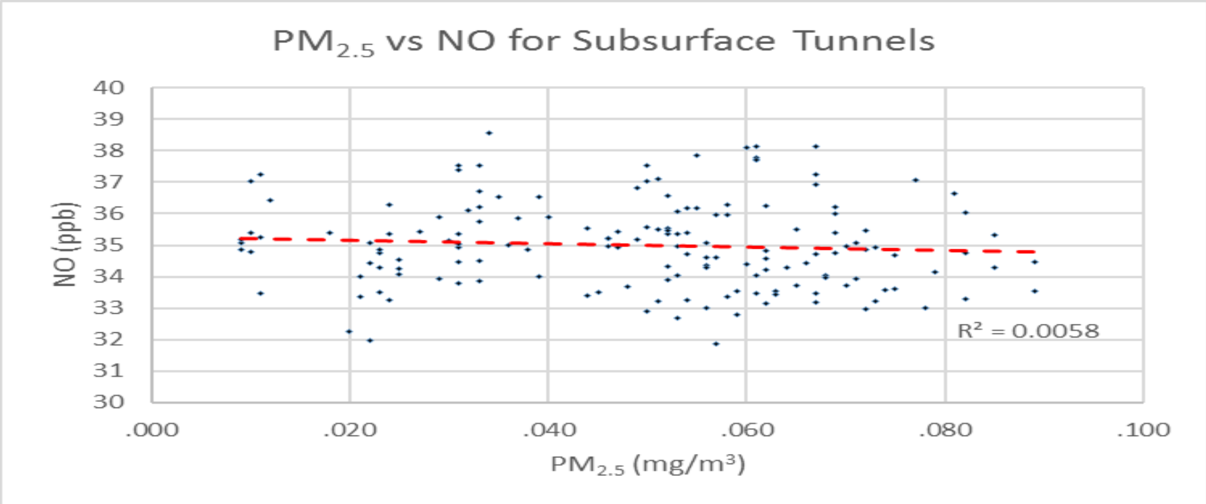
(Figure 25. Correlation Between PM_{10} and NO for Deep Tunnels)



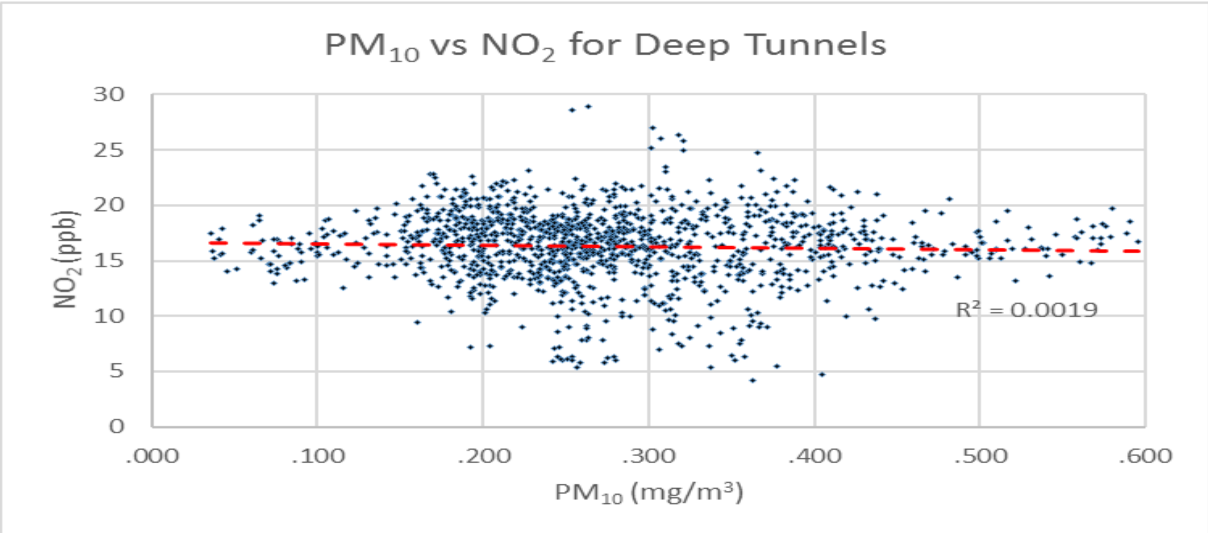
(Figure 26. Correlation Between PM_{10} and NO for Subsurface Tunnels. Note that trend is only significant at 95% confidence level rather than 99%)



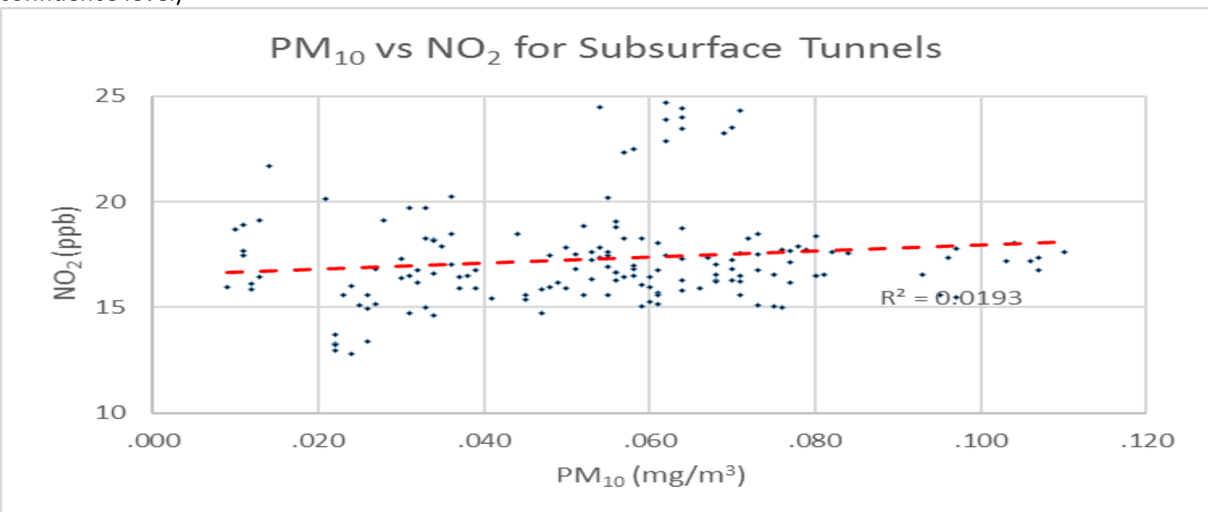
(Figure 27. Correlation Between $PM_{2.5}$ and NO for Deep Tunnels)



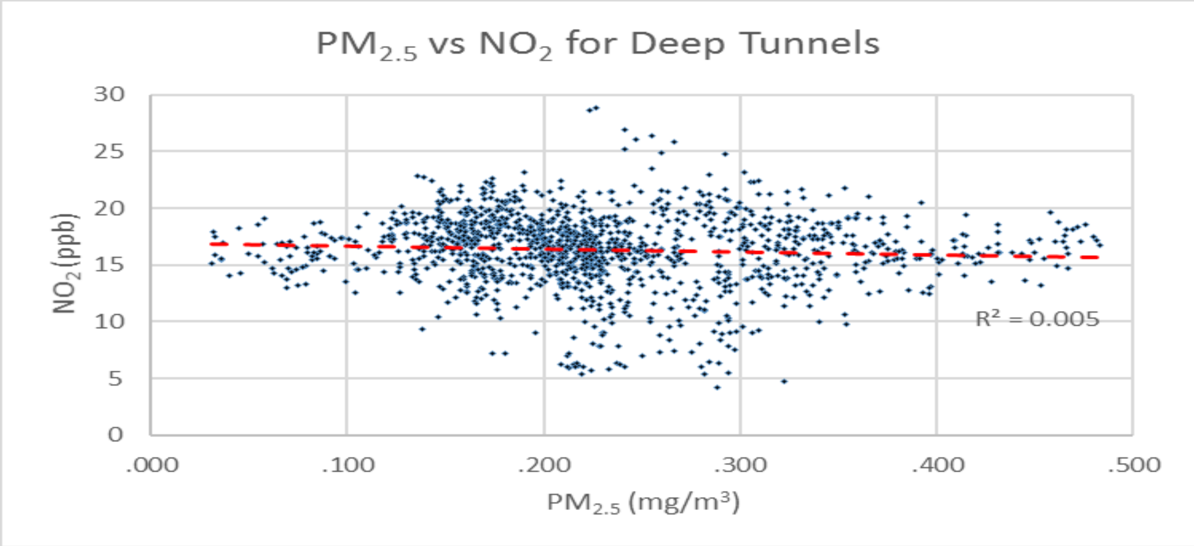
(Figure 28. Correlation Between $PM_{2.5}$ and NO for Subsurface Tunnels. Note that trend is insignificant at 95% confidence level)



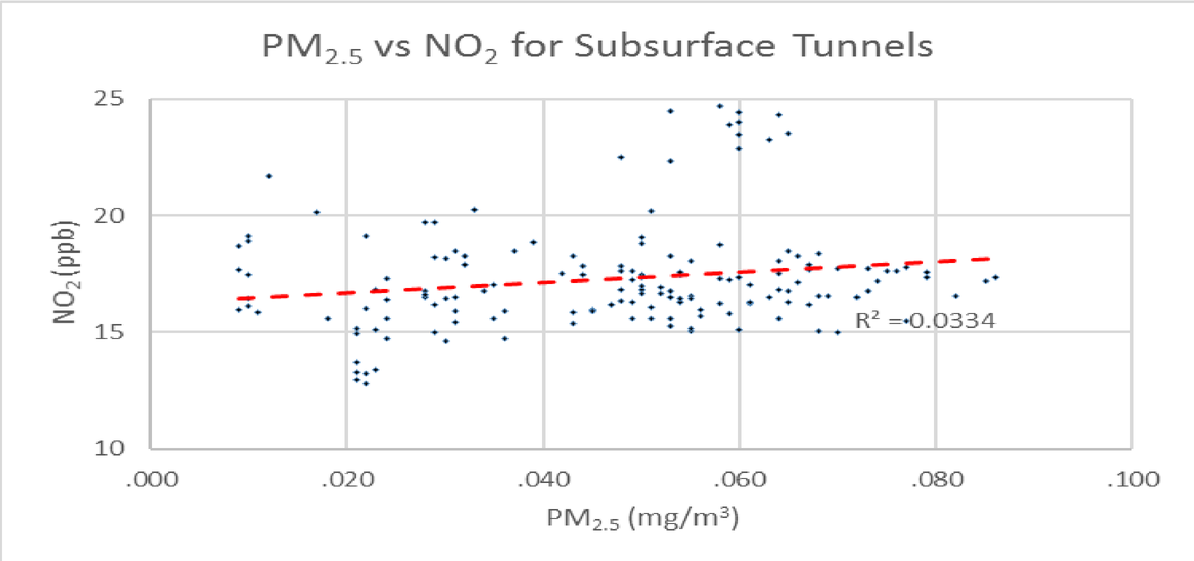
(Figure 29. Correlation Between PM_{10} and NO_2 for Deep Tunnels. Note that trend is insignificant at 95% confidence level)



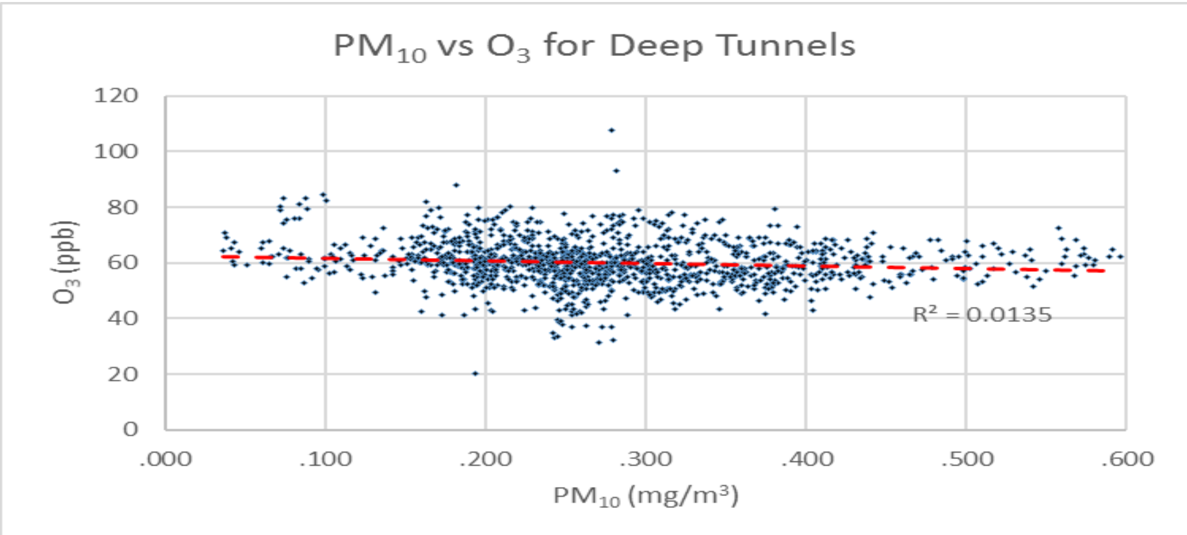
(Figure. 30 Correlation Between PM_{10} and NO_2 for Subsurface Tunnels)



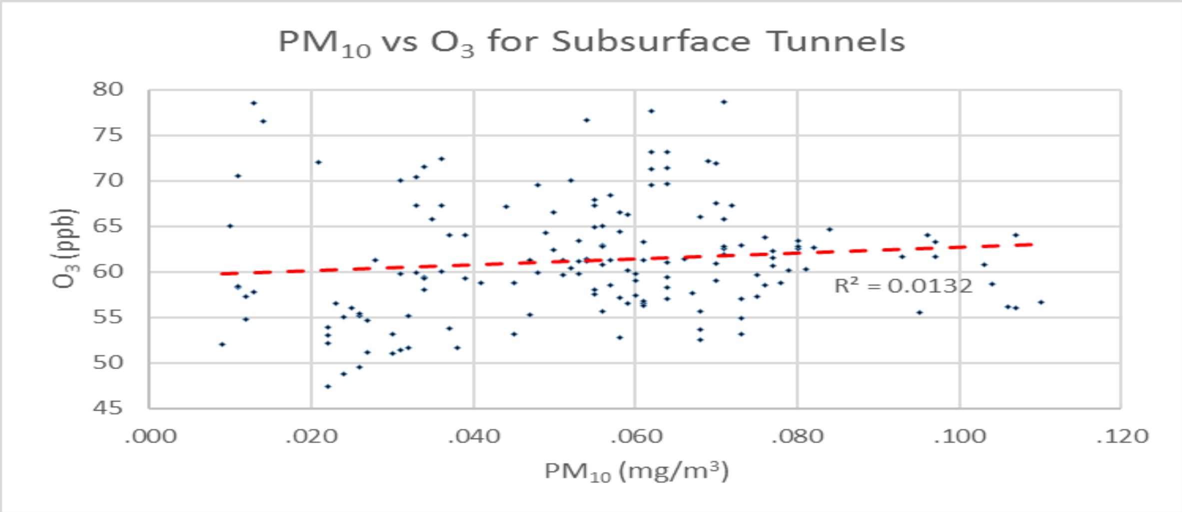
(Figure 31. Correlation between $PM_{2.5}$ and NO_2 for Deep Tunnels)



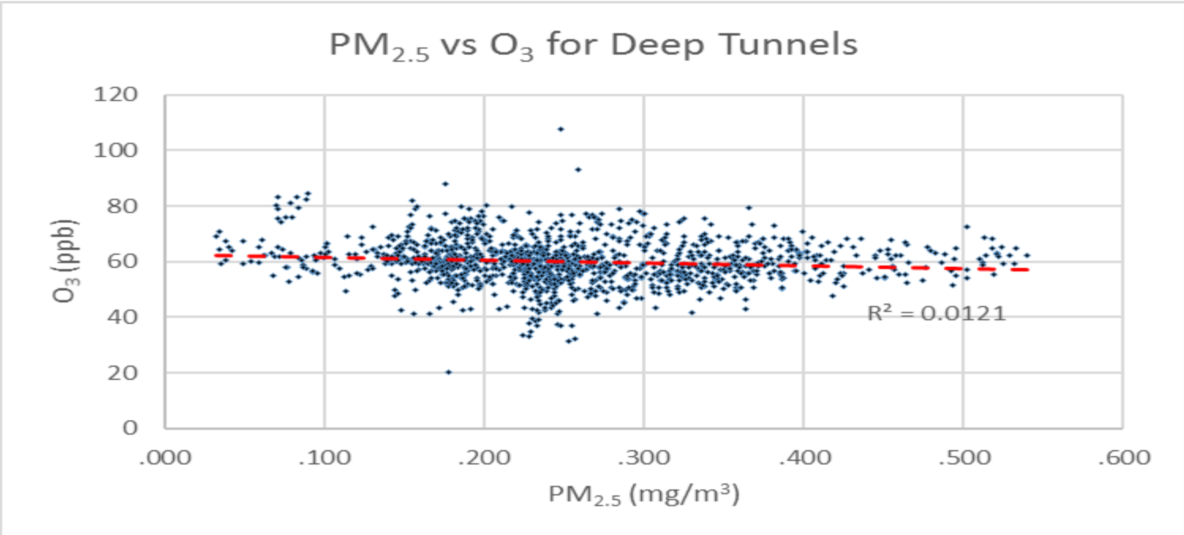
(Figure 32. Correlation Between $PM_{2.5}$ and NO_2 for Subsurface Tunnels)



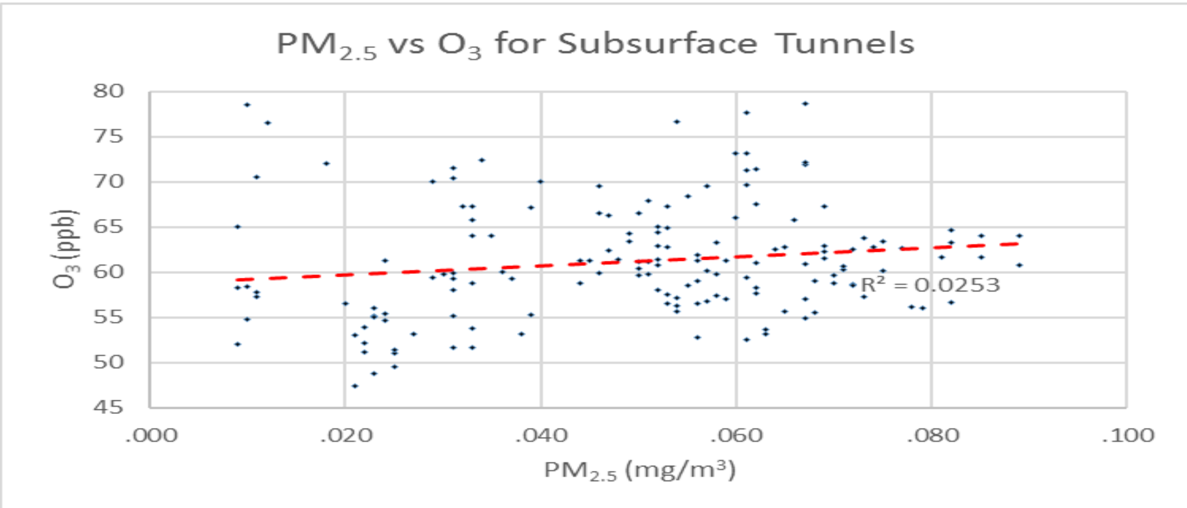
(Figure 33. Correlation Between PM_{10} and O_3 for Deep Tunnels)



(Figure 34. Correlation Between PM_{10} and O_3 for Subsurface Tunnels. Note that correlation is insignificant at 95% confidence level)



(Figure 35. Correlation Between $PM_{2.5}$ and O_3 for Deep Tunnels)



(Figure 36. Correlation Between $PM_{2.5}$ and O_3 for Subsurface Tunnels. Note that correlation is significant only at 95% confidence level rather than 99% confidence level)

Correlations Across Deep Tunnels										
		Proximity	NO	O_3	NO_2	PM_1	$PM_{1\text{-}2.5}$	$PM_{2.5}$	$PM_{2.5\text{-}10}$	PM_{10}
Proximity	Pearson Correlation		.036	.117**	.227**	.269**	.315**	.335**	.351**	.357**
	Sig. (2-tailed)		.230	.000	.000	.000	.000	.000	.000	.000
	N		1120	1120	1120	1120	1120	1120	1120	1120
NO	Pearson Correlation	.036		.294**	.022	-.143**	-.140**	-.135**	-.130**	-.128**
	Sig. (2-tailed)	.230		.000	.423	.000	.000	.000	.000	.000
	N	1120		1350	1350	1350	1350	1350	1350	1350
O_3	Pearson Correlation	.117**	.294**		.479**	-.080**	-.100**	-.110**	-.116**	-.114**
	Sig. (2-tailed)	.000	.000		.000	.003	.000	.000	.000	.000
	N	1120	1350		1350	1350	1350	1350	1350	1350
NO_2	Pearson Correlation	.227**	.022	.479**		-.095**	-.071**	-.057*	-.044	-.044
	Sig. (2-tailed)	.000	.423	.000		.000	.009	.037	.110	.104
	N	1120	1350	1350		1350	1350	1350	1350	1350
PM_1	Pearson Correlation	.269**	-.143**	-.080**	-.095**		.987**	.971**	.950**	.946**
	Sig. (2-tailed)	.000	.000	.003	.000		0.000	0.000	0.000	0.000
	N	1120	1350	1350	1350		1350	1350	1350	1350
$PM_{1\text{-}2.5}$	Pearson Correlation	.315**	-.140**	-.100**	-.071**	.987**		.996**	.986**	.982**
	Sig. (2-tailed)	.000	.000	.000	.009	0.000		0.000	0.000	0.000
	N	1120	1350	1350	1350	1350		1350	1350	1350
$PM_{2.5}$	Pearson Correlation	.335**	-.135**	-.110**	-.057*	.971**	.996**		.996**	.992**
	Sig. (2-tailed)	.000	.000	.000	.037	0.000	0.000		0.000	0.000
	N	1120	1350	1350	1350	1350	1350		1350	1350
$PM_{2.5\text{-}10}$	Pearson Correlation	.351**	-.130**	-.116**	-.044	.950**	.986**	.996**		.998**
	Sig. (2-tailed)	.000	.000	.000	.110	0.000	0.000	0.000		0.000
	N	1120	1350	1350	1350	1350	1350	1350		1350
PM_{10}	Pearson Correlation	.357**	-.128**	-.114**	-.044	.946**	.982**	.992**	.998**	
	Sig. (2-tailed)	.000	.000	.000	.104	0.000	0.000	0.000	0.000	
	N	1120	1350	1350	1350	1350	1350	1350	1350	

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Correlation is insignificant at 0.05 level (2-tailed).

(Table 5. Summary of Bivariate Correlations Between Deep Tunnels)

Correlations Across Subsurface Tunnels										
		Proximity	NO	O_3	NO_2	PM_1	$PM_{1\text{-}2.5}$	$PM_{2.5}$	$PM_{2.5\text{-}10}$	PM_{10}
Proximity	Pearson Correlation		-.283**	-.220**	-.154	.256**	.252**	.261**	.305**	.341**
	Sig. (2-tailed)		.000	.006	.056	.001	.002	.001	.000	.000
	N		155	155	155	155	155	155	155	155
NO	Pearson Correlation	-.283**		.613**	.594**	-.056	-.063	-.076	-.121	-.172*
	Sig. (2-tailed)	.000		.000	.000	.488	.435	.348	.132	.032
	N	155		155	155	155	155	155	155	155
O_3	Pearson Correlation	-.220**	.613**		.756**	.181*	.169*	.159*	.115	.077
	Sig. (2-tailed)	.006	.000		.000	.024	.035	.048	.155	.343
	N	155	155		155	155	155	155	155	155
NO_2	Pearson Correlation	-.154	.594**	.756**		.198*	.183*	.174*	.139	.101
	Sig. (2-tailed)	.056	.000	.000		.014	.023	.030	.085	.210
	N	155	155	155		155	155	155	155	155
PM_1	Pearson Correlation	.256**	-.056	.181*	.198*		.999**	.997**	.970**	.875**
	Sig. (2-tailed)	.001	.488	.024	.014		.000	.000	.000	.000
	N	155	155	155	155		155	155	155	155
$PM_{1\text{-}2.5}$	Pearson Correlation	.252**	-.063	.169*	.183*	.999**		.999**	.970**	.868**
	Sig. (2-tailed)	.002	.435	.035	.023	.000		.000	.000	.000
	N	155	155	155	155	155		155	155	155
$PM_{2.5}$	Pearson Correlation	.261**	-.076	.159*	.174*	.997**	.999**		.976**	.880**
	Sig. (2-tailed)	.001	.348	.048	.030	.000	.000		.000	.000
	N	155	155	155	155	155	155		155	155
$PM_{2.5\text{-}10}$	Pearson Correlation	.305**	-.121	.115	.139	.970**	.970**	.976**		.948**
	Sig. (2-tailed)	.000	.132	.155	.085	.000	.000	.000		.000
	N	155	155	155	155	155	155	155		155
PM_{10}	Pearson Correlation	.341**	-.172*	.077	.101	.875**	.868**	.880**	.948**	
	Sig. (2-tailed)	.000	.032	.343	.210	.000	.000	.000	.000	
	N	155	155	155	155	155	155	155	155	

**. Correlation is significant at the 0.01 level (2-tailed).

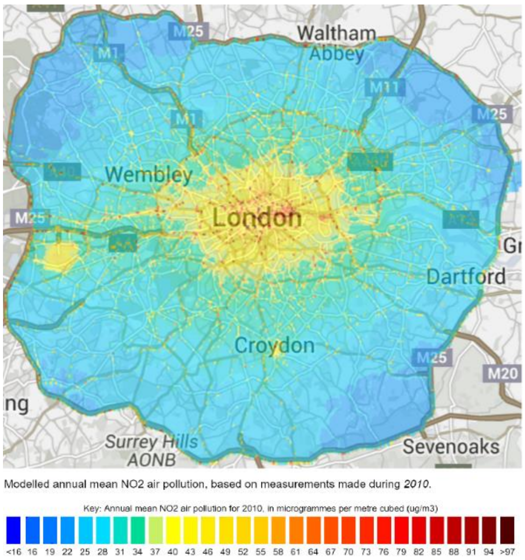
*. Correlation is significant at the 0.05 level (2-tailed).

Correlation is insignificant at 0.05 level (2-tailed).

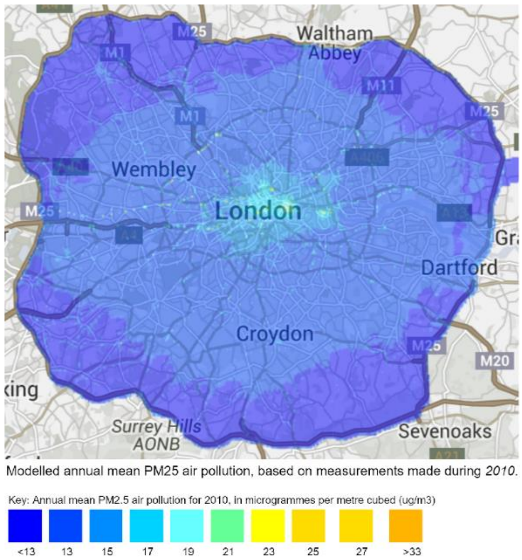
(Table 6. Summary of Bivariate Correlations Across Subsurface Lines)

- Secondary Data

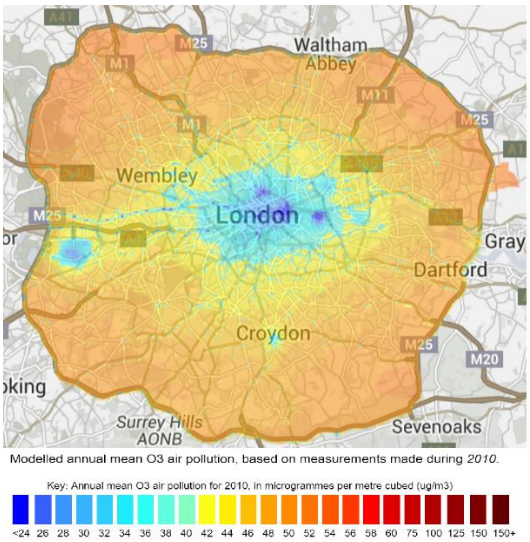
Baseline levels for Greater London of various pollutants were obtained from the London Air Quality Network run by the London Air group based at King's College London. LAQN have produced annual pollutant maps of average pollutant concentrations for $PM_{2.5}$, PM_{10}, NO_2 and O_3. When calculating yearly exposure levels for passengers and staff, typical levels found in London Zones 2-3 were utilised, as they were considered a reasonable middle ground for pollutant exposure between the commercial city centre and residential areas where passengers using underground sections of the tube were likely to reside.



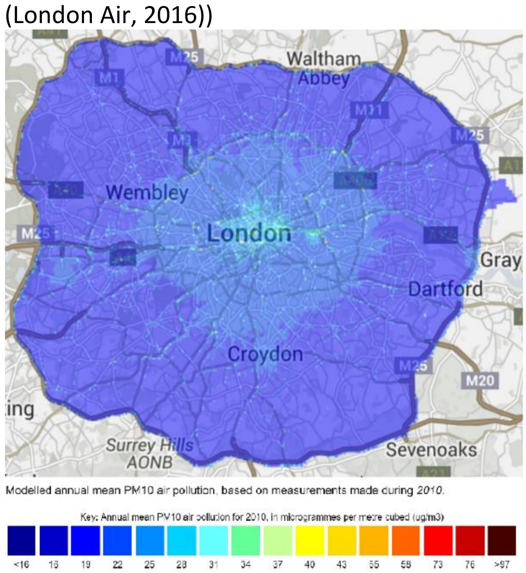
(Figure 37. Distribution of NO_2 Across London (London Air, 2016))



(Figure 38. Distribution of $PM_{2.5}$ Across London (London Air, 2016))



(Figure 39. Distribution of O_3 Across London (London Air, 2016))



(Figure 40. Distribution of PM_{10} Across London (London Air, 2016))

Pollutant	Range of Values	Zone 2 Value used for Calculations
$PM_{2.5}$	13 - >33 ug/m^3	17 ug/m^3
PM_{10}	20 – 76 ug/m^3	25 ug/m^3
O_3	56 - <24 ppb	34 ppb
NO_2	22 - >97 ppb	45 ppb

(Table 7. Summary of Secondary Data Taken from London Air Quality Network)

Discussion

The data obtained through this investigation allows both primary research questions to be answered: What is the spatial distribution of air pollution on the London underground, and does this pollution pose a health risk to passengers or staff? In addition to answering these questions, the data identified several unexpected trends between test variables, which may shed light on the original sources of underground pollution as well as reveal previously unidentified NO-NO_2-O_3 dynamics in environments devoid of sunlight.

Pollution Distribution

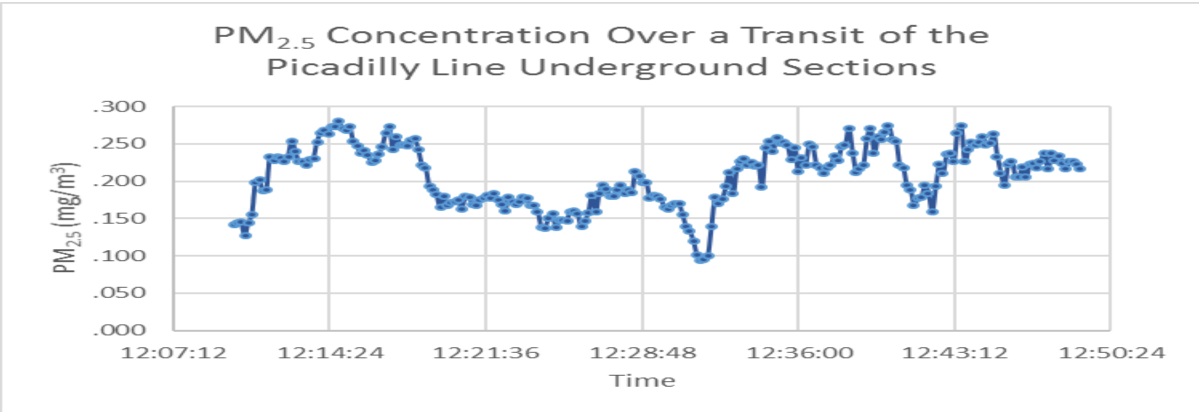
- Aerosols

General PM concentrations were very high across the underground portions of the Tube, particularly the deep lines as opposed to the shallow subsurface lines. For respirable $PM_{2.5}$, the mean concentration for subsurface lines was 50 ug/m3, compared to 252 ug/m^3 across the deep lines. However, both line categories are far in excess of the WHO and EU limits of 10 and 25 ug/m^3. These findings are consistent with PM levels reported by TfL and the IOM, and are similar to findings in other underground metros around the world.

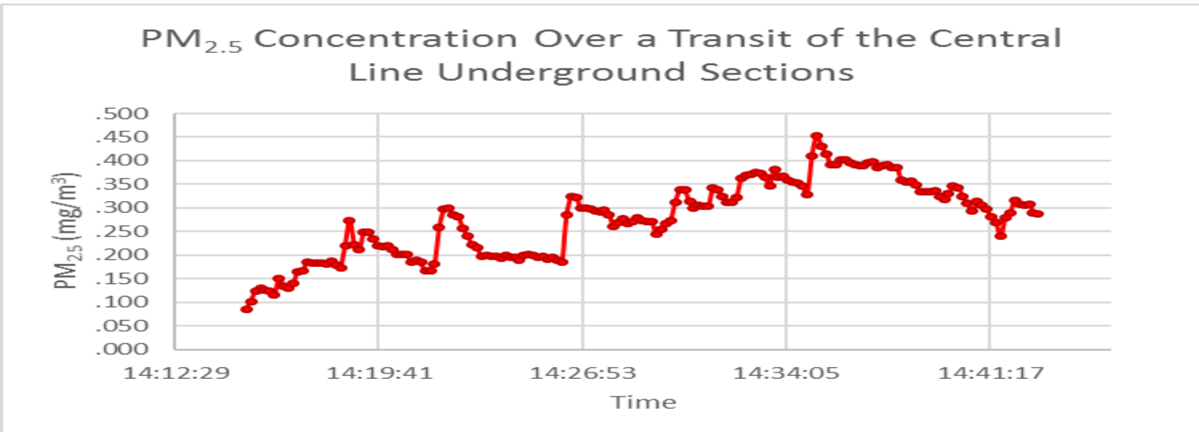
The stark difference between deep and subsurface lines is consistent with the theory that PM is primarily created within the underground network by friction between carriage wheels and rails, as opposed to being drawn in from surface sources. Although not fully mapped, air intakes for the subsurface lines track very closely with major roads as the lines run along major surface transport routes, as opposed to the deep lines where no such relationship appears to exist. Additionally, the tunnel mouths on the surface lines are more centrally located than those of the deep lines (in fact, two deep lines, the Victoria and Waterloo & City Lines, are wholly enclosed and have no aboveground tunnel mouths). Thus, the increased ventilation on subsurface routes is a net negative influence on PM concentrations, rather than allowing more PM to be drawn into the tunnels.

Across the deep lines, a spatial pattern was identified with respect to proximity to tunnel mouths. A weak positive correlation between greater distance from tunnel mouths and PM counts was identified, marginally stronger for larger particle sizes. This relationship was insignificant for $PM_{2.5}$ across the subsurface lines. Distance from a tunnel mouth approximates both distance and depth for the deep tube, but only distance for the subsurface lines, suggesting that the effect is primarily due to a relationship with depth rather than lateral distance from a tunnel mouth.

The slightly increased magnitude in this effect with larger particle sizes (r=0.335 for $PM_{1.0}$ vs r=0.358 for PM_{10}) is consistent with Seaton *et al.*'s conclusion that a greater proportion of more dangerous low-diameter dust is from external sources and drawn in through ventilation and tunnel mouths (Seaton *et al.,* 2005). However, the tiny difference illustrates that this is in fact a very minor consideration. Beyond this however, it is worth noting that proximity is a fairly poor predictor of actual PM levels in a given section of tunnel. Figures (NUMBER and NUMBER) show example time series plots of individual journeys along the entirety of underground sections of lines.



(Figure 40. $PM_{2.5}$ Concentration Over a Transit of the Picadilly Line)



(Figure 41. $PM_{2.5}$ Concentration Over a Transit of the Central Line)

As shown in figures 40 and 41, individual tunnel segments often buck the overall trend, being either significantly cleaner or dirtier than expected. For example, between Russel Square and King's Cross-St. Pancras, almost the farthest point on the Piccadilly Line from a tunnel mouth, $PM_{2.5}$ counts are actually the lowest across the entirety of the underground section of the line, shown as a trough in the centre of the plot. A closer look at other unexpectedly low readings reveals a pattern: tunnels near major nodes between multiple lines tend to be less polluted than isolated tunnels. Along with King's Cross-St. Pancras (Northern, Piccadilly, Victoria and Subsurface Lines), other major interchange stations such as Bank/Monument (Northern, Central and Subsurface Lines) and Charing Cross/Embankment (Northern, Bakerloo and Subsurface Lines) exhibit similar behaviour. This may be associated with the composite nature of these stations providing more ventilation than typical stations, it is notable that Waterloo, which doesn't serve any subsurface lines but is a major node has very high aerosol pollution levels in adjacent tunnels, perhaps suggesting that interchanges between deep and subsurface lines lead to reduced aerosol levels in nearby deep tunnels. What this variation unambiguously shows, however, is that individual station and tunnel characteristics account for much more variation in aerosol pollutant levels than the general spatial trends identified in this study.

- Gasses

The generalised spatial patterns of gaseous pollutants in the London Underground are somewhat more complex than those of aerosol pollutants. There is no meaningful difference between deep and subsurface lines for the actual levels of gaseous pollution, however there are differences in the distribution. NO exhibits no relationship with proximity for either subsurface lines or deep lines, while NO_2 and O_3 exhibit very weak negative relationships with proximity for subsurface lines and weak positive relationships with proximity for the deep lines. These contradictions are fairly surprising and do not fit with previous expectations. Particularly puzzling is the finding that NO and NO_2, both exhaust products, do not follow the same distribution across both types of line (although they are correlated with each other).

The relationship between surface NO_2 and O_3 is complex; NO_2 is an O_3 precursor, rapidly breaking down into NO and a free oxygen atom in the presence of sunlight. This free oxygen atom then combines with molecular oxygen (O_2) to form O_3. Thus, during time series on the surface, a decrease in NO_2 is linked with an increase in O_3 and NO (Han *et al.,* 2010). The measured increase in O_3 concentration relative to surface levels contrasts with a decrease in NO_2 concentration relative to surface levels, further complicating the pattern. It is feasible that O_3 is being produced in the tunnels by the electric rails through the reaction $3O_2$ ->electricity-> $2O_3$, which would explain the increased concentration relative to the surface, as well as the reversing of the typical inverse relationship between NO_2 and O_3. O_3 can interact in a redox reaction with NO to form NO_2, thus one would expect to see a positive correlation between the two gasses assuming continuous production of O_3 from the electric rails.

However, this scenario does not explain why concentrations of both NO_2 and O_3 are higher near tunnel mouths in subsurface lines but higher further away from tunnel mouths in the deep lines. This discrepancy may be down to depth; proximity to a tunnel mouth approximates depth and distance in the deep lines, but only distance in the subsurface lines. However, the mechanism by which depth would impact the spatial distribution of gas concentrations is unclear. Further gas-focused study across a broader range of gasses is likely required to gain an adequate picture of gas dynamics on the London Underground. No previous investigation of an underground metro has either sampled both O_3 and NO_2 or analysed data with distance/depth as a factor, so there is little information with which to contextualise these findings. Furthermore, ongoing research into these kind of gas dynamics is being undertaken in the context of atmospheric science where a lack of sunlight is only considered in the context of diurnal cycles in gas ratios rather than indoor or underground pollution (Jacobs, 2002)(Wallace & Hobbs, 2006). The most likely explanation would be the interaction of the sampled gasses with unknown other variables, such as volatile organics, sulphurous pollution from combustion reactions, products of human respiration such as CO_2 or relative humidity in tunnels.

Associations between aerosols and gasses are significant even when compensating for spatial factors such as proximity, however these trends are quite weak. Without knowing the composition of the aerosols found in the underground it is difficult to explain this relationship. It is possible these associations are due to partial aboveground sources, which would vary with each other, but it is more likely due to the interaction of the compounds composing aerosols with gasses or effects from passenger traffic which were beyond the scope of this study.

Health Risks

When taking into account both background surface levels of pollutants and EU/WHO recommended limits, this study allows an informed assessment of the health risk posed by the air quality on the London Underground to both staff and passengers. Background levels of O_3, NO_2 and $PM_{2.5}$ are taken from the London Air Quality Network, and are consistent with initial aboveground calibration readings collected as part of this investigation, while NO and CO are disregarded as they were detected in concentrations orders of magnitude lower than the most stringent health recommendations. NO_2 levels in central London already exceed health guidelines by 5-120% depending on location, while O_3 levels account for only about 34% of the WHO guidelines. In general, the scale of increase O_3 relative to surface concentrations is minor compared to exposure levels, as well as somewhat offset by the reduction in NO_2 compared to surface concentrations. When considering the amount of time passengers and staff actually spend on the underground portions of the tube, there is no meaningful change in overall health risk due to gas concentrations compared to the surface. Despite this finding, a very meaningful difference exists between the surface and underground tunnels, particularly the deep tube lines when considering aerosols. An examination of exposure levels is required to fully understand the significance of this difference and its potential health effects.

Naturally, aerosol exposure levels are different for passengers and staff. Tube drivers have a 36.5-hour work week (TSSA, 2015). Approximately 35% of the Underground is deep tunnel; even under the most conservative scenario (there is a higher train frequency within the central zones that contain the deep tube), the average driver is exposed to 12.78 hours of deep tube air every work week, and approximately 555 hours total annually. This means that in the hypothetical absence of any other source at all (background levels in London are in fact 15-20 ug/m^3 (London Air, 2016)), a $PM_{2.5}$ count of 395 ug/m^3 across the deep tube would cause a tube driver to exceed the annual limit set by the EU and WHO for exposure. Station workers at the most polluted points on the tube may face significantly higher exposures.

The mean concentration of $PM_{2.5}$ across the deep tube was 252 ug/m^3, more than 1000% of the WHO health recommendations. In addition to this, aerosol pollution on the surface in London is about 17 ug/m^3 on average (London Air, 2016). Exposure levels calculated by Seaton *et al.* set 200 ug/m^3 as the maximum exposure faced by workers averaged over an 8-hour shift, which yields an annual mean 24 hour exposure of 38.4 ug/m^3 with no other factors, increasing to 53.7 ug/m^3 with a background exposure of 17 ug/m^3. This study's analysis for general drivers is more conservative, estimating an exposure of 12.78 hours/working week on the deep tube based on statistics from the major London Underground unions (TSSA, 2016). This yields an average exposure of 16.0 ug/m^3 with no other factors, increasing to 32 ug/m^3 including baseline London levels. However, this could be significantly higher for certain drivers, such as those on the wholly enclosed Victoria and Waterloo & City lines, who could face maximum annual exposures of 57.3 ug/m^3 if working exclusively as drivers on these lines. Each increase of 10 ug/m^3 of $PM_{2.5}$ corresponds to a mortality increase of between 6 and 9%, 7.52% according to Shi *et al.* (2016). Therefore, the mortality risk of staff could be increased between 11.3 % and 30.3% due to underground aerosol pollution. Obviously, passengers will generally face lower exposure levels than drivers and staff, however, averaged across all deep lines, a passenger commuting one hour each day would nonetheless face an incremental increase of 10.5 ug/m^3 over their normal exposure of $PM_{2.5}$, equivalent to a 6.3-9.5% increased risk of mortality.

These statistics do not account for increased or decreased health impacts based on the composition of PM pollution, which are currently unknown for chronic exposure, but is expected to have a significant impact on the chronic toxic, carcinogenic and inflammatory effects of respirable aerosols (Franklin *et al.*, 2006,2008). Determining aerosol composition was beyond the scope of this study, as was a thorough investigation of the chronic health effects of aerosol composition, which comes more under the purview of medical science rather than geography. However, it is unambiguous that elevated $PM_{2.5}$ concentrations on the deep tube represent a health risk to both London Underground staff and regular passengers. These findings contribute to the growing body of evidence that many metro systems worldwide pose some measure of public health risk from aerosol pollution. However, adequately quantifying the risk posed will require significantly more data beyond the scope of an undergraduate dissertation. In order to build a complete picture of the atmosphere of the London underground it will be necessary to conduct longer-term monitoring of a wider range of pollutants utilising a network of sensors, as well as determining the composition of aerosol pollutants and the chronic, rather than merely acute, health effects of differing aerosolised particles. It may well be the case that pollutant levels on the London Underground are determined to pose an acceptable risk, particularly given that there is no lower threshold for negative health effects. However, currently passengers and staff are not only uninformed, but potentially misinformed about the risk posed due to methodological flaws in the only previous broad investigation of Tube dust and adherence to grossly inappropriate safety regulations not supported by the medical literature. An advocacy group, Clean Air in London (CAL), have critiqued both the little TfL data publically available and Seaton *et al.*'s 2005 study, particularly interpretation of safety regulations, accusing TfL and the Mayor's Office "'turning a blind eye' to a potentially significant public health risk for vulnerable Londoners and others who use the most polluted parts of the London Underground" (Birkett, 2013). However, CAL have not published any scientific, peer-reviewed reports themselves, instead calling for publically funded investigations into pollutant levels on the Underground. Bringing scientific scrutiny to what may become a contentious public issue will be necessary to inform any future debate. However, this author's analysis of TfL's published data is similar to Clean Air in London's conclusions -that TfL and the Mayor's Office are seriously misinterpreting the health risk of the air quality on the Tube. What is not clear is whether this is intentional misdirection to avoid a scandal or simply a misunderstanding of what the grossly inappropriate HSE regulations represent. However, taken in the context of repeated strikes over introduction of the 24-hour Tube (BBC, 2015), there is a clear incentive for authorities to avoid bringing attention to any further risks to TfL staff from air pollution.

Mitigation and Future Study

These results beg the question, “what can be done to minimise the risk to passengers and staff?” A number of potential courses of action should be examined based on these findings. Firstly, it would be prudent to create standards, potentially on an EU-wide basis, that govern acceptable levels of aerosol pollution in underground metros that are in line with standards used to regulate aboveground $PM_{2.5}$ and PM_{10} levels rather than continued inappropriate reliance on the outdated acute HSE regulations. Secondly, methods of cleaning tunnel air such as filters on trains, tunnel wall cleaning strategies and deployment of “cleaning trains” should be scientifically examined for efficacy in reducing $PM_{2.5}$ and PM_{10} concentrations specifically. Finally, information should be made available publically so that both staff and passengers are informed of what may well be considered an acceptable risk and have the option to utilise alternative transport of personal protective equipment such as facemasks. The creation of a real-time monitoring network and appropriate air quality index would allow passengers to make informed decisions of risk, much like those used in typical weather forecasts worldwide. Most developed cities, including London have air quality forecasts and “nowcasts” that citizens may use to stay informed of health risks and authorities may use to take decisions such as reducing traffic or closing schools. Extension of these systems to include underground transport networks would be a logical step not only for London, but also for other cities operating deep metro systems. One of the most publicised uses of air quality indices is that of Beijing, which has extremely problematic surface air pollution due to high reliance on coal-fired power plants and heavy road traffic, with the 2015 “airpocalypse” garnering much attention in the international media (Phillips, 2015). The fact that $PM_{2.5}$ levels found in the London Underground in consistently exceed the scale used in Beijing and would trigger school and business closures alongside traffic bans highlights the need for further research (US State Department Mission to China, 2016). Underground metros like the Tube represent a potentially major public health risk that merits future thorough investigation.

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Appendices

- Appendix 1: Ethics Opt Out Form and Risk Assessment Form

Department of Geography

‘Opt-out’ from submission of ethical approval forms

This form is intended for Undergraduate and Postgraduate students undertaking research that will not encompass: a) the collection of primary data from people; b) the re-use of primary data collected by other researchers; or c) work that might be reasonably considered to have ethical implications (*e.g.* an environmental impact).

If your project does not meet these criteria, do not complete this form.

Statement of Principle

Many research projects undertaken by physical or quantitative geographers do not involve the collection of data directly from people, which is the principal source of ethical risk in most human geography research projects. **However, since nearly all projects involve some level of ethical ‘risk’, you are expected to discuss and assess the sources of possible risk with your supervisor/student.**

By completing this form, the student and supervisor are certifying that the following issues have been discussed and that no ethical issues have been identified:

1. **Impacts on Supporting Staff**: consideration must be given to potential impacts of the researcher’s activities on supporting staff based overseas: *e.g.* might the nature of the research (or the results) expose them to retaliation from the local or national authorities?
2. **Impacts on the Natural Environment**: consideration should be given to the potential impacts of the researcher’s activities on the environment in which their research is undertaken. In general, the researcher should seek to ‘leave no trace’ on the landscape or its ecology.
3. **Impacts on the Human Environment**: consideration should be given to the potential impacts of the researcher’s activities on the way that humans interact with, or perceive, their environment. In most cases this is unlikely to result in an ethical ‘risk’; however, findings that led to a sudden revaluation of an area may have unintended & severe consequences for the nearby residents (*e.g.* the finding of valuable natural resources leading to land seizures). Consequently, due consideration should be given to the potential ethical dimension of any impacts.

If the supervisor and student are agreed that the named research project presents no obvious or known ethical issues then the supervisor may certify this by returning this form to the Undergraduate Senior Programme Officer in the Geography Department.

If at any time the level of ethical risk is considered—for any reason—by the student or supervisor to have changed then they should contact the relevant Research Ethics Committee immediately and file an application for ethical approval.

Note: Data collected from individuals and groups without *prior* ethical approval may not be incorporated in the research project via retrospective approval and may expose the researcher to severe sanctions by the College. *Submitting this form does not constitute an application, or approval, for work with human subjects.*

Submitting this form

This form must be sent to the appropriate administrator fom the supervisor’s KCL email account.

Confirmation of opt-out from submission of ethical approval forms

Name of Project:	Mapping Pollution on the Tube
Applicant's Name:	Brynmor Saunders
Supervisor's Name:	Thomas Smith
Supervisor's Approval:	*I approve this research on the grounds that I have discussed this research with the named applicant and no ethical risks have been identified*
Date of Approval:	4th November 2015

3 SAFETY AND RISK MANAGEMENT PLAN AND ASSOCIATED DOCUMENTATION

After reading through ALL risk categories (pages 4-9), please select RISK TYPE A or B below.

RISK TYPE A

You are only eligible for RISK TYPE A if ALL of the following are true:

- **Your work takes place within: college premises or home or within organizations/premises that have their own clear risk assessment in place.**
- **Your work involves ONLY library/archival data or existing on-line/other data.**
- **Your work WILL NOT expose you to risks greater than in everyday life i.e. you are carrying out activities that are normal for your everyday life and thus you are accustomed to managing associated risks.**

DECLARATION: I have considered ALL categories in this form (see page 4 onwards) and I declare that I am undertaking a student project/dissertation where: a) NONE of my research will be outside of college premises or home or organizations/premises that have their own clear risk assessment in place; and b) it does not involve ANY of the risks identified in ANY of the categories of this risk assessment form, except those I experience in my everyday life. Should my research project change, such that there are now risks involved, then it is my responsibility to resubmit this form after completing an assessment for Risk Type B.

RISK TYPE B

Fill out THIS PAGE and ALL OTHER PAGES in this form.

DECLARATION: I have considered ALL categories in this form and have indicated which risks apply to me that are greater than in everyday life and normal activities (writing yes/no for every section). Where I have answered 'yes' then I have also indicated the degree of risk from 1–5 (1=low, 5=high) and, where appropriate, added notes or comments relating to the level of risk. I have identified and added any additional risks not explicitly covered by this form in the final section.

SIGNATURES OF PERSON FILLING IN A RISK ASSESSMENT AND COUNTERSIGNATURE.
A. Person filling in this risk assessment
Signature **(TYPE YOUR NAME AND STAFF OR STUDENT ID IN PLACE OF A SIGNATURE)**: Brynmor Saunders 1312196
Date: 4/11/15
B. Countersignature and date. I sign to indicate that I have read this and consider it an appropriate assessment FOR THE REASONS I GIVE BELOW [if no reasons are given this form may be returned] (Students – Research Supervisor; Research Staff – Project Leader; Academic Staff – Head of Department)
REASONS: This project presents low risk and no risk beyond that of day-to-day activities. Signature **(TYPE YOUR NAME AND STAFF OR STUDENT ID IN PLACE OF A SIGNATURE)**: Thomas Smith
Date: 4/11/15

- Appendix 2: Original Research Proposal

IGS Proposal
Effect of the Urban Solar Flux Island on PV Solar Power: KCL Case Study

Word Count: 1878

Student ID: 1312196

Due 16th March, 2015

5SSG2049 PGI 2 14-15

Effect of the Urban Solar Flux Island on PV Solar Power: KCL Case Study

Research Question

It is widely agreed that solar energy will be a crucial component of any future green energy portfolio. Mega-engineering projects are an exciting possibility, however, complete overhaul of the EU energy grid is required before large-scale solar projects such as DESERTEC and TuNur in North Africa will be feasible, which could cost in the region of $100 billion (Alikhanzadeh *et al.,* 2013).Thus, for the time being, a sensible approach is to focus on developing local solar energy generation that can be plugged directly into the existing infrastructure. The efficacy of solar energy in urban areas is an area of contention within the academic literature, with some studies almost completely ruling out urban generation (Byrd *et al.,* 2013) and others proposing it as a key component for future energy generation (Close, 1996)(Yu, *et al.,* 2009)(Brandoni, 2014).

City-scale variation in solar generation potential is something that has not been well explored. Knowing where is most efficient to locate PV within an urban environment is hugely important for potentially marginal areas such as London. This project will explore the effect on energy generation of what Ryder and Toumi (2011) describe as the “urban solar flux island,” (USFI) which is the city-scale variation in irradiance (potentially on the order of 10%) largely caused by the distribution of particulate pollutants. The three main KCL campuses, which reside in different zones of the USFI mapped for London, will be used as a test case to determine the potential efficacy of PV installation for the College, and to help determine if the USFI is an important factor in urban solar power. This project seeks to answer whether the USFI can be a decisive factor in locating urban solar panels.

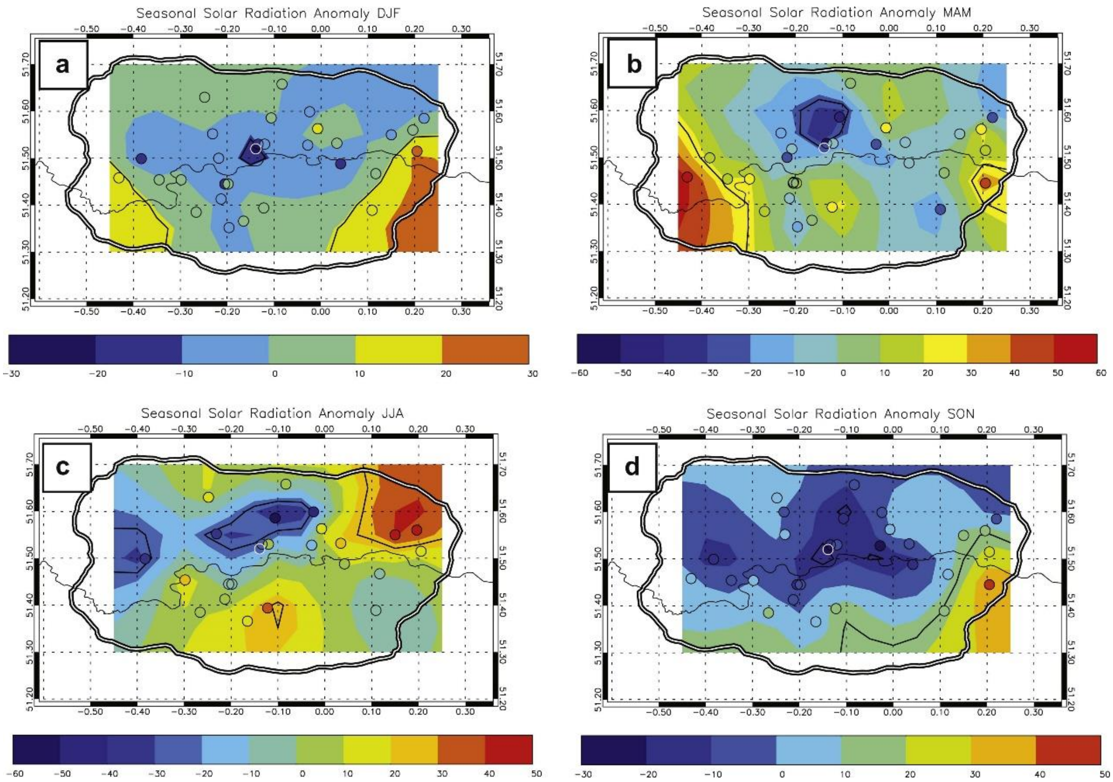

Figure 1. Urban Solar Flux Island (Ryder & Toumi, 2011)

Literature Review

Table 1. Summary of Key Studies (not exhaustive)

Study	Key Points
Ryder and Toumi, 2011	• Discovered urban solar flux island • City scale variability of mean 9% in insolation • Largely explained by pollution
Byrd *et al.*, 2013	• Mapped solar energy profile of Auckland • Found suburbia to be promising for energy generation • City centre not useful, but did not examine all surfaces or

	take into account open space/breaks in shading etc
Close, 1996 Khan & Hauge, 2012	• Strong evidence in support of PV use in dense urban SE Asia
Vaziri & Kellier, 2009	• Case study of high-rise PV in Florida
Yu *et al.,* 2009	• City wide insolation variability • Used LIDAR in Houston
Saunders *et al.,* 2014	• Forerunner to this project, strengths and weaknesses of Arduino controllers discovered

Ryder and Toumi's work is key to this project. Their examination of London's solar profile is unique, as London has a much denser weather sensor network than anywhere else with available data, allowing variation at this scale to be examined. If there is a correlation between the USFI and the actual energy that can be generated from PV panels then it will have major implications for cities beyond London, which may have vastly different USFIs based on prevailing wind, terrain etc. They provide a method for mapping the USFI from the London Air Quality Network datasets that will be utilised for this project.

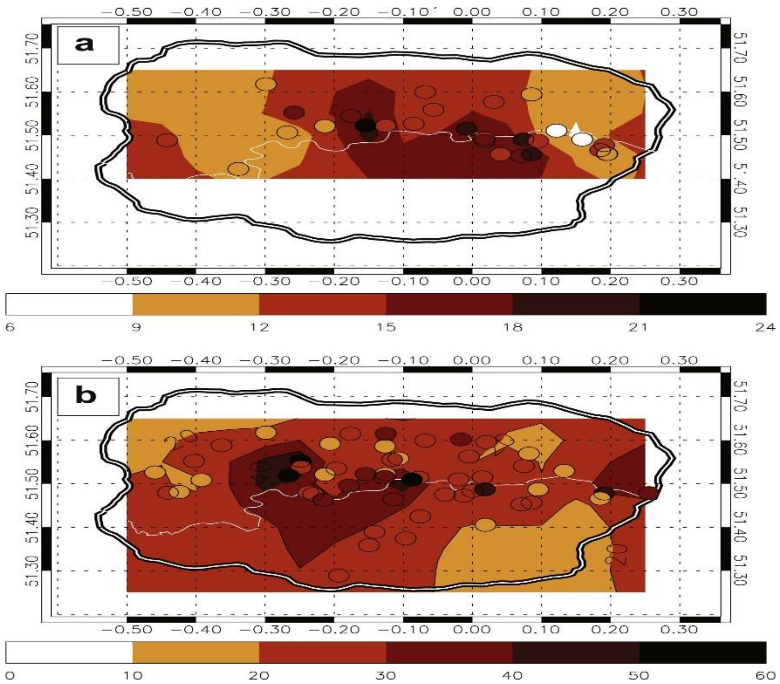

Figure 2. Particulate Distribution in London (Ryder & Toumi, 2011)

This project is in many ways a continuation and expansion of a previous undergraduate assignment. (Saunders *et al.,* 2014) Previous experience with the Arduino controllers and statistical methods that will be used is crucial to this project.

Byrd *et al*. is the primary paper that argues against PV deployment within the city centre, suggesting that dense suburbia provides the greatest potential for PV deployment and that the centre of the city should be avoided. However, the study excludes a great deal of surfaces within the city centre that may very well me useful for PV deployment, potentially skewing the results. This view is supported by studies (Yu *et al.,* 2009)(Close, 1996)(Jardim *et al.,* 2008)(Khan & Hauge, 2012) that provide evidence for the economic viability of dense urban solar power. Yu *et al.* is interesting as it maps the city-scale spatio-temporal variability in insolation of Houston using a LIDAR scanner. They show that the built up area has greatly changed the solar flux of the city on the small-scale due to shading. However, the effect of pollution distribution is not considered as a factor. In fact, particulate concentration is generally ignored completely as a factor by the literature, with the exception of desert dust for desert installations, which is not relevant to most urban areas. (Gueymard, 2011) This is quite startling given the size of the effect found by Ryder & Toumi, however, the scale is far below what current satellites can be used to detect (1km resolution) (Legrand et al., 2001) so any studies undertaken in cities without London's monitoring system would have to use LIDAR scanners deployed on aircraft, which would likely be prohibitively expensive.

Vaziri & Keller, 2009 is notable as a case study of their successful attempt to install PV panels on their high-rise university building, which can serve as a model for future solar endeavours at academic institutions.

Data provided by the UK government also shows that despite being in the South of the UK, London's installed solar capacity significantly lags behind other areas of the country. (Department of Energy & Climate Change, 2015) This is particularly acute in installation of PV on existing buildings, as the vast majority of installed capacity is from new builds such as the Blackfriars station bridge. It is suggested in the Guardian (2015) that this is largely due to the mobile nature of the London population –residents do not remain long enough to gain the financial benefits of PV- and the inflated property market. Thus, even if solar power is shown to be viable for existing buildings despite any problematic variability from shading or the USFI there may be added challenges on the political front in propagating it within the capital.

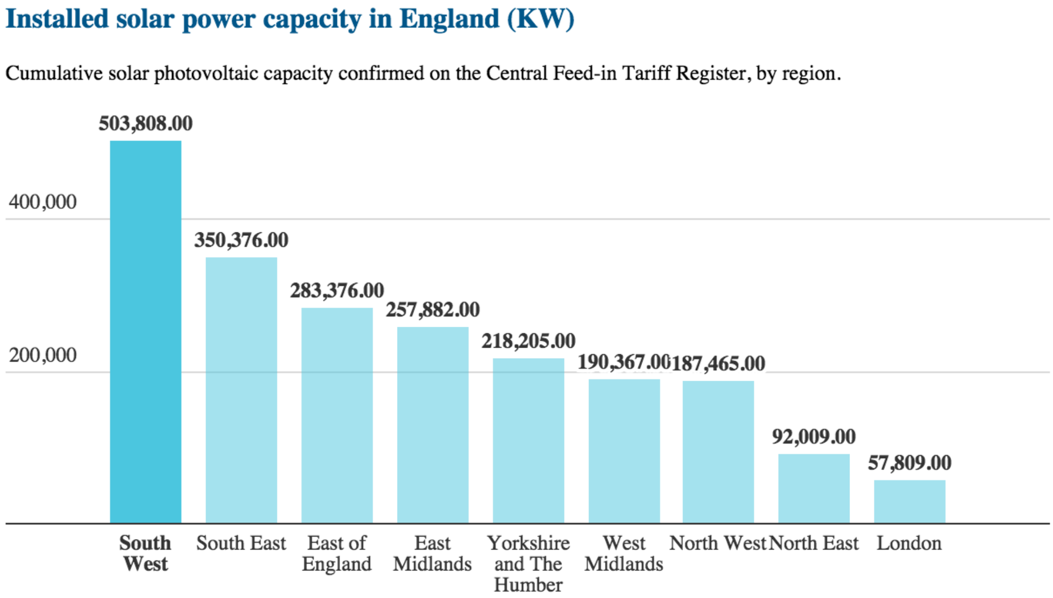

Figure 3. Installed Solar Capacity in England (Guardian, 2015)

Newton & Newman (2013) show that for Australia growth in the PV industry is being driven by suburbia, but show strong uptake in the major cities. This is in contrast to the situation in London of low uptake and shows a middle ground between (Byrd *et al.,* 2013) and (Yu *et al.,* 2009),(Close, 1996),(Jardim *et al.,* 2008), and(Khan & Hauge, 2012). It is worth noting that the definitions of “urban” and “suburban” are open to interpretation when considering these studies and that the characteristics of urban areas between countries at different levels of development may in fact be quite different. However, all the KCL sites are in what would be surely considered an urban rather than suburban zone. Ultimately, this project aims to look at intra-Urban variability, which is something that has not been greatly discussed in the literature, likely due to a paucity of data available.

Methodology

In order to determine whether the USFI will have any effect on the efficacy of PV installations at King's it will be necessary to collect primary data from the rooftops of the target buildings. In order to do this a series of probes will be deployed on the three main campuses to measure the incoming solar irradiance. These will be produced using Arduino programmable micro controllers with a n insolation sensor and small PV panel attached. Previous experience suggests that the Arduinos, while cheap, are not particularly robust, therefore there will be multiple backup sensors at each location and data network shields will be used to communicate data on a daily basis in order to allow immediate replacement if a sensor fails. These sensors will have to be wired, calibrated and programmed in the lab which will be a time consuming process at the start of the project that will need to be done promptly. Despite their limitations, the low cost of the Arduino controllers will allow more sensors to be deployed, thereby gaining a more detailed dataset that could be achieved with a single station on each target building.

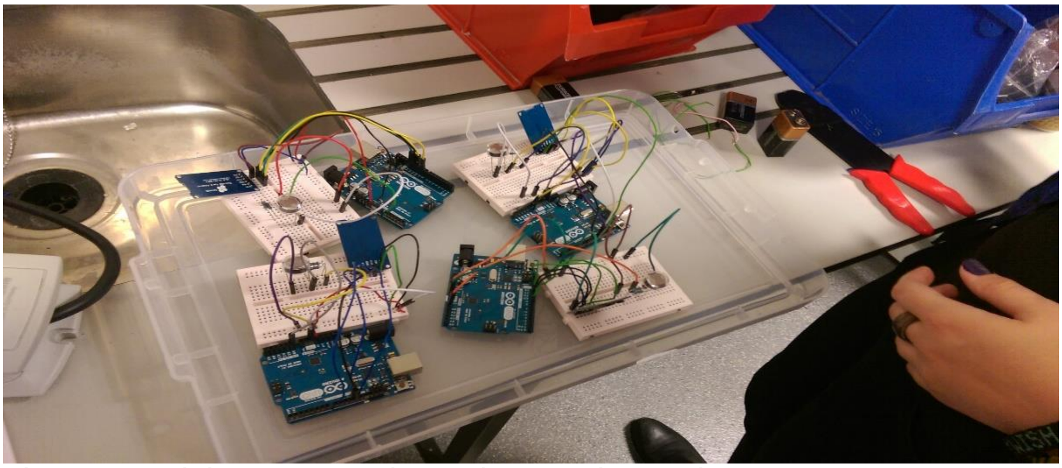

Figure 4. Arduino Sensors (Saunders *et al.,* 2014)

Secondary data will be taken from the same datasets that were used by Ryder and Toumi, which used a weather station network that is still in place and freely available. This will allow direct comparison to their results after the new data is processed using their method and model. The data provided by the London Air Quality Network (run by King's) and the Met Office will also allow some independent verification of the readings obtained by the sensors.

The Arduinos will be deployed from the end of June through August for data collection on identified sites on the three main campuses, Strand, Waterloo and Guy's. The sites will be selected for their avoidance of shading, which will be achieved by analysing time-lapse footage from deployed cameras.

Once data collection is complete, statistical analysis will be used to explore the variation between the sites and within the sites and compare it to the secondary data from the existing weather station network. ANOVA testing will be the primary analysis for variability within the sites and between the sites, hoping to determine how much of the variability between sites can be explained by particulate counts in the USFI (this is assuming a correlation) while simple linear regressions will be used to determine the relationship between the actual particulate level and its effect on the resulting insolation at the sites. Further statistical testing may be required if shading of the sites has to be taken into account.

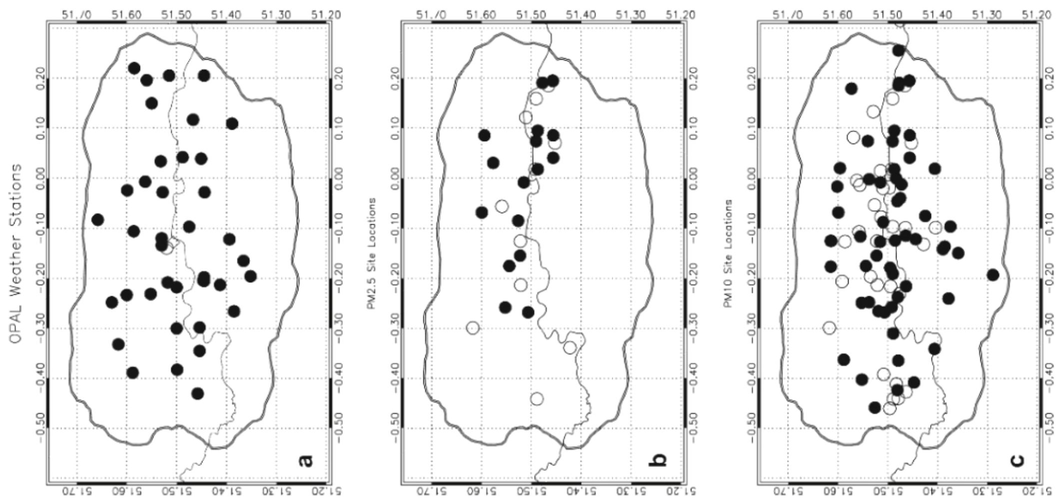

Figure 5. Distribution of London Sensors (Ryder & Toumi, 2011)

Table 2. Approximate timetable for IGS

May 20-June 30	Design, construct, calibrate and program sensors
June 30-August 31	Sensors deployed
September-December	Data analysis
December-January	Write first draft of IGS
January-February	Revise first draft
February-March	Complete final draft
March 15	Submit final draft
March 29	Final date for submission

Expected Results and Limitations

It is expected that the results will show a linear correlation between the particulate pollutant levels at the sites and the solar irradiance measured. It is also expected that the two sites South of the Thames, Guy's and Waterloo will have higher irradiances than Strand in alignment with the distribution of the particulate model. There is an expected variance in the region of up to 6-12% between the sites due to the USFI. The limitations of this project include, 1. The length of time that the sensors can be deployed for –only one season will be represented by the study as it is impossible to deploy the sensors year-round in this project. 2. Variability from other sources may obscure any effect from pollutants. 3. Shading from nearby buildings may need to be taken into account during the data analysis (this is a particular concern for Guy's). 4. An ideal way of better examining this question would be to use airborne LIDAR scanners (Yu *et al.,* 2009). However, this is far out of the budgetary scope of this project.

It is expected that the magnitude of the effect of the USFI on solar power generation will be assessed through this project and conclude whether or not it can be a significant factor in solar panel placement, with implications for the industry beyond London. In the process, the suitability of the various KCL campuses for PV installation will be assessed.

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- Appendix 3: Changes to Original Proposal

This project diverged completely from the original research proposal. Throughout the summer of 2015, two major issues with the original project became clear. Firstly, the number of Arduino Microcontroller Sensors required to collect enough data was impractical to build and deploy in the timeframe required, and secondly, that data from a high-density sampling network had already been collected, removing the need for primary data collection and reducing the potential investigation below the scope of an 8000-10000 word dissertation. The idea of a project investigating the urban solar flux island was abandoned due to these issues. After further consideration I decided to change my focus to air pollution itself rather than its effect on solar flux, which eventually lead to a decision to narrow my focus to the London Underground after discussions with my supervisor, resulting in the final project.

- Appendix 4: Calculation of PPB for Alphasense ISBs

The purpose of this manual is to explain how the circuit operates, how to connect power and take readings, mount the circuit board and correct the data in Excel.

1. How the circuit operates

Figure 1 below shows the circuit for the ISB, issue 4. This circuit is designed for use only with Alphasense B4 family of four-electrode gas sensors. The ISB uses low noise components and in order to achieve good resolution, best practice for grounding and screening is necessary. Take time to optimise your EMC environment to a low level to achieve low ppb resolution.

The ISB includes a low noise bandgap to provide a bias voltage for NO sensors and can measure both oxidising (CO, H_2S, NO) and reducing (O_3, NO_2) gas sensors. The ISB is configured as four versions for specific sensors: NO, NO_2, O_3 and CO/ H_2S/ SO_2:

Part number	Sensor
810-0016-00	CO-B4, SO2-B4, H2S-B4
810-0016-01	NO-B4
810-0016-02	NO2-B4
810-0016-03	O3-B4

Table 1. Part numbers for the four types of ISBs

Ensure your ISB is matched to the sensor type according to Table 1 if the ISB has been supplied separate from the sensor.

The circuit uses a single op amp to provide balance current into the counter electrode. In addition, both the working electrode (*WE*) and auxiliary electrode (*Aux*- used to compensate for zero current) have equivalent two stage amplifiers: the first stage is a high gain transimpedance amplifier and the second buffer stage allows for inverting sensor signals for NO_2 and O_3 sensors. Both signals are available on the 6-way Molex socket as separate pairs, but note that the power and output ground (-) pins are connected together.

There are no adjustments on the ISB. The offset voltages for both channels have been measured and are marked on the label attached to the packing sleeve for the ISB. If the ISB was shipped with a B4 sensor, the label will include both the zero voltage (expressed as mV) and sensitivity (expressed as mV/ppm) for the sensor with ISB. If you swap the sensor and ISB then the offset voltage will change but the sensitivity will be the same (±1%) since sensitivity is dependent on the sensor, not the ISB.

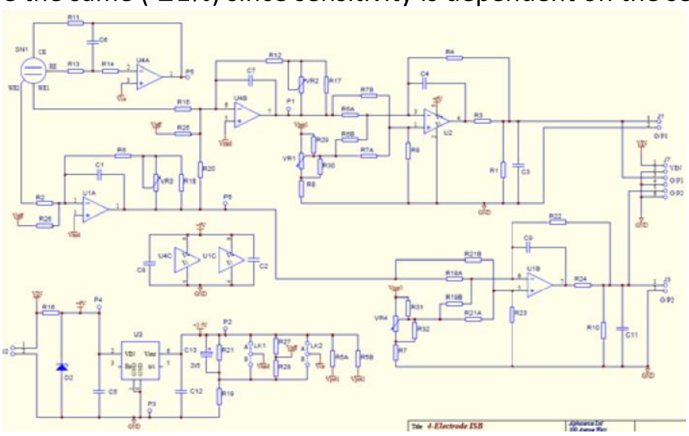

Figure 1. Schematic of Issue 4 ISB

2 Connecting power and taking readings

The socket for power and signals is shown in figure 2 below. The Molex socket is polarised.

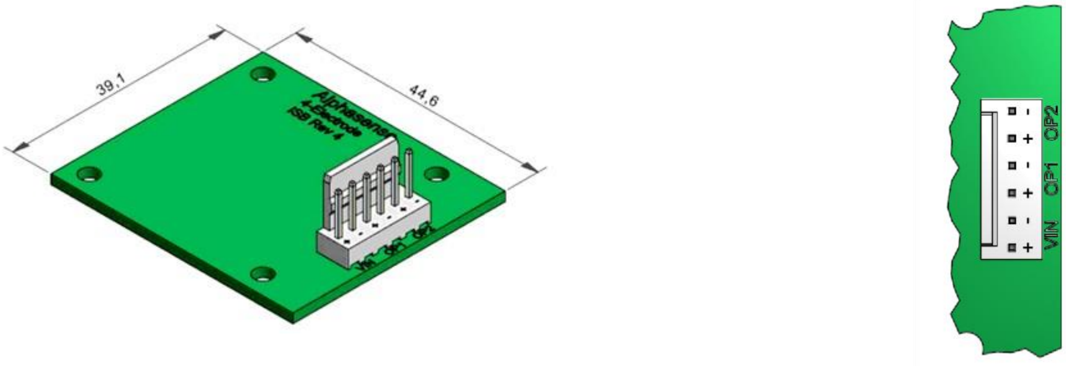

Figure 2. ISB socket for power and signals

DC power is required: 6.0 ±0.2 VDC. Ensure your power supply is low noise and decoupled, or its noise component will be added to the measured signal.

OP1 is the signal from the Working Electrode and OP2 is the signal from the Auxiliary Electrode. The –ve pins are connected so you can use either 6-way or 4-way cable to connect to the ISB. OP1 and OP2 are buffered DC signals so a normal A/D converter will be fine, so long as it does not inject noise back into the ISB. If you are concerned about noise injection, then decouple using 10nF plus 100nF capacitors close to the Molex connector.

Table 2 below lists expected outputs from ISB with a typical B4 sensor.

Gas	**Zero offset** mV (WE / Aux)	**sensitivity** mV/ppm	**Min/ max sensitivity** mV/ppm	**Full scale** ppm	**Gain** mV/nA
CO	270/ 340	320	230/ 450	13	0.80
H_2S	350/ 350	1650	1600/ 1700	3	0.80
SO_2	355/ 345	450	370/ 520	11	0.80
NO	545/ 510	800	550/ 930	6	0.80
NO_2	225/ 245	430	340/ 520	11	0.726
O_3	260/ 300	1150	1000/1200	5	0.746

Table 2. Offset, sensitivity and full scale for typical B4 sensors with ISB

Noise

1 These gas sensors are very sensitive to gas and are also very susceptible to EMC pickup. Ideally the sensors would be housed in a Faraday cage, but this is not normally practicable, so shield and ground as best you can. Nearby digital circuits can also disrupt the signal quality.

2 Typical noise at Alphasense, when calibrating on a bench without additional shielding, but with good power supply is 3 mV (p-p). Digital averaging can reduce this to less than one mV, equivalent to typically 2 ppb. Further reduction of noise can be achieved by shielding.

3 It is important to decouple your power supply and A/D converter from the ISB. Since the 0V line is shared by the power supply and output, any noise injected by your power supply or reading circuit will appear on the measured signal. We recommend using two decoupling capacitors close to the Molex socket: 10nF and 100nF.

3 Mounting the circuit board

The mounting hole locations and diameters are shown in figure 3 below.

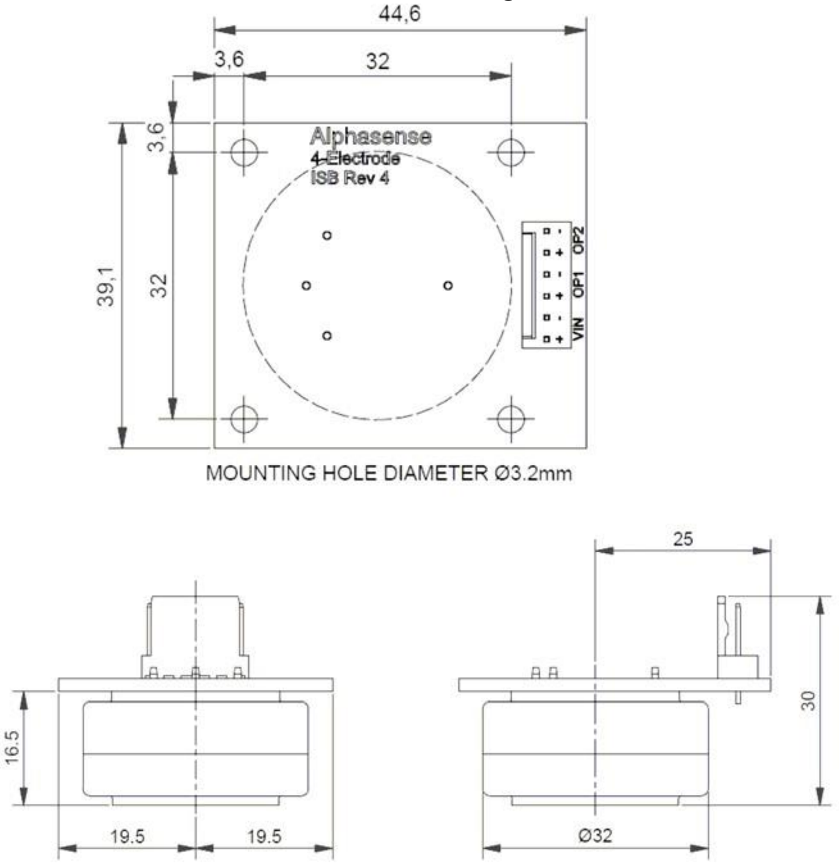

Figure 3. ISB dimensions and mounting hole locations

An optional **ISB Fitting Kit** can be purchased. Order part number **000- 0ISB-KIT**. The kit includes:

4x pillars	16.0 mm length, M3 tapped
4x washers	M3: fits between pillar and ISB to achieve 16.5 mm pillar height
4x screws	M3 x 6
1x header	Molex 22-23-2061, 6-way, Series KK6373 Other Molex part references:
	Housing: Molex 22-01-2065, Series KK6471
	Crimp: Molex 08-50-0032

4 Correcting the data using a spreadsheet

The two DC signals can be measured at any desired interval. It is normal to measure frequently and apply a smoothing algorithm to digitally filter noise.

The method for determining the concentration depends on whether you have purchased sensor with ISB or sensor and ISB separately. Alphasense recommends purchasing the ISB and sensor together- this allows us to measure accurately the zero gas voltage before shipping.

4.1 Measuring when the ISB and sensor were shipped together

Create a spreadsheet similar to the layout below:

	Vo (OP1)		Vo(OP2)		mV/ppm		
Time	**WE (OP1)**	**WE- Vo**	**Aux (OP2)**	**Aux-Vo**	**ppm**	**We-Aux**	**ppm**

Each column is specified as:

Column	Label	Cell data	Comments
A	Time	From your data acquisition system	Sampling faster than 1 second is rarely useful unless it reduces noise.
B	WE (OP1)	mV from ISB channel 1	0.1 mV resolution is ideal
C	WE-Vo	Column B- Vo (constant specified on ISB bag label)	Subtract the WE offset voltage- typical values are the second column in table 2.
D	Aux (OP2)	mV from ISB channel 2	0.1 mV resolution is ideal.
E	Aux-Vo	Column D- Vo (constant specified on ISB bag label)	Calculates the Aux offset voltage shifttypical Vo are the second column in table 2.This difference is a few mV.
F	ppm	Column C * sensitivity (specified on ISB bag label)	ppm calculated from the sensitivity constant (mV/ppm), corrected for offset voltage but not the auxiliary electrode.
G	WE-Aux	Column C – Column E	Correction for any drift in the auxiliary and WE (as mV)
H	ppm	Column G * sensitivity (specified on ISB bag label)	ppm, corrected for offset drift

Table 3. Typical data spreadsheet layout and cell assignment

4.2 Measuring when the ISB and sensor were shipped separately

If the ISB and sensor were shipped separately then set up the same spreadsheet as above, but the zero voltage will be for the ISB only and does not include the sensor. You must measure the zero voltage with the sensor connected to the ISB:

Plug sensor into ISB and apply 6 VDC to power the sensor/ISB pair.

1. Allow to stabilise in clean air for at least 6 hours.
2. Apply zero air (synthetic air or scrubbed/ cleaned zero air) for 20 minutes.
3. Record Vo for both WE (OP1) and Aux (OP2). Enter these values in cells C1 and E1.

Additionally, the sensor is calibrated as nA/ ppm but this must be converted to mV/ppm. The last column in Table 2 lists the scaling constant which must be applied for your sensor type. The ISBs have a gain that is repeatable ±1.2% (95% confidence interval) so this conversion constant is the same for all ISBs for a specific sensor/ gas.

5 Recalibration

The ISB with sensor calibration has been measured before leaving the factory, but environmental conditions and sensor drift mean that periodic checking of the calibration may be required.

Also, at low ppb concentrations both temperature and humidity will affect the offset voltage of both the WE and Auxiliary electrodes. Previously it was thought that simple subtraction of the Auxiliary would correct for ambient changes but this is not true. Contact Alphasense for help with the correct method for compensation in your application.

5.1 Zero correction

Follow the procedure in 4.2 above and modify the Vo mV in your spreadsheet after zero calibration. Be careful that the zero air you use is very clean: ambient or lab air is not sufficiently clean to be used as a zero calibration air source.

Gain/ sensitivity correction: unless you have access to an accurate 1 ppm (or less) gas supply, it is advisable to return the sensor and ISB to Alphasense for gain recalibration.