**Public health risks from respirable particles on the ‘London Underground’ metro network; should we be concerned?**

Smith, J.D., Saunders, B. Green, D., Priestman, M., Tremper, A., Mudway, I., Fuller, G., Nicolosi, E., Smith, T., Barratt, B.M.

# Abstract

**Objectives**: To characterise the health-relevant chemical and physical properties of PM2.5 on the London Underground network

**Design**: Observational study of air quality on the London Underground

**Setting**: London mass-transit network

**Population:** X million people making 1.34 billion journeys per year

**Main outcome measures**: Quantification of air quality on the London Underground

**Results:** Mean PM2.5 concentrations of X µg/m3, with a range of 0-X µg/m3. Particles have a median diameter of B, with a range of . Something about toxicity.

**Conclusions:** Regular use of the London Underground is likely to be having a detrimental effect on public health of all ages and demographics.

# Introduction

Exposure to fine particles on subway systems is being accepted as an important contributor to urban population exposure around the globe (Martins, V. (2015), Grass, D. (2010), Klepczyńska-Nyström, A. (2012)).

In 2005 Seaton et al. measured concentrations of dust, as mass (PM2.5) and particle number, both health relevant metrics, at a selection of stations and in train cabins on parts of the London Underground (LU) metropolitan rapid transit network. The PM2.5 mass comprised approximately 67% iron oxide, 1–2% quartz, and traces of other metals. They concluded that the levels of metals recorded were well below occupational health standards, that the particles are larger and heavier than harmful traffic-dominated outdoor particles, and that the composition was mostly iron rather than carbon; meaning that those principally at risk from dust inhalation by working or travelling in the tube should not be seriously concerned.

No comprehensive evaluation of fine particles on the LU network has been undertaken since Seaton et al (2005) despite our understanding of the toxicological mechanisms improving (IAN REF), the susceptibility of subgroups of large populations being of interest, and analytical techniques being re-evaluated and improved (DAVE REF).

In this novel research we measured PM2.5 mass across the LU using both stationary and mobile monitoring equipment, and considered whether passengers should be concerned about the effects on their health of the environment they are being exposed to on a daily basis, focussing on passenger exposure, particle composition and size, and the spatial variability thereof.

<< OCUS ON PASSENGERS … variability spatially …. Exposure implications …. Composition … unlike static/composition/one monitor etc. Occupational health limits probably fine … short journeys …. But very high concentrations. Something about welders?seaton 2005 underground Shouldn’t discount metals anymore.>>

# Methods

A series of experiments were carried out in order to characterise the health-relevant chemical and physical properties of PM2.5 on the LU network, including diurnal and day to day variability and spatial distribution (above ground, depth below ground and subway line). Additional work was undertaken to allow the derivation of source specific calibration factors for the portable equipment used.

## Spatio-temporal mapping

Two distinct spatial monitoring campaigns were carried out using portable sampling equipment. The first campaign (‘Campaign one’) assessed day to day variation underground, in comparison with above ground concentrations. The second campaign (‘Campaign two’) mapped particle concentrations across the LU network.

For campaign one, a test route incorporating below ground and contrasting above ground environments was selected. This ran between King’s College London’s Waterloo Campus, and alternating destinations of Oxford Street (high traffic location) and Hyde Park (low traffic location) via the Jubilee Line. Twenty-two repeat journeys were made on weekday mornings over a period of five months. On each journey, a TSI AM510 SidePak (TSI Inc, Shoreview, MN, USA) was used to continuously measure PM2.5 mass, and a Philips Aerasense (Royal Philips NV, Amsterdam, The Netherlands) diffusion charging monitor was used to measure ultrafine particle number and mean particle diameter. The averaging period of both devices were set to one-minute, and the devices placed in a backpack with inlet tubes fed out the top of the bag. The backpack was placed on the seat of a carriage next to the researcher during the journey on the underground, then worn while walking for two hours adjacent to congested diesel traffic (Oxford Street) or in a parkland (Hyde Park). The two locations were approximately 1.5 km apart in Central London.

The same monitors were used for the second campaign, whereby a researcher rode a LU train on all lines of the network. A detailed diary indicating time of arrival and departure at each station was kept to relate logged concentrations against location, as no GPS location tracking was possible below ground. All train lines were ridden in alternating directions of travel two to five times on separate days over a 3 month period, totaling c. 31 hours of sampling (89% of stations sampled). Measurements were linked to the transcribed time-location diary data, and then further linked to a GIS representation of the LU network created in a PostGIS database based upon data from the London Data Store (Greater London Authority, 2017).

## Population weighted station rankings

To understand the relative importance of concentrations at different stations and lines, passenger ‘tap in/tap out’ data was downloaded from the London Datastore (Greater London Authority(a), 2017) for the year 2015. This dataset records the numbers of times the automatic gates are opened by an Oyster card on an average weekday, Saturday and Sunday. The figures used in our analysis are annual figures, calculated as entries plus exits, weighting weekdays by 253, Saturdays by 52 and Sundays by 59. The weighting assumes that 7 bank-holidays are represented by 7 Sundays, and then grossing up to 364 day year excluding bank holidays. For each station we then divide the annual number for that station, by the mean of all stations, to give a number which represents whether the station is more or less busy than the average station - this is termed the the ‘passenger ranking’.

For each of the stations on the network we then calculated the mean PM2.5 recorded while the train was at that station. For stations with only one line passing through it, this is typically a minute or two of data as the train paused at the station in one direction, and then again on the repeat journey. For stations with more than one line, concentrations were averaged across the data recorded on those lines. We then divided the recorded PM2.5 for each station, by the mean of all stations, in a similar manner as with the station passenger numbers, and called this the ‘PM2.5 ranking’. By multiplying the passenger ranking and the PM2.5 ranking we can see where the impact of high concentrations are having the most impact on passengers.

## Chemical composition & oxidative potential of PM2.5

Measurements of the physical and chemical characteristics were made between 4 and 18 November 2015 on the southbound platform at Hampstead Northern Line station. Hampstead is the deepest station on the network and was selected as a sampling location representing PM2.5 from subway sources with minimal dilution from above ground sources. PM2.5 was collected onto pre-weighed quartz fibre filters (PALLFLEX, type Tissuequartz 2500QAT-UP) every four hours using pumped samplers (Thermo Scientific Partisol 2025, Waltham, MA USA); these were subsequently weighed and analysed for mass concentration (CEN, 2014) and for elemental carbon (EC) and organic carbon (OC) (Quincey et al. 2009); both methodologies are reference procedures for ambient regulatory purposes. PM2.5 was also sampled onto mixed cellulose esters filter media (GN-4 Metricel, 0.8 µm pore) filters every four hours (Thermo Scientific Partisol 2025); these were subsequently analysed for 30 elements, including Fe and other indicators of wear products in the LU using acid digestion and inductively coupled plasma mass spectroscopy (DAVE REF).

IAN ADD OP

## Derivation of calibration factors for optical PM mass measurement

TSI AM510 SidePak (‘Sidepak’) light-scattering laser photometers were operated continuously alongside the filter samplers in both LU (Hampstead Station) and London ambient (surface) conditions in order to derive a source-specific calibration factors applicable to both subway and ambient PM2.5. Laser photometers are typically calibrated to ’the respirable fraction of standard ISO 12103-1, A1 Test Dust’ (formerly Arizona Test Dust). As dust from different sources has different light-scattering properties, environments with dominant source types, such as the subway, require derivation of specific calibration factors (Torrey2015, Jiang2011). In each case, continuous measurements of PM2.5 from the Sidepak were correlated against reference PM2.5 mass for each of 14 four-hour mean filter exposure periods and the regression slope taken as the calibration factor. A parallel sampling method was carried out at the North Kensington AURN monitoring site [REF JAMES] (location 51.4750, -0.1198) using the same equipment to derive a surface background calibration factor; this is an established location representative of urban concentrations (Bigi, 2010). A scaling factor of 0.44 for ambient PM2.5 concentrations, and 1.82 for LU concentrations were calculated [Figure S1].

PM2.5 concentrations recorded by the Sidepak during the spatial campaigns were multiplied by the derived calibration factors. In recognition that the LU air comprises a mix of below and above ground particulate sources when underground, these factors were proportionally applied (Equation 1), illustrated with simulated data in Supplementary Figure 1.

[lutrue]i = ([lu]i - [sb]i/ks) \* ku + [sb]i Eq 1.

Where *lutrue* is the calibrated concentration at time *i*, *lu* is the measured concentration, *sb* is the paired measured concentration from a surface background monitoring site, *ku* is the derived underground calibration factor (1.82), and *ks* is the surface background calibration factor (0.44).

When above ground (defined as when recorded concentrations were equal to or less than concentrations recorded at the surface background monitoring site), only the surface background factor of 0.44 was applied.

# Results

Results from the spatial campaigns were used to highlight how the physical properties of respirable particles in underground sections of the LU contrasted with those in above ground environments, how this varied across the network and locations with greatest population exposure. Mass and chemical analysis then established the potential for these particles to impact on population health based on established ambient regulatory guidelines. Further, an in vitro toxicological assay highlighted the potential human health impacts of the particles.

## Surface and metro comparisons

Measurements taken over the five month period of repeat journeys (spatial campaign one) were aggregated to contrast metro, high traffic and parkland surface concentrations of PM2.5 mass, particle number and mean particle diameter (Figure 1a,1b,1c). An exposure profile for the aggregated journey to and from Oxford Street is also shown (Figure 1d).

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| oxford_timeline.png | | |
| Figure 1(a): Mean PM2.5 (µg/m3) measurements (25-75th percentile confidence intervals shown in grey) for the Oxford Street journeys of campaign one. Above and below ground calibration factors of 0.44 and 1.82 respectively have been applied.  Figure 1(b),(c),(d): Boxplot summary statistics for PM2.5, particle number, and particle diameter in each of the environments sampled. The lower and upper hinges correspond to the 25th and 75th percentiles, the horizontal line to the median, and the whiskers to 1.5 x the IQR (approx 95% percentile). The red circle shows the mean. | | |

Figure 1(a) shows how PM2.5 mass was approximately 15 times higher in the LU (mean 302 µg/m3) than in other surface background (Mean 18 µg/m3) and roadside environments (Mean 26 µg/m3) in central London. While there were significantly fewer, larger particles measured (Figures 1b and 1c) in the metro (mean 15,070 particles/cm3, 77 nm) than the high traffic surface environment (mean 26,810 particles/cm3, 54 nm), the mean particle number was many times higher than the surface background environment of Hyde Park (mean 6,521 particles/cm3, 68 nm).

## Spatial variation across the network

Summary boxplot statistics for PM2.5 for each line of the London Underground are shown below in Figure 2(a), with the line mean shown as white circles. Calibration factors have been applied according to the proportional calibration method described.

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| pm25_on_underground.png |
|  |
| Figure 2(a): PM2.5 concentrations by line, ordered by line median. Mean line depth shown in brackets, means shown as white circles.  Figure 2(b): PM2.5 concentrations in µg/m3 recorded at each station of the Central Line. Station icons are colour-coded by depth (metres). |
|

The highest concentrations across the network were found on the Victoria Line, which had a mean PM2.5 concentration of 381 µg/m3, followed by the Northern Line (Mean 168 µg/m3), the Bakerloo line (Mean 118 µg/m3), Central line(Mean 108 µg/m3), Jubilee (Mean 103 µg/m3) line and Piccadilly line (Mean 92 µg/m3) before a noticeable drop to the concentrations on the District (Mean 32 µg/m3), Metropolitan (Mean 28 µg/m3), Circle (Mean 27 µg/m3), Hammersmith & City (Mean 25 µg/m3) and DLR (Mean 10 µg/m3) lines. The highest concentrations on the Victoria line, over 800 µg/m3, were measured on the stretch of line between Pimlico and Brixton. The lowest concentrations recorded were on stretches of the Docklands Light Railway and District lines, which have large sections of line entirely above ground.

It is evident that there was a general relationship between mean line depth and PM2.5 concentration. Figure X(b) illustrates this relationship in more detail for the Central line, relating each station’s depth to the mean concentration. The Central line was selected as it was one of the busiest lines on the network, with a relatively large heterogeneity in measured station concentrations.

The concentrations shown in Figure 2(b) were recorded whilst the train was stationary inside the station. Concentrations tended to be highest in the deeper lines within Central London, and lowest in outer London. However, concentrations were also linked to distance from an above ground station; medium depth stations flanked by deep stations (e.g. Lancaster Gate and Holland Park) had higher concentrations than medium depth stations flanked by shallow stations (e.g. Wanstead and Gants Hill).

## Passenger exposures to PM2.5 mass

Figure 3 shows the top 30 Tube stations ranked by passenger numbers (red), PM2.5 concentrations (green) and notional passenger population-weighted exposure (mean station PM2.5 mass \* passenger number) (blue).

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| tube_pm_passenger_weighting.png |
| Figure 3: Top 30 London Underground stations ranked by passenger numbers (red), PM2.5 concentrations (green) and population-weighted exposure (blue). |

The passenger population-weighted exposure analysis highlighted stations that could be prioritised for remediation. For example, King’s Cross St Pancras Tube station was not within the top 30 stations for PM2.5 concentrations (shown in green in Figure 3), but high passenger numbers meant that it was the 10th highest station in terms of population-weighted exposure. In contrast, Pimlico had the 3rd highest PM2.5 concentrations recorded, yet due to its relatively low passenger numbers, it was 25th in the population-weighted exposure ranking.

## Chemical compositionCombBarChart_IM_V1.jpg

Figure 1: Chemical composition of PM2.5 on the London Underground

The chemical composition of PM2.5 sampled on the LU is illustrated in Figure X, where the contribution is shown relative to the independently measured total mass. It was not possible to measure all of the chemical components, as the techniques used were not sensitive to some key elements such as silicon and oxygen. To account for the missing oxygen the elemental concentrations were adjusted for their associated oxides (e.g. Fe2O3) based on previous studies (Querol et al. 2012) and using widely accepted approaches used in ambient atmospheric science (Chow et al. 2015). PM2.5 was found to contain 47% iron oxide while the remaining mass was made up of elemental carbon (?? ugm-3, 7%), organic carbon (?? ugm-3, 11%) as well as other oxides metallic and mineral oxides (14%). 21% of the mass remained unidentified by comparison to the direct mass measurement and this was likely made up of silicon from aluminosilicate minerals. Seaton et al (2005) reported 93% iron oxide at the same location (using the less robust transmission electron microscopy method); the iron oxide contribution to PM2.5 measured in this study is more consistent with other studies on the LU (Sitzmann et al, 1999, Nieuwenhuijsen et al. 2007). The chemical composition of PM2.5 measured here is clearly very different to surface measurements. At a typical surface background location organic carbon is the most abundant source (?? ugm-3, 35%) followed by secondary inorganic aerosols, such as nitrate (?? ugm-3, 18%), sulfate (?? ugm-3, 11%), and ammonium (?? ugm-3, 9%), with smaller contributions from marine aerosol components, such as chloride (?? ugm-3, 7%) and sodium (?? ugm-3, 4%), and combustion emissions, such as elemental carbon (Bohnenstengel et al. 2014).

\*\*\*Health relevant metal results - arsenic, nickel, manganese… To be drawn out in discussion.\*\*\*  
\*\* Add ug/m3 as well as percentages\*\*

\*\* what's the percentage of iron. Also how does the absolute mass compare for key elements (Fe, OC, EC) \*\*  
\*\* Table of concentrations for supplementary \*\*

# Discussion [Five paragraphs max]

**Statement of principal findings**

We find that the chemical composition, particle size and number of PM2.5 particles on the London Underground is more complex than found in previous studies, with significant elemental and organic carbon present, arsenic and nickel concentrations in excess of target values for ambient air, and concentrations of nanoparticles higher than recorded at above ground locations. In particular we note that there are particles in the size fraction small enough to deposit in the alveolar region of the lung, contrary to reported by Seaton et al. (2005). There is also significant PM2.5 spatial heterogeneity across the network ranging from ambient concentrations to several orders of magnitude higher than ambient. By calculating environment-specific calibration factors for optical measurement devices on the London Underground, we conclude that previous published studies using light-scattering monitors (REFs) may have substantially under-reported particle mass concentrations.

* POPULATION/DEMOGRAPHICS/SENSITIVE/AGES/LUNGS/
* Something about Bronchial deposition factors from the data Ian? Let me know if you need any numbers from the above figures to back this up? < -- put this in discussion.
* Cross-reference to Tom and Brynmor paper about line depth and spatial patterns being explored more in other paper.
* Shallow/deep - Influx of cleaner air from ambient environment into the carriages stays with the train.

PM mass many times higher, but varies spatially, not all of network is equal

Personal exposure studies have a challenge and may be underestimating PM exposure if they use an ambient cal factor (0.8 vs 2)

Subway usage increasing, including sensitive populations

Proportion of time spent small, but over full day significant

Therefore design of subway systems and relation to underground air quality should be considered for public health protection

**Strengths and weaknesses of the study**

By calculating bespoke scaling factors for the optical PM2.5 mass monitor, and sampling across all lines of the network, we are able to provide a calibration method for use in other studies in similar underground metro systems, and an exposure dataset for use in future studies (Link to download?). Our population weighting method allows policymakers to consider where intervention strategies e.g. cleaning of tunnels, will have most impact. However the method is station-centric, rather than line-centric, meaning that a line with low concentrations, and a line with high concentrations, that intersect at a station, will rank that station as a mean of the two.

The higher/lower concentrations of stations are likely due to depth and distances from tunnel exits. Needs further investigation of the data (set-up for Geog paper)

**Strengths and weaknesses in relation to other studies, discussing important differences in results**

Ian to “expand on the crux of the Seaton paper; namely that primary combustion particles are the main problem, not metal rich PM. The WHO couldn't conclude this, after much discussion, so it's an easy target. Even more so if the black carbon data is included.”

It is worth noting that our measurements are of a higher quality than the Seaton paper (IMHO) and we should contrast the 93% iron oxide that he reports with the more varied chemical composition we find here

Five examples. Need to do population.

Comment on other studies that use the TSI-Sidepak in the London Underground

**Meaning of the study: possible explanations and implications for clinicians and policymakers**

Members of the population of London who use the London Underground typically spend between 17.2 minutes (0-5 years old) and 20.2 minutes (45-59 years old) on each trip they undertake, taking between 2.6 (0-5 years old) and 2.83 (17-24 years old ) trips each day (Transport for London, 2017). Other age groups fall between these ranges. This means that these people, including sensitive subgroups such as the young and the elderly, are spending between 44 and 57 minutes of their day in an environment where PM2.5 concentrations are many times higher than ambient concentrations. Failure to include this environment in epidemiological studies of the relationship between PM2.5 and health in London is likely leading to large misclassification error.

**Unanswered questions and future research**

Spatial PM2.5 needs further investigation

The unknown parts of the chemical composition

What effects the variability within trains i.e. windows open/closed. ‘Suicide doors’ at stations. How quickly PM disperses/settles. Passenger numbers. Air con. Etc.

Future research will use Oyster card data to conduct research into health associations (?)

Difficult challenge to clean up.

Get off and walk.

# What this paper adds box

**What is already known on this subject**

1. Worldwide billions of people use subway transport systems on a daily basis
2. High concentrations of PM2.5 are found in these systems and are often substantially higher than ambient concentrations
3. Wear products from wheels, rails and brakes contribute large amounts of iron to the underground environment which is found in both metallic and oxide form

**What this paper adds**

1. Spatially resolved PM2.5 concentrations across the London Underground network, accompanied by a detailed understanding of the chemical composition.
2. The high concentrations, allied to population journey profiles, result in high exposures to respirable PM in sensitive subgroups i.e. the young and the old
3. A data resource for use in exposure-health studies in London.

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**Supplementary Information 1 – Diagrammatic representation of the correction equation**

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| tube_correction_example.png |
| SI Figure 1: Diagram illustrating how scaling factors were applied to PM2.5 data collected by the TSI Sidepak when used on the London Underground. Ambient air highlighted by a blue box, underground air by a green box |

## **Supplementary Information 2 – Population weighted London Underground stations**

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| A close up of a piece of paper  Description generated with high confidence | Si Figure 2: London Underground stations ranked by passenger numbers (red), PM2.5 concentrations (green) and population-weighted exposure (blue). |