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COMEAP/2018/04 WORKING PAPER 2

COMMITTEE ON THE MEDICAL EFFECTS OF AIR POLLUTANTS

A viewpoint on the characterisation of airborne particulate matter in the London Underground

1. This paper prepared by Dr David Green (King's College London) and Mr John Stedman (Ricardo Energy and Environment) and summarises the characteristics and sources of fine particulate matter (PM) in the London Underground.

2. Note: This is a draft working paper for discussion. It does not reflect the final view of the Committee and should not be cited.

COMEAP Secretariat

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1. Sources of $PM_{2.5}$

1.1. Sources of $PM_{2.5}$ in ambient air

The Air Quality Expert Group (AQEG) have provided information on the source apportionment of ambient $PM_{2.5}$ for an urban background location in Birmingham (AQEG, 2012). Table 1 has been adapted from the results reported by AQEG for both measurement based receptor modelling using a chemical mass balance approach and dispersion modelling using the pollution climate mapping (PCM) model. More recent results from the PCM model for 2016 have also been included in this table.

Table 1: Source apportionment of urban background ambient $PM_{2.5}$ in Birmingham.

	CMB (2007-2008)*		PCM (2008)**		PCM (2016)***	
	Mass (ug m^{-3})	%	Mass (ug m^{-3})	%	Mass (ug m^{-3})	%
Sea salt	0.78	6.7%	0.66	4.7%	0.61	4.9%
Secondary inorganic aerosol	5.10	43.9%	4.31	30.7%	5.47	43.8%
Secondary organic aerosol	1.66	14.3%	0.85	6.0%	1.11	8.9%
Soil and dust	0.85	7.3%	1.90	13.5%	1.07	8.6%
Traffic sources	1.51	13.0%	2.26	16.1%	0.55	4.4%
Stationary sources	1.34	11.5%	2.86	20.3%	3.67	29.4%
Other/Residual	0.39	3.4%	1.22	8.7%	0.00	0.0%
Total	11.63	100.0%	14.06	100.0%	12.48	100.0%
Primary	2.85	24.5%	5.12	36.4%	4.22	33.8%
Secondary	6.76	58.1%	5.16	36.7%	6.58	52.7%
Non-inventory sources	2.02	17.4%	3.78	26.9%	1.68	13.5%

*** Chemical mass balance (CMB) receptor modelling results from Yin. at al 2010, as tabulated by AQEG (2012) for May 2007 to April 2008**

**** PCM model results for 2008 (AQEG, 2012)**

***** PCM model results for 2016 form the Birmingham Tyburn monitoring site. Calculated using a model similar to that presented by Brookes et al (2017).**

Ambient PM concentrations typically include contributions from:

- primary PM from sources included in emission inventories
- secondary aerosol formed in the atmosphere from reactions involving gaseous pollutants (including sulphur dioxide (SO_2), nitric oxides (NO_X), ammonia (NH_3), and volatile organic compounds (VOC))
- non-inventory sources including sea salt and dusts.

The PCM model results suggests that primary sources contributed roughly one third of ambient $PM_{2.5}$ in 2016, secondary aerosol contributed more than half, with non-inventory sources contributing the rest. The source apportionment for the average of the 51 UK urban background, suburban background and rural background sites with model results in 2016 was similar to that for Birmingham.

The National Atmospheric Emissions Inventory (NAEI) provides a breakdown of the sectors contributing to UK total $PM_{2.5}$ emissions (Figure 1). The largest contribution in 2015 was from combustion in Industrial/Commercial/Residential sources. Residential was the largest contributor to this with 41% of the total of UK emission from all sources, with the majority if this (36% of the UK total from all sources) coming from residential wood combustion. The contribution from road traffic sources has declined since the 1980s because of reductions in exhaust emissions (5% of UK total in 2015) associated with more modern vehicles. Emissions from break and tyre wear (5%) and road abrasion (3%) have not reduced. Emissions from public electricity and heat production (power stations) have also declined over this period, although these emissions are typically released from tall chimneys and therefore do not have a large impact on local ambient concentrations.

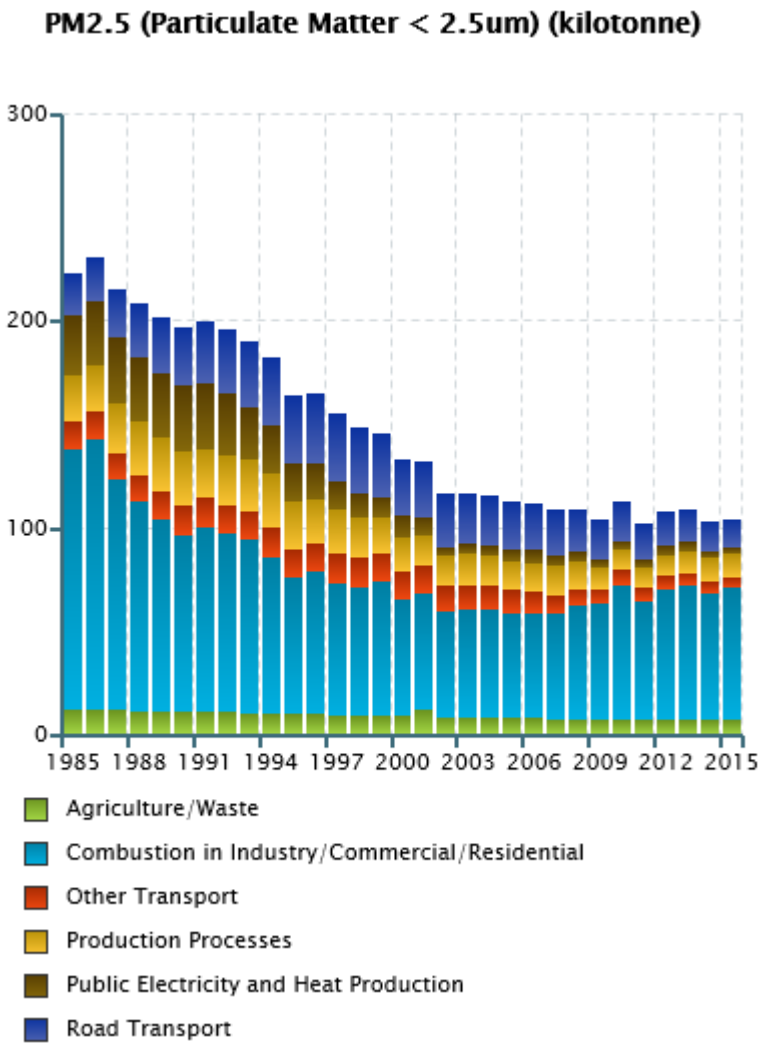

Figure 1: UK $PM_{2.5}$ emissions from the 2015 NAEI (http://naei.beis.gov.uk/overview/pollutants?pollutant_id=122)

1.2. Sources of $PM_{2.5}$ in subway air

The concentration of $PM_{2.5}$ in subway air is influenced by the air drawn into the underground system, principally through the above ground areas of the network via tunnel entrances and through the station entrances by the piston effects of the train movements and via active ventilation shafts. The elevated concentrations are caused by additional sources within the network, principally the wear of train consumables (eg wheels, brake blocks etc.), non-rolling sock sources (eg rail wear, rail grinding, people etc.) and station sources (escalators, refurbishment work etc.). These are emitted as primary sources and then resuspended by the train movements. Some additional information on sources, as well as characteristics such as ventilation systems, has been provided by Transport for London and is appended Appendix A.

1.2.1. Emission source in subway systems

Train consumables are the equipment fitted to trains and the emissions from these sources have been assessed by London Underground (Borgese, 2018) and are summarised in Figure 2. Emissions have changed over time and newer materials and changes to train technology (eg from DC to AC drive systems) have reduced emissions. Current collector shoes are made of various grades of cast iron and steel and wear against the conductor rails. Train wheels are steel and wear against both the rail and against the brake blocks. Train brake blocks wear against the steel wheel to bring the train to a complete stop. However, most of the braking is either rheostatic or regenerative. The exact composition of train brake blocks is commercially sensitive but an approximate composition is ‘filler’, organic material, glass fibre, metals and inert organic material. Stick Lube is used to lubricate the wheel flange. This is a styrene compound containing molybdenum disulphide. DC carbon motor brushes can be found in the traction motor, compressor and alternator in the older train stock; the traction motor is the largest contributor to this source and is only found on the Bakerloo, Central Waterloo and City and Piccadilly line trains. The emissions from all of these sources have been quantified by assessing their relative weights before and after usage or, in the case of wheels, their change on diameter.

Non-rolling stock sources include biological sources (anthropogenic, animal, fungal etc), station sources (eg escalators), rail wear, rail grinding, ballast, engineering work and infrastructure. Anthropogenic sources such as skin flakes and clothing fibres are likely to contribute to the concentration of $PM_{2.5}$ as they do in other indoor environments (Amato et al., 2014). Anthropogenic sources are also acknowledged as major contributors to airborne bacteria at subway stations (Dybwad et al., 2012). A range of fungal spores have also been measured and shown to be higher in the underground environment than above ground and highest concentrations were found in the deepest sections; possibly due to elevated temperatures (Gilleberg et al., 1998). Sources such as rail wear and rail grinding (when rails are reprofiled) are difficult to quantify as there are no usage rates for the former and the emissions from rail grinding are mainly fugitive emissions of particles much larger than $PM_{2.5}$. Potential sources of mineral dust include ballast (although this is generally restricted

to curved and above ground areas of track in the London Underground), as well as engineering and infrastructure work, whose impact is episodic and localised.

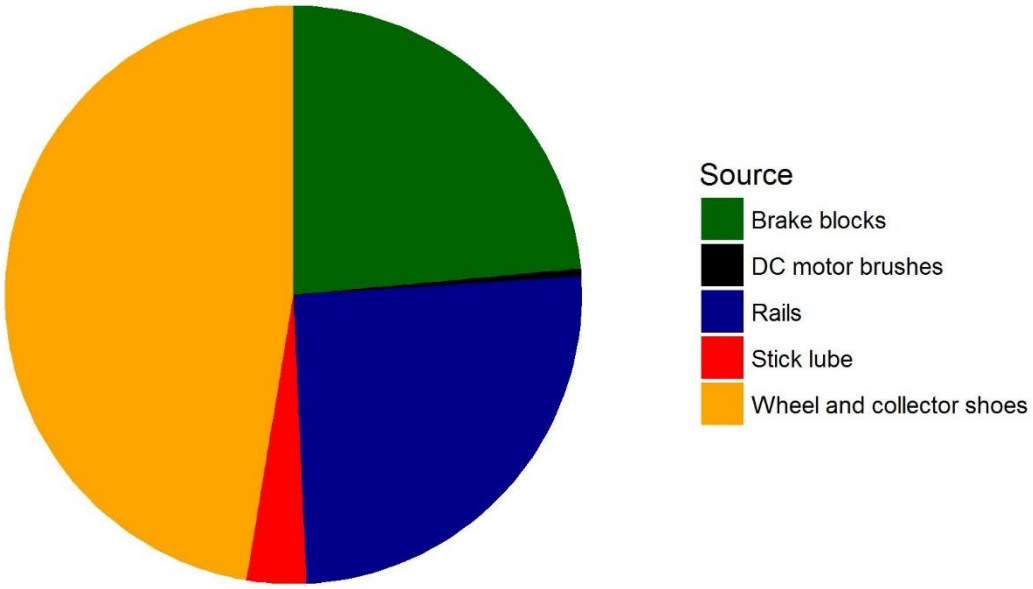

Figure 2: Estimated source contribution on London Underground (Borgese, 2018). Note: Many sources (eg biological remain unquantified)

The particulate matter concentration measured in a subway depends on both the sources and sinks. The principal sinks are the removal through the piston effects on the trains at tunnel and station exit points and through cleaning. The amount of material available for resuspension is dependent on both the deposition rate and the cleaning frequency. The cleaning frequency in the London Underground is currently often defined by observational reports of litter and visible material build up. This activity is principally aimed at reducing the incident of trackside fires resulting from sparking rather than a desire to reduce the airborne dust concentration. The relative contribution of the different sources varies in the London Underground due to a range of factors. These include (but are not limited to): the line (as different rolling stock is used on different lines), the ventilation rate (defined by degree of active ventilation and distance from tunnel portal amongst other factors), passenger numbers and the depth underground.

Many studies have been conducted on subway systems around the world (Nieuwenhuijsen et al., 2007, Martins et al., 2015, Martins et al., 2016). The concentrations of $PM_{2.5}$ or PM_{10} measured varied considerably and some of the highest concentrations have measured at stations in London. The sources vary between different subway systems, for instance some use catenary systems for power supply, this leads to different relative concentrations of different metallic components (eg Cu) while some systems (eg the Métro Line 14 in Paris) use rubber wheels. Nevertheless, there is a consistent elevation of Fe across subway systems, contributing approx. 30-70% of $PM_{2.5}$ due to wear of steel components of the trains and rails (Seaton et al., 2005, Martins et al., 2016).

2. Mass Concentration Measurements

$PM_{2.5}$ and PM_{10} concentration measurements have been used widely to assess exposure of the public and workers on subway systems around the world. Typically, measurements have been made for either short-term campaigns using regulatory and aerosol science measurement techniques eg (Raut et al., 2009), portable techniques eg (Martins et al., 2015) or a combination of both eg (Smith et al., 2018).

2.1. Measurement Approaches

Measurements made using regulatory techniques, such as reference $PM_{2.5}$ or PM_{10} samplers, which use the measured instrument flow and the difference between pre and post exposure filter weights in controlled environments according to standardised conditions to calculate a mass concentration (CEN, 2014), are unlikely to suffer any bias due to the proportion of metallic elements found in subway PM. However, these methods have only been used in a handful of studies (Seaton et al., 2005, Martins et al., 2016, Smith et al., 2018). This is also true of equivalent regulatory methods with direct mass measurement approaches, such as the Tapered Element Oscillating Microbalance (TEOM), which has been used in Stockholm (Johansson et al., 2003) and Paris (Raut et al., 2009). However, where instrumentation relies on the interpretation of the optical properties of particles, careful calibration against direct mass measurement techniques in the subway environment is required to avoid bias (Seaton et al., 2005, Querol et al., 2012, Martins et al., 2016, Smith et al., 2018).

2.2. Evidence from UK and worldwide

In the UK, station measurements in the London Underground have been limited to the work undertaken by Seaton et al. (2005) using the TSI DustTrak which reported station platform $PM_{2.5}$ concentrations of 270–480 μg m^{-3} and shift averaged train cab $PM_{2.5}$ concentrations of 130–200 μg m^{-3}. More recent work (Smith et al., 2018) at Hampstead station (the same location as studied by Seaton et al (2005)) mean $PM_{2.5}$ concentrations of 492 μg m^{-3} using filters collected using a low volume sampler (Thermo Scientific Partisol 2025). A TSI DustTrak was also used to provide high time resolution measurements (shown in Figure 3) which demonstrated elevated concentrations during the day when trains are running. In Europe substantially elevated $PM_{2.5}$ concentrations have been found in Barcelona (125 μg m^{-3}, (Querol et al., 2001)) and Stockholm (258 μg m^{-3}, (Johansson et al., 2003)) as well as internationally in Seoul (129 μg m^{-3}, (Kim et al., 2008)). Elevated $PM_{2.5}$ concentrations up to 100 μg m^{-3} have also been measured in many other cities including Helsinki, Los Angeles, New York, Mexico, Paris, Shanghai and Taipei (Martins et al., 2015). Many of the $PM_{2.5}$ measurements made in the London Underground therefore are higher than those measured in other locations worldwide, most probably due to its age, depth, tunnel distance and limited ventilation.

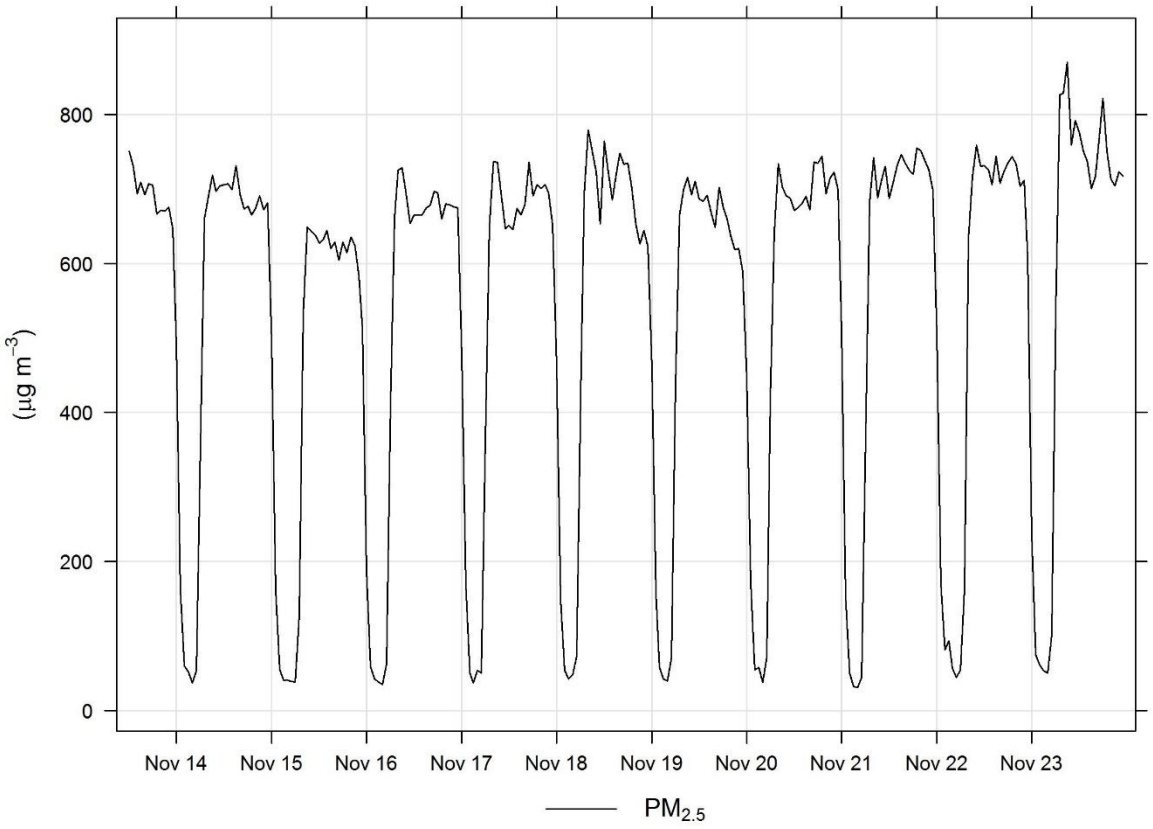

Figure 3: High time resolution measurements of $PM_{2.5}$ on platform at Hampstead Station, London

2.3. Personal exposure measurements

Elevated exposure levels on the London Underground were sampled and reported by Adams et al (Adams et al., 2001, Adams et al., 2001); these techniques are still used in some studies (Gómez-Perales et al., 2004). Small optical particle counter technology, such as the TSI DustTrak, has enabled personal exposure measurements to be made more easily on subway systems worldwide and has resulted in the mapping and evaluation of networks with respect to their source and dispersion characteristics (Chan et al., 2002, Braniš, 2006, Kim et al., 2008, Cheng et al., 2010, Kam et al., 2011, Querol et al., 2012).

2.4. Spatial variation across the London Underground

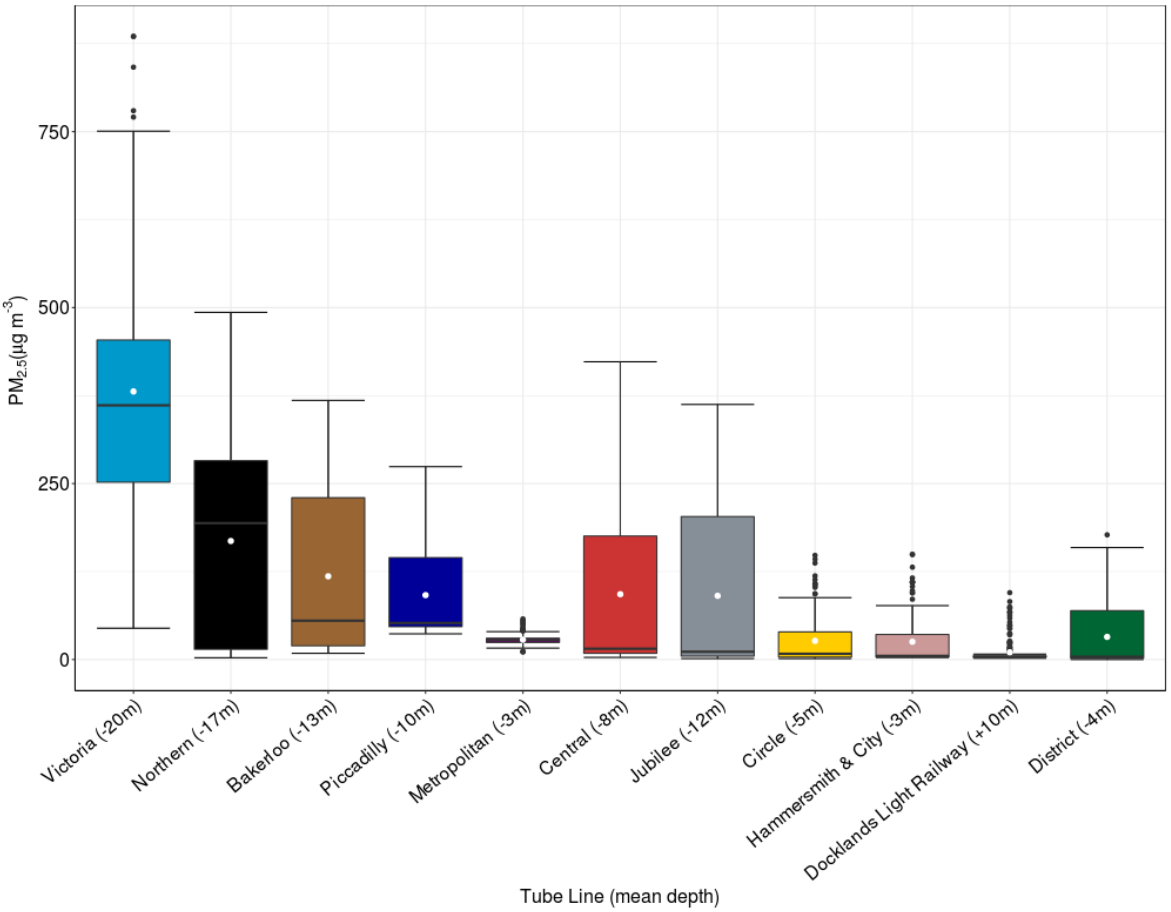

Figure 4: $PM_{2.5}$ concentrations by line, ordered by line median. Mean line depth shown in brackets, means shown as white circles (top).

$PM_{2.5}$ mass was measured on all London Underground lines using a TSI DutstTrak over a three-month period, totalling c. 31 hours of sampling by Smith et al. (Smith et al., 2018). Summary boxplot statistics for $PM_{2.5}$ for each line of the London Underground are shown in Figure 4 . The highest mean concentrations across the network were found on the Victoria, which had a $PM_{2.5}$ concentration of 381 µg m^{-3}, followed by the Northern (168 µg m^{-3}), the Bakerloo (118 µg m^{-3}), Central (108 µg m^{-3}), Jubilee (103 µg m^{-3}) and Piccadilly (92 µg m^{-3}) before a noticeable drop to the concentrations on the District (32 µg m^{-3}), Metropolitan (28 µg m^{-3}), Circle (27 µg m^{-3}), Hammersmith & City (25 µg m^{-3}) and DLR (10 µg m^{-3}) lines. The highest concentrations on the Victoria line, over 800 µg m^{-3}, 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. Note that all of the lines shown have varying lengths of track above ground, apart from the Victoria Line, for which all stations are underground.

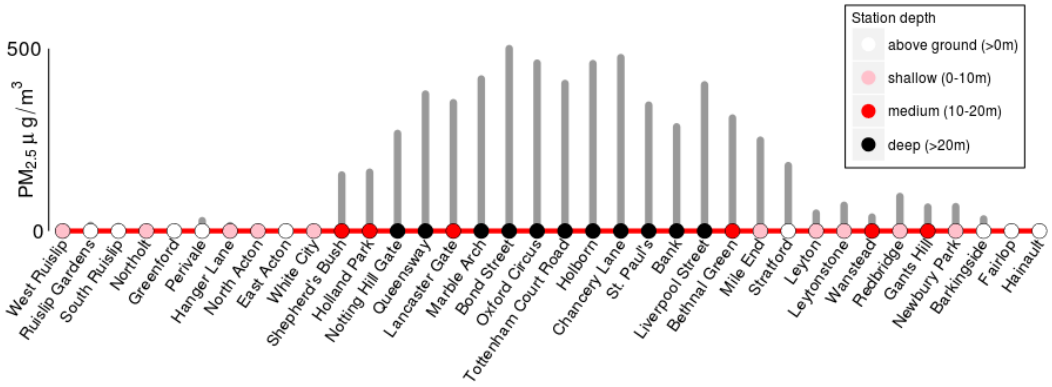

Figure 5: $PM_{2.5}$ concentrations in µg/m³ recorded at each station of the Central Line. Station icons are colour-coded by depth in metres (bottom).

It is evident that there was a general relationship between mean line depth and $PM_{2.5}$ concentration. Figure 5 illustrates this relationship in more detail for the Central line, which relates each station's depth to the mean concentration recorded whilst the train was stationary inside the station. 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. 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 (eg Lancaster Gate and Holland Park) had higher concentrations than medium depth stations flanked by shallow stations (eg Wanstead and Gants Hill).

3. Particle number and particle size distribution

Particle number concentration measurements and particle size distribution provide additional useful information relating to the source of particles and their potential health effects. Generally, small particles <1 µm are released through high temperature sources such as combustion but in subway environments could also comprise particles from high temperature braking, electrical motors and the contact between the power supply and pick up.

3.1. Measurement approaches

In London, and across Europe, above ground comprehensive measurements are made using Condensation Particle Counters (CPCs) for particle count, Scanning Mobility Particle Spectrometers (SMPS) for size distribution between 14 and 700nm and, less commonly, Aerodynamic Particle Sizer (APS) for size distribution between 500nm and 20µm. The latter two measurement methods can be used in tandem to provide a broad size distribution but have rarely been used in subway environments.

As with the particle mass concentration measurements, the particle number concentrations measurements for subway systems are typically made using portable measurement equipment. Many measurements have been made using portable optical particle counters (eg TSI DustTrak Model 8532 or 8533), these have minimum particle size detection limit of 0.1 µm and therefore do not measure the concentration of ultrafine particles. This range has been extended in some studies by using systems such as the P-Trak (TSI Model 8525) which use an atmosphere saturated with isopropyl alcohol to lower the minimum particle size detection limit to around 0.02 nm. These measurement size issues need to be considered when interpreting these measurements and, in particular, when comparing to above ground concentrations which have different sources.

3.2. Measurements on the London Underground

Priest et al. (Priest et al., 1998) were the first to measure particle size distribution on the London Underground using a cascade impactor and reported that most particles were smaller than 2.2 µm and 23 % were submicron. Seaton et al (2005) measured the particle number size distribution in Holland Park, Hampstead and Oxford Circus stations using a P-Trak; mean concentrations were 29,000, 14,000 and 24,000 particle/cm^3 respectively and mean particle diameters were 0.35-0.4 µm. It is difficult to compare the size distribution with above ground kerbside concentrations where the ultrafine mode is dominated by vehicle emissions peaking at 0.02-0.03 µm measured using the SMPS/APS system by Beddows et al (2010), as this is close to the size cut off of the P-Trak.

Comparing number concentrations measured at Hampstead and Oxford Circus above ground and in the subway, Seaton et al (2005) observed that subway concentrations were 40-60% of those above ground. Recent work in London (Smith et al., 2018) made measurements using a Philips Aerasense NanoTracer, which uses a diffusion charging approach and results in a lower size cut off of 10nm and also provides a median particle diameter. Measurements taken over a five-month period of repeat journeys were aggregated to contrast subway (Jubilee Line), high traffic and parkland

surface concentrations of $PM_{2.5}$ mass, particle number and mean particle diameter and are shown in Figure 6. $PM_{2.5}$ mass was found to be approximately 15 times higher in the London Underground (mean 302 µg m^{-3}) than in surface background (mean 18 µg m^{-3}) and roadside environments (mean 26 µg m^{-3}) in central London. While there were significantly fewer, larger particles measured in the London Underground (mean 15,070 particles per cm^3, mean diameter 77 nm) than the high traffic surface environment (mean 26,810 particles per cm^3, mean diameter 54 nm), the mean particle number was higher than the surface background environment in Hyde Park (mean 6,521 particles per cm^3, mean diameter 68 nm).

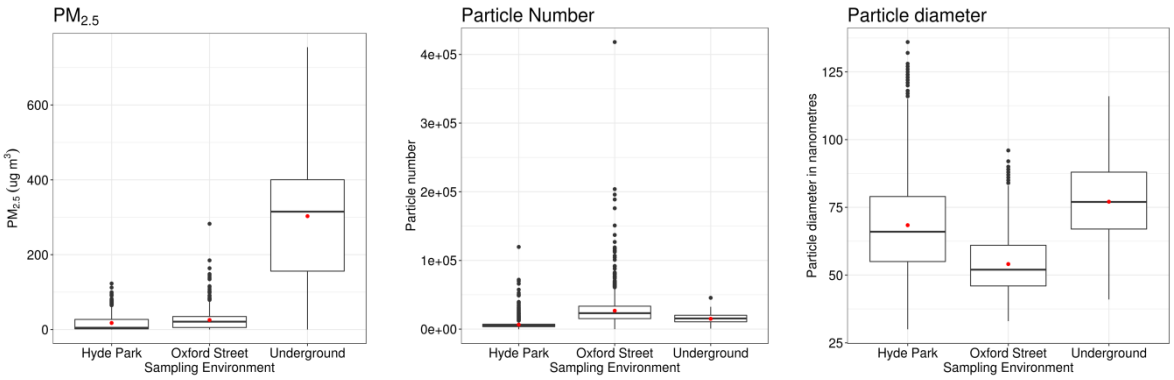

Figure 6: Boxplot summary statistics for PM2.5, particle number, and particle diameter in each of the environments sampled. The lower and upper hinges correspond to the 25th and 75th percentiles, the horizontal line to the median, and the whiskers to 1.5 x the IQR (approx 95% percentile). The red circle shows the mean.

3.3. Evidence from the rest of the world

Particle number and size distributions have been measured in very few subways, notably in Paris (Mazoué et al., 2005) and Stockholm (Gustafsson et al., 2006) and there is little information in the published literature. These studies are consistent in their detection of ultrafine particles, which were attributed to the ingress of polluted air from above ground especially in shallow depth stations.

4. Chemical Composition

The chemical composition of sampled PM can be used to understand the source of particles and their potential health effects. As described, the source of the particles in a subway environment is related predominantly to wear products from wheels, collector shoes and rails but also from human sources. As such the mixture is very different from that found above ground.

4.1. Evidence from UK

The chemical composition of $PM_{2.5}$ sampled on the London Underground at a four hour resolution for 48 hours and is illustrated in Figure 7, where the contribution is shown relative to the independently measured total mass and is reported fully in (Smith et al., 2018). To account for the unmeasured components, the elemental concentrations were adjusted for their associated oxides (eg Fe_2O_3) based on previous studies (Querol et al., 2012) and using widely accepted approaches used in ambient atmospheric science (Chow et al., 2015). $PM_{2.5}$ was found to contain 47% iron oxide while the remaining mass was made up of elemental carbon (32 µg m^{-3}, 7%), organic carbon (51 µg m^{-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 67% iron oxide at the same location; the iron oxide contribution to $PM_{2.5}$ measured in this study is also consistent with other studies on the London Underground (Sitzmann et al., 1999).

The bulk chemical composition of $PM_{2.5}$ measured underground is clearly very different to surface measurements. At a typical surface background location organic carbon is the most abundant contributor (6.8 µg m^{-3}, 35%) from local and distant sources followed by secondary inorganic aerosols, (ammonium nitrate (4.7 µg m^{-3}, 24%) and ammonium sulphate (2.4 µg m^{-3}, 12%), marine aerosol components (sodium chloride (2.2 µg m^{-3}, 7%) and direct combustion emissions (elemental carbon (1.0 µg m^{-3}, 5%) (Bohnenstengel et al., 2014).

Table 2: Concentrations of metals with health relevant standards measured at Hampstead Station and at the London Marylebone Road Measurement station where an estimate of the $PM_{2.5}$ concentration is made by multiplying the PM_{10} concentration by 0.5

	Hampstead tube in $PM_{2.5}$ fraction (KCL measurements)		London Marylebone Road	
Metal	**24 h Mean Concentration**	**Day-time mean concentration (8 am - 8 pm)**	**Annual mean; PM_{10} fraction**	**Annual mean; $PM_{2.5}$ fraction (using conversion factor of 0.5)**
Arsenic (As)	13.07 ng/m^3	15 ng/m^3	1.12 ng/m^3	0.56 ng/m^3
Cadmium (Cd)	3 ng/m^3	4 ng/m^3	0.17 ng/m^3	0.09 ng/m^3
Cobalt (Co)	14.71 ng/m^3	19 ng/m^3	0.21 ng/m^3	0.11 ng/m^3
Total chromium (Cr)	780.43ng/m^3	973 ng/m^3	8.91 ng/m^3	4.46 ng/m^3
Copper (Cu)	143.21 ng/m^3	190 ng/m^3	53.98 ng/m^3	27 ng/m^3
Iron (Fe)	183,646 ng/m^3	240,432 ng/m^3	1544 ng/m^3	772 ng/m^3
Manganese (Mn)	2233 ng/m^3	2927 ng/m^3	14.06 ng/m^3	7.03 ng/m^3
Nickel (Ni)	77.36 ng/m^3	99 ng/m^3	1.78 ng/m^3	0.89 ng/m^3
Vanadium (V)	18.86 ng/m^3	25 ng/m^3	1.01 ng/m^3	0.51 ng/m^3
Zinc (Zn)	469.43 ng/m^3	757 ng/m^3	33.59 ng/m^3	16.8 ng/m^3

The concentrations of a range of health relevant metals were also measured on Hampstead Station in 2015 and are shown in Table 2. All were generally found in very low concentrations in PM_{10} at the surface, even close to the roadside at Marylebone Road (values for 2016 for this monitoring site are also in Table 2). The mean $PM_{2.5}$ concentrations underestimate the short-term exposure to PM_{10} as they only capture a subset of the larger particle fraction and include a night-time, low concentration period; an 8am to 8pm concentration is also calculated and shown in Table 2. To allow a more direct comparison, the above ground concentrations are multiplied by 0.5 to provide an estimate of the likely $PM_{2.5}$ concentration.

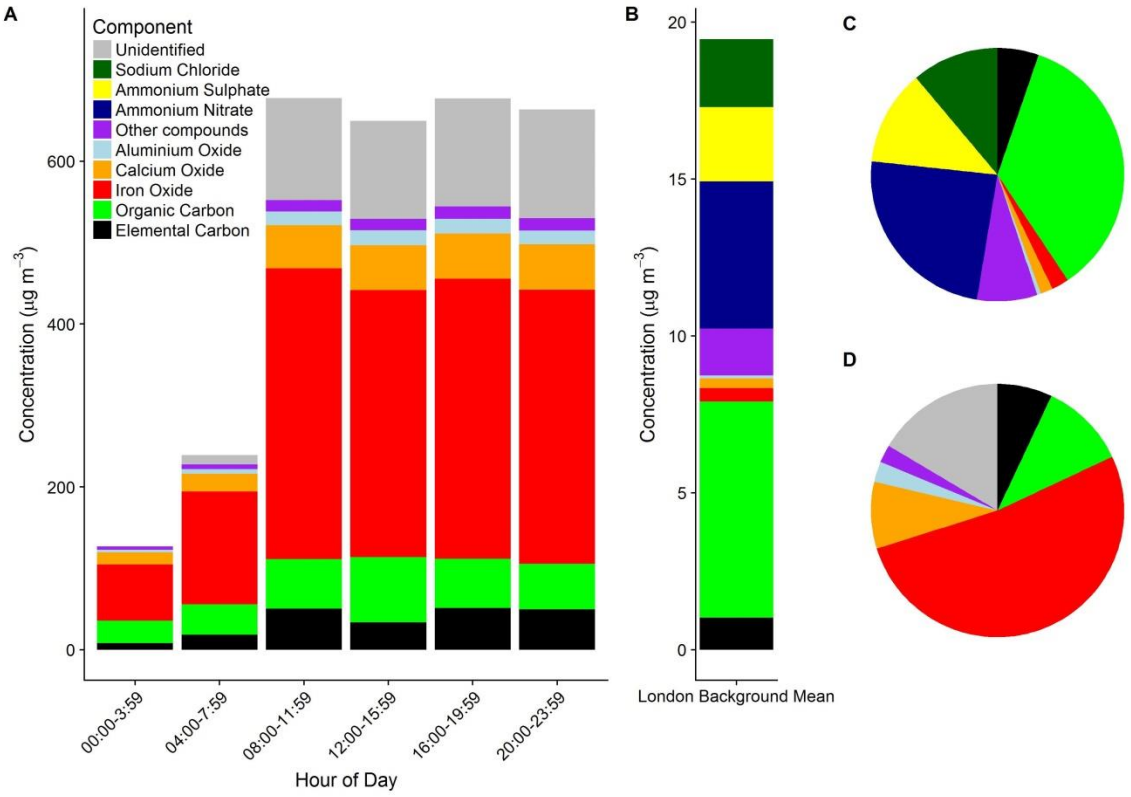

Figure 7: Chemical composition of $PM_{2.5}$ as A – Hampstead Station at four hour time resolution, B – bar chart of mean London background, C - pie chart for London background, D - pie chart for Hampstead Station

Few studies have been undertaken to comprehensively measure the bulk chemical composition of $PM_{2.5}$ in subway systems as shown in Figure 7 for London. However, the results of the study undertaken by Smith et al. (Smith et al., 2018) can be compared to a similar study undertaken in Barcelona by Querol et al. (Querol et al., 2012) and these are summarised in Figure 8. These demonstrate both broadly similar contributions to ambient concentrations while the subway chemical compositions recorded both much higher concentrations and a greater contribution from iron oxide.

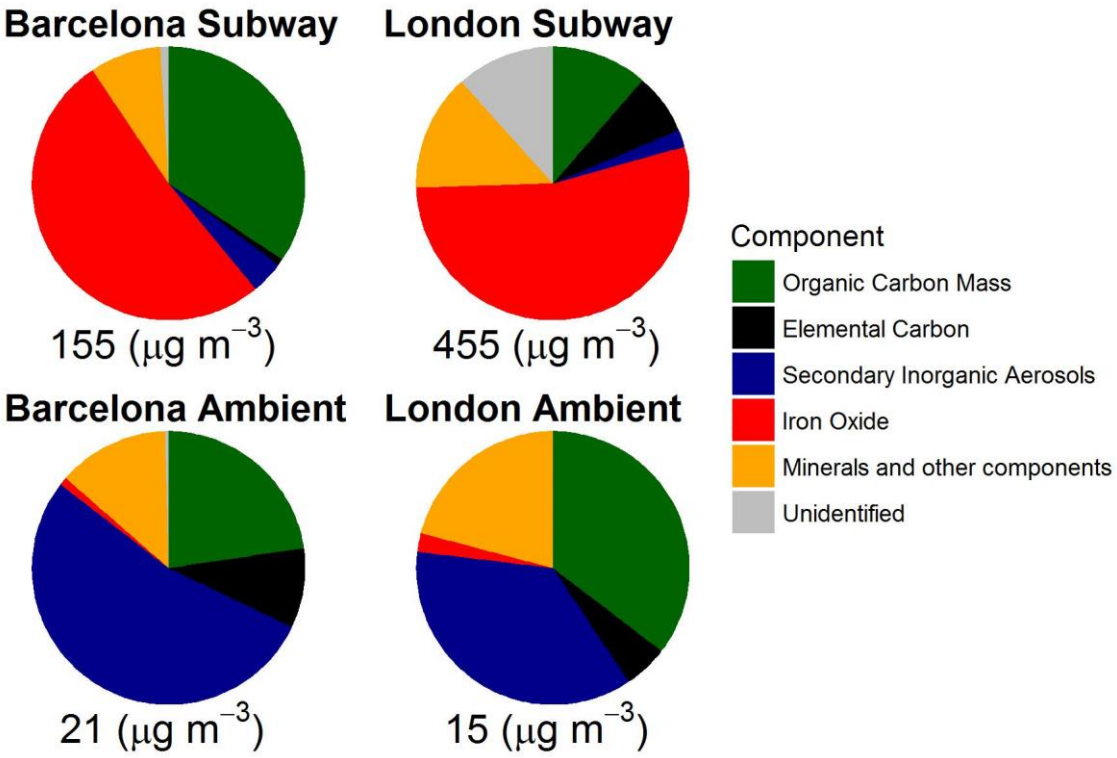

Figure 8: Comparison of chemical composition in London (Smith et al., 2018) and Barcelona (Querol et al., 2012)

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Appendix A

Information provided by Transport for London

Particulate Matter Sources

Activities that generate these dusts include rail, wheel, brake disc and pad wear from the trains and contact with the rails. Other similar activities include rail grinding to improve the track face. Dust from these sources are mostly composed of metals, particularly iron and in the case of brake pads include some ceramic material and resins as these are a composite product. It is dust from these sources that are the predominate content of dust samples taken and analysed. Most dust samples analysed by scanning electron microscope (SEM) show iron content by mass of 40-60%.

Construction and maintenance work, which includes the removal and laying of aggregate ballasts, generates dusts predominated by silicon and calcium compounds. In dust samples analysed by SEM silicon content can be as high as 30% and calcium by 14%. Such samples normally coincide with major construction work so are intermittent in appearance rather than routine. Some maintenance work will involve the use of diesel locomotives and generators in tunnels although efforts are being made to move as much work as possible to battery supplied power.

The ventilation system of the London Underground is primarily one where air is extracted by ventilation shafts, which are normally based midway between stations. Intake air largely comes through station and tunnel entrances. An additional source of ventilation, although variable from line to line is that provided by trains travelling from open sections in tunnels and out again which creates a piston effect. This is particularly notable where trains enter and leave tunnels at speed.

The intake of air through station and tunnel entrances will draw in particulates in the ambient air and will be the source of some of the elemental and organic carbon identified in dust samples. The travelling public introduce much of the organic particulate matter including skin flakes, microorganisms, and foot trodden dust. Correspondingly, these people also help remove some particulate matter (PM) as it becomes entrained in their clothes and hair.

Transport for London Particulate Monitoring

Occupational hygiene surveys have been undertaken over many years to assess the level of dusts in the Network. The focus of this work is assessing staff exposures as the duration of their exposure in station and tunnel environments normally exceeds 30 hours (h) per week.

Since 2005, there has been a modest reduction in train operator exposures. Current average driver exposures on the deep tube lines to respirable dust are approximately 0.3 mg/m^3 8 h time-weighted average (TWA) per work shift. Platform dust levels have largely been static since 2005 with levels at approximately 0.5mg/m^3. This is against a background of running more trains and carrying more passengers. Exposures on sub-surface lines are much lower.

All samples taken since 2005 have been well within the Health and Safety Executive (HSE) Regulatory Limits for respirable dust (4 mg/m^3 8 h TWA) and most (>95%) have been compliant with the Institute of Occupational Medicine (IOM) recommended limit for respirable dust (1mg/m^3 8 hr TWA)

In addition to gravimetric measurements some samples are analysed for elemental content which includes iron, copper, chromium, zinc, nickel and manganese which are the main metals used in Steel alloys for rail track and wheels. With the exception of iron the levels of other metals are minor and usually below the limit of detection for the methodology used to analyse the samples. The iron is predominantly in oxide form rather than as a salt.

Other substances analysed for as part of the surveys include respirable crystalline Ssilica and asbestos. Neither showed high levels with results being a small percentage of the HSE's regulatory limits.

Tunnel Design

London Underground has two types of tunnel – deep tube and sub-surface. The design of the deep tube is one where circular tunnels approximately 3.6 metres wide are run, and are single lane and direction. Sub-surface tunnels are effective cut and cover designs where a trench is excavated and rail lines are run in it, normally two and then covered again. Sub-surface lines are invariably shallow. The deep tube depth ranges from being on the surface to approximately 60 metres below the surface. 55% of the whole network by length is on the surface.

As a general rule, deep tube is much dustier than sub-surface lines and this is also influenced by the amount of line that is covered. For example, the entire Victoria line is covered whereas sections of the Central, Piccadilly, Northern, and Bakerloo deep tube lines are on the surface which assists in reducing dust levels.

Dust removal

Dust is removed from the underground network by cleaning and ventilation. In addition, there is coincidental removal as dust accumulates on trains and in the upholstery fabric and is removed during periodic cleaning.

Cleaning processes are manual. Previously tunnel cleaning trains have been used and were not found to be particularly effective. In addition, the design of the network is not uniform which would there involve using multiple trains. Manual cleaning is undertaken manually by contractors using brushes and vacuum cleaners. This cleaning is primarily of a dry nature due to the electrical installations in the tunnels. Stations are wet mopped regularly.

Ventilation removes particulates, gaseous pollutants (mainly carbon dioxide (CO_2) and odours), heat and humidity from the network. The ventilation systems are thought to be particularly effective at removing finer dust fractions. Ventilation is provided by extract vents across the network. An additional source of ventilation is where lines have sections of surface line. The movement of trains, particularly those at speed have the piston effect of drawing in fresh air and pushing old air out of the tunnels.