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Understanding Microenvironment and Particulate Matter: A Case Study of Underground Train Systems for a Sustainable Environment

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Abstract

In this paper, we assessed particulate matter (PM) in microenvironments to understand environmental sustainability in a typical underground train system (UTS). The focus on air quality has become paramount in line with the climate goals which has direct influence on human health, society, built environment, and sustainability. To ensure a sustainable underground train system, it is paramount to establish a policy covering occurrence, investigation, monitoring, and mitigation of PM in such microenvironments. Several studies have reported on air quality of the outdoor environment with minimal consideration of microenvironments such as in UTS. There also exist paucity of data on hourly PM using a portable device. It is therefore necessary to assess exposure concentration of PM in selected UTS using a portable device. The average international standard for PM2.5 in the environment is established as 25 µgm-3. Concentration of PM less than 2.5 µm in aerodynamic diameter (PM2.5) was measured in selected underground train and platforms using a portable Aeroqual device. The data obtained were analysed quantitatively using statistical mean and qualitatively using international standards for permissible PM limits. Using a pollutant of PM2.5 as a datum, concentrations in µgm-3 ranged between 103-165 on platforms and 115-153 inside the train - indicating the need for improved air exchange on the platform. It was observed that PM2.5 concentration on the platform and the train are much above the international standards. This study argues for the need for an efficient ventilation system. A further study of UTS covering a longer period of exposure time (annual) and the use of different methodologies (equipment, sample size, etc.) are strongly recommended.

Keywords: Particulate Matter, Microenvironments, Underground Train Systems, Sustainable Transport, Human Health.

1. Introduction

Air pollution is the contamination of the indoor and/or outdoor environment by either chemical, physical, or biological substances which negatively affect the natural properties of the atmosphere [1]. Outdoor pollution is a significant public health issue that impacts on populations of both global South and global North. In 2016, it was estimated that ambient (outdoor) air pollution led to 4.2 million premature deaths across all geographical settlements in the world [2]. This is mainly from particulate matter exposure leading to various cardiovascular and respiratory disease, as well as cancers. Ischemic heart disease and stroke accounted for 58 percent of ambient air pollution-related premature deaths, whereas chronic obstructive pulmonary disease and acute lower respiratory infections accounted for 18 percent and lung cancer for 6%, respectively according to the same report. Asides outdoor air pollution, indoor pollution remains a major causative of various health implication due to its enclosed microenvironment nature.

Rail transport is generally considered to make a quantifiable contribution to poor air quality (1% of PM2.5 emissions in the UK) [3]. This can be in form of fuel being used, construction and maintenance activities among others influencing various receptors. Exposure to air pollution is largely influenced by the concentration of pollutants in a microenvironment and the duration people spend within [4]. In traffic-related microenvironments, traffic emissions account for most of the air pollution [5]. Commuters are subjected to high levels of pollutants, which frequently fall short of the WHO global air quality regulations [6].

Underground transport systems remain one of the most important modes of urban transportation in many cities across the globe. Previous studies have indicated a sustainable urban growth where underground spaces are well utilized [7], likewise the development of resilient cities [8]. By 2050, it is projected that more than half of the world's population will live in cities. This future challenge is being addressed by the utilisation of underground spaces as a key tool [9]. Cities have chosen UTS as effective options to tackle

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urbanisation challenges including commuter traffic, land scarcity, noise, and air pollution [10]. Urban rail transportation system is expected to serve roughly half to eighty percent of all urban commuters [11]. Cities using underground train systems include London, Budapest, Stockholm, Glasgow, New York, Paris, Barcelona amongst others [12]. However, the impact of UTS on the health of passengers is a continuous subject of concern for the sustainability of this transport system.

UTS are described as poorly ventilated confined microenvironment with high tendencies of accumulating pollutants from the external atmosphere and from within [13]. Particulate matter concentrations in underground rail systems are often several times greater than in outdoor ambient environments, according to research conducted in different nations [12]. It was first reported by Health and Safety Executive (HSE) 1982, that employees and passengers are likely to be exposed to particle risk in London underground systems. A similar report was presented in USA [14] and in Stockholm [15]. The air quality of the Shanghai subway system for example aroused considerable concerns [16], because of the potential impacts on passengers' health. A considerable amount of particulate matter was observed both inside the trains and on platforms. Various studies related to epidemiology on short-term symptoms indicate an evident and persistent link between PM concentrations and harmful health consequences at low concentration levels, routinely observed in global North countries. Nonetheless, the current database does not allow for the determination of precise guideline values [17]. Much of the information available today originates from studies in which PM10 particles in the air were examined. There is already a substantial amount of evidence on PM2.5, and recent research demonstrate that it is a greater determinant of health impacts than coarser particles. The enormous amount of research linking daily fluctuations in particulate matter to daily changes in health yields quantifiable evaluations of particulate matter's impacts that are typically consistent. The evidence provided does not allow for a determination of levels at which no impacts are likely. At PM10 concentrations considerably lower than 100 g/m3 daily average, impacts on mortality, pulmonary, circulatory related hospitalization, and other health indicators, have been identified. As a result, there is no recommended limit for short-term average levels. Furthermore, the amount of data on protracted impacts is currently limited. Protracted exposure to PM has been linked to decreased survival and life expectancy of 1–2 years, according to some reports. Additional findings have linked fine particulates intake to the predominance of bronchitis symptoms and impaired lung function in children and/or adults. At yearly average exposure levels below 20 µg m-3 (as PM2.5) or 30 µg m-3 (as PM10), these effects have been seen. As a result, there is no recommended threshold value for long-term average concentrations.

It is pertinent to note that outdoor air quality, architectural designs of the train cars and stations, ventilation system, chemical properties of braking systems and rail track material, passenger population, train velocity amongst others are determinant factors of concentration and chemical composition of particulate matter in subway stations [12]. Several studies have reported on air quality of the outdoor environment with no consideration of microenvironment such as UTS. Therefore, there is a paucity of data on PM2.5 data obtained in such microenvironment.

2. Literature Review

2.1. Theoretical framework: urban built environment

This section describes the theoretical background of the subject PM as a pollutant in relation to urban built environment. We use the term urban built microenvironment as the framework that will guide its understanding and analysis of data. Urban built environment centres on the axiom that the continuous urbanisation and sustainability of the society results in multiple challenges and one of such is the increase in the concentration of pollutants in the air, water, and land. As observed by Wahida [18], the urbanised society consists of various receptors (plants, animals, humans, and ecosystem) exposed to pollutants from various sources from human activities and pathways.

2.2. Conceptual review

This section reviews various studies to define and describe the concept of PM. Several scholars and corporate institutions have offered diverse conceptions of what particulate matter (PM) entails. Yang [19] explained that particulate matter is a mix of heterogeneous components (organic carbon, elemental carbon, nitrate, sulphate and iron, vanadium, nickel) which varies greatly by season and by region. Yadav [20] described particulate matter as the aggregate of the potentially hazardous solid and liquid particles which float in the air. For [21], particulate matter refers to solid, liquid, and gaseous pollutants which are harmful because they exist in higher concentrations that impede on the quality of the natural environment. These complex combinations of various substances are of different sources with composition largely influenced by emissions, meteorological factors, regional and local contributions, and temporal fluctuation [22]. They can be primary or secondary particles in form of dust, smog, and sooty particles, pollens, and soil. Primary particles are directly released to the environment while secondary particles are generated from atmospheric gas reactions. DEFRA [23] identified particulate matter as a major air pollutant and defined it in terms of size (diameter ranging between few nano meters and hundred micrometres) and composition. Fine Particles (PM2.5): these refer to fine particles and they are regarded as the most popular classification particulate matter. PM2.5 have an aerodynamic diameter of less than 2.5µm and they are capable of penetrating deep into the lungs of humans [24]. Several points can be gleaned from the above conceptions of particulate matter. First, particulate matter is a combination of particles which could be solid, liquid, and gaseous. Second, these participles have the proclivity to be harmful to human and environmental health when they exist in larger concentrations beyond the limit that the environment and humans can bear. This explains why [25] stated that particulate matter are the major drivers of climate change and health toxicity. In buttressing this, the World Health Organization observed that particulate matter is one of the most defining factors that contributes to health risks as cited in [26]. On the other hand, particulate matter may not be hazardous when they are effectively managed and do not exist in large concentration. Third, the concentration volume of the solid, liquid, and gaseous is dependent on seasons and locations. This means that at a particular time of the year, there is a tendency for an increased presence of pollutants in the atmosphere. Similarly, an industrial location, for example, can result in a large-scale concentration of pollutants in such location.

2.3. Sources and composition

This section identifies a knowledge gap while it describes the sources and composition of PM. The determination of sources of particulate matter has always been complex due to lack of background data and limited speciation measurement of particulate matter composition across the UK [27]. Furthermore, the group established that high levels of particulate matter in England are largely influenced by secondary sources such as from regional rural areas, organic particles, and continental flow from Europe during spring. Primary sources such as road traffic (both exhaust and non-exhaust particles), domestic (oil and fuel combustion) and commercial sources generate about 50 % of particulate matter.

However, industrial sources generate considerable amount based on current data. According to [28], the source and composition of particulate matter grants insights on how to measure the impact of certain sources and to understand the components of particulate matter that have the capacity to impact on the health of individuals and that of the natural environment. Air pollutants from diesel engines (automobiles, trucks, and commercial vehicles), as well as wear and tear of tyres, brakes, and road surface friction from all vehicles, are the main sources of particulate matter with significant impacts. Throughout the European Union including the UK, a relatively similar pattern exists. Many of these emissions estimates, especially the estimates of fine particulate matter from non-exhaust traffic sources, are subject to non-negligible uncertainties. The non-exhaust constituents of traffic emissions will become considerably more important when PM emissions are reduced, emphasising the need to develop mechanisms to regulate emissions from these sources. [29] To specifically mention some of the composition of PM2.5, including sodium ion, elemental carbon and organic carbon, sulphate, ammonium, silicon, and nitrate as the makeup of PM2.5.

2.4. Policy, strategy, and outlook

This section briefly reviews governmental policies and strategies, and how it can influence future outlook through models. Several policies, programs, and plans have been promulgated by the government of the United Kingdom to ensure that the risks associated with particulate matter are effectively reduced and, in cases of high concentration, managed. Some of these key policies are reviewed below. The Pollution Prevention and Control Act of 1999 is a policy which aimed at implementing the EU Pollution Prevent and Control (IPPC) Directive. The aim of this policy is to ensure that industrial and agricultural activities that have a high proclivity to environmental pollution work within laid down standards [30]. As such the policy was targeted at reducing waste, improving the quality of water, enhancing air quality, ensuring the participation of industries in environmental campaigns, reduction of noise from industrial and agricultural activities and controlled use of chemicals. Secondly, there is the UK Plan for Tackling Roadside Nitrogen Dioxide Concentrations of 2017 which was aimed at ensuring a cleaner transportation network in the United Kingdom and further ensure clean air. Particularly, the policy identified the fact that there is a high concentration of nitrogen oxide on UK and this needs to be reduced [31]. The EU's Air Quality Directive, the Directive on Ambient Air Quality and Cleaner Air for Europe (2008/50/EC), provides precise air quality targets as well as standards by which air pollution can be monitored. There are a variety of additional legislative instruments that try to mitigate air pollution by limiting emission sources to achieve these objectives. A new method for PM2.5 was established in the Directive in consideration of the absence of evidence indicating that there is a level of PM concentrations below which health consequences do not occur. This new strategy attempts to minimise the population's overall exposure to PM2.5, built on the concept that a comprehensive reduction in exposure will result in more public health benefits than a policy geared solely at lowering exposure in hot spots. The goal of PM2.5 policy is to limit prolonged exposure through the implementation of annual standards, as well as to reduce PM2.5 background concentrations in metropolitan areas across the UK between 2010 and 2020. Furthermore, there is the Clean Air Strategy of 2019 policy of the United Kingdom aimed at improving the overall air quality of the United Kingdom. This strategy builds upon the Clean Air Act of 1993. The cardinal aim of the policy is to reduce the concentration of particulate matter emissions in the United Kingdom by 30% at the end of 2020, and by 2030, the particulate matter is expected to have dropped by 46% [3]. There are provisions targeted at reducing emissions in public spaces, in homes, in farm steads, in industries. To achieve this aim, below are some proposed action plans of the policy:

- by 2040, the UK should actively be using zero exhaust emissions vehicles;
- the formulation of new standards for the manufacturing of tyre and brakes to combat toxic non-exhaust emissions from vehicles;
- phasing out of diesel-only powered train by 2040;
- legislate on the sale of fuels that cause pollution;
- ensure that only clean stoves are used by 2022;
- legislate on standards for building homes to ensure ventilation;
- support farmers to use only farm equipment and machinery with low or zero emission;
- ensure minimal pollution from the use of fertilizers and manures;
- regulate the use of ammonia to reduce emissions from the farm;
- encourage the use of clean technology to ensure eco-friendly industrial activities.

Having explained the above policies aimed at reducing the mean concentration of particulate matter, it would suffice to present the trend and outlook of particulate matter in the United Kingdom. Furthermore, the major source of PM10 and PM2.5 in the United Kingdom include emissions from the combustion of the manufacturing and construction industries (which accounted for 34% of the PM10 and PM2.5 particulate matter in 2020), combustion from domestic burning (which accounted for 15% of PM10 and 25% of PM2.5 respectively in 2020), emission from road transportation (which accounted for 12% of PM10 and 13% of PM2.5 in 2020)[32]. Despite the above the annual emission rate for PM2.5 decrease by 85% between 1970 and 2020 [32]. In the light of the above however, the particulate matter as it emanates from vehicle exhaust need to be better controlled. This is because the emissions from tyre and break wear is projected to result in about 70% of emissions from vehicle usage [27].

In 2002, the United Kingdom government set up an air quality strategy to protect, mitigate and enhance air quality within its territories [23]. The strategy aim was to address air pollution by investigating various sources of air pollutants, establish their concentrations and model trends. Models are useful for deducing the relationships between emissions and observational data, as well as producing self-consistent forecasts of ambient concentrations of particulate matter. Due to uncertainties, lack of observed data, failure to understand key factors of the evolving, physical, and chemical processes that must be defined within the models, and complexities in emission data and projections, modelling of particulate matter remains a significant challenge.

2.5. Empirical review

This section moves away from theoretical reviews and describes some key empirical studies that have been conducted in the United Kingdom in relation to particulate matter. Harrison [33] conducted a study to examine the processes that affect the concentration of PM in the European Union, setting targets for members states to reduce exposure to PM2.5. In the light of this, their study reviewed several data on particulate matter collected in the United Kingdom in 2009. In addition, they also observed the concentration levels of particulate matter in rural and urban road sites. From their analysis of the data and from the observations, they discovered that road sites (particularly high trafficked streets) were typically composed of high concentration of PM2.5. Furthermore, it was discovered that concentrations of PM2.5 usually reach its peak during winter and was lowest during summer. Formulation of a policy was recommended that would empower an agency or individuals to effectively monitor hot spots of PM2.5 concentration daily. There have also been studies on the prevalence of particulate matter in homes. [34], observed that there is a correlation between residential indoor locations and the exposure of individuals to particulate matter. Using Fixed Site Monitors, they indeed affirmed that smoking and cooking increase individual's exposure to particulate matter. In corroboration, [35] argued that much of the studies on particulate matter centres around its concentration within the macro environment of the society while there are continually rising levels of particulate matter in homes and indoor spaces. Using Grimm's Environmental Dust Monitoring (EDM) to sample 82 households, they discovered that the concentration of particulate matter in most living rooms were higher than what was obtainable in bedrooms. Similarly, they observed that PM2.5 had the highest concentration in the home which was from the use of gas stoves and activities of those who smoke on the streets where homes are located. Furthermore, routine household activities like cleaning, sweeping, and cooking increase the particulate matter level in homes.

Martins [36] further explored the concentration of particulate matter in the subway of different European subway systems. The major finding of their study is that the concentration of particulate matter in subway platforms are higher than the concentration of particulate matter in the air. According to them, the concentration of particulate matter in subways are influenced by the frequency of train movement in the subway stations. They further argued that particulate matter within the train was lower when the air-conditioning system is functional but increased when the windows of the train were opened. This means that that ventilation system plays a part to the concentration of particulate matter in subway stations and as observed by [12], the quality of ventilation and air-conditioning systems in the subway stations impacts positively on the quality of air at the subway stations.

The above view is also corroborated by [37], after using spatial monitoring campaigns to measure the physical properties of particulate matter in the London Subway, explained that the concentration of PM2.5 is higher on the surface of subway platforms compared to in the ambient air. Specifically, they observed that that dust which contributes to the increased concentration of PM2.5 in subway stations manifests because of the wear of components trains which is further sustained in the subway air by other trains in motion. In the light of the large concentration of particulate matter in the subway, they recommended that studies be carried out to explore the specific health impacts of exposure to subway particulate matter. In another study in China, [38], it was explained that the mixture of air between indoor and outdoor locations entails that there is also a large concentration of particulate matter in micro-environments as obtained in macro-settings. The sources of particulate matter according to them include burning of incense, cooking, cleaning activities, heating from the combustion of fuel, and lighting of fireplaces among others and could be very harmful to children and the elderly members of the home in the short term and to other household members in the long term. They further argue that indoor particulate matter if not properly managed can have far reaching impacts than outdoor concentration of particulate matter. Spruijt [39] focused their study on the contentions that exist in the process of policy formation on particulate matter. They further discovered that the experts believe that precautionary roles need to be taken to prevent particulate matter emissions and that science and policy should not be bifurcated in the quest to reduce particulate matter emission. In essence, they recommended that to reduce the concentration of PM10 and PM2.5, there is a need for effective legislation, regulation, and monitoring of all activities that lead to emissions. Manisalidis [21] conducted a study to determine how to combat the effects of particulate matter. According to them, particulate matter can lead to respiratory, cardiovascular, reproductive, and central nervous system dysfunctions. In the light of these challenges, they recommended that there is a need to raise public awareness. In addition, there is a need for a multidisciplinary study by experts. Furthermore, there is a need for synergy between national and international organisations to tackle the threat posed by particulate matter. Furthermore, there is a need to constantly review policy on air quality legislation to align with current trends in air pollutant (PM10 and PM2.5) concentrations to ensure that the international standards of the World Health Organisation on mean daily and annual concentration of PM10 and PM2.5 are not exceeded. The need to manage particulate matter concentrations in the atmosphere stems from its well-known and quantifiable consequences on human health, such as premature mortality, hospitalisation, anaphylaxis, lung impairment, and cardiovascular illnesses. The potential for particles to cause health problems is directly proportional to their size [33]. Several studies have been carried out on particulate matter, its effect on the environment, and potential effect on life. Krall [40] and Bell [41] described particulate matter as a mixture of various nonhomogeneous constituents which can be influenced by the season of the year and region. The conclusion of the study revealed no evidence of seasonal influence and no association between mortality and particulate matter. However, components of PM2.5 have varying toxicity and effect on human health.

There is compelling evidence that particulate matter plays a substantial influence in all-cause mortality in humans, especially cardiopulmonary mortality [42]. Prolonged particle exposure is associated with a greater risk of deadly cardiovascular and respiratory illnesses, such as lung cancer, which manifest as higher mortality rates in cities with increased particle exposures. According to [43], the best estimate of the long-term health effects of PM exposure is a 6% increase in death rates per 10 micrograms per cubic metre PM2.5 concentration. There is no safe threshold of particle exposure as regards severe impacts. The human respiratory system is profoundly penetrated by fine particulate matter. Increased hospitalisations, early mortality of the elderly and illness due to disorders of the respiratory and cardiovascular systems are among the severe impacts of exposure. Following emission exposure, less severe impacts of short-term particle exposure occur, such as increasing asthma attacks as well as an overall sense of being ill, resulting in a decreased level of activity. Wang [16] assessed particulate matter in Shanghai subway trains and platforms. Their research found that PM levels on the platforms were higher than within the train, and that PM amounts on the platforms were influenced by the "piston wind" effect generated by incoming trains. A piston wind is the wind generated from the movement of subway train through the tunnel, causing the positive pressure at the head of the train to push polluted air out, while the negative pressure at the tail draws in fresh air. Furthermore, the influence of the piston wind changed depending on where you were on the platform, and it was greater at both endpoints than in the centre. The installation of adequate ventilation systems in tunnels and trains were recommended.

In London tunnels, there have been several reports on high levels of tunnel dust which are also forms of particulate matter. Research in London found that the quantities of tunnel dust on the London Underground are unlikely to pose a major cumulative harm to the health of workers or commuters. Efforts to lower dust concentrations are encouraged since dust can pose potential toxic risk [44]. In California, [45] examined the link between PM2.5 constituents and cardiopulmonary mortality using a distance-based exposure assessment approach. Using the same approach, Ibrahimou [46] assessed the relationship between particulate matter and low birth weight while [47] examined PM with risk of preterm birth. Results and conclusion derived from these studies established a strong positive correlation linking PM2.5 to (i) various mortality particularly cardiovascular deaths [45], and (ii) elevated risk of preclampsia during pregnancy [46]. However, [47] found no sufficient evidence relating PM2.5 as a potential cause of preterm birth.

The above chapter has reviewed relevant literature on particulate matter. It is evident that there is the prevalence of particulate matter not just in the United Kingdom but also around the world. It is also clear that there have been several interventions by governments of nations, national and international organisations to reduce the concentration of PM10 and PM2.5. It is also evident that in countries where there is effective monitoring, there are marked decrease in the mass of particulate matter. In terms of the empirical studies that were reviewed, the potential for particulate matter to result in health hazards for human is well established. In addition, particulate matter can negatively impact on the health of the environment. It was however stressed that effective legislation, regulation, and monitoring are required for reducing the concentration of PM10 and PM2.5. However, it was discovered that scant attention was paid to the prevalence of particulate matter in the subway areas of the United Kingdom. This is the knowledge gap that this present study has attempted to fill. Therefore, effective monitoring and regulations are required in combatting the health and environmental implications of PM.

3. Methodology

Particulate matter less than 2.5 μm in aerodynamic diameter (PM2.5) was measured at selected UTS in the study area using a portable Aeroqual Series 500 device (PM sensor head), calibrated from the factory, and re-calibrated at the University of Newcastle laboratory for both indoor and outdoor analysis. The device was further calibrated within area of study by running the device along multiple outdoor and microenvironment locations.

3.1. Sampling and analysis

Six subway platforms in a single narrow circular tube were sampled for this study with tag P1, P2, P3, P4, P5, and P6. The Aeroqual device was located approximately 1 m above the platforms closest to where trains entered the station and at the far end of the platform. A continuous reading was taken by the device on arrival and departure of the train at one minute interval. Other observations were made and noted such as number of passengers present and location of station close to water body, hence influencing humidity. The Aeroqual handheld device was then placed at sitting level of the tail end inside the passenger train. Multiple readings were taken in the train at one minute interval while the train was in motion through tunnels between platforms. Multiple readings were taken and averaged to give minimum and maximum readings within train between Platform 1 and 2, 2 and 3, 3 and 4, 4 and 5, 5 and 6 tagged as Train T1, T2, T3, T4, T5, T6 respectively. This was repeated at different platforms to capture and compare data both in the Train and the platforms. The measurements were continuous while exiting the station platforms to determine variation in concentration of particulate matter. The sampling was carried out at different intervals over a period of 1 hour at morning periods between 9 am and 12 noon while the ventilation information of the stations was not accessible. The data was read off directly on the Aeroqual screen while the full data was downloaded on the Aeroqual PC software. The statistical analysis employed for data interpretation is described in the section below.

The PM concentration data in mg/m3 obtained were analysed both qualitatively and quantitatively and converted to µg m-3. The correlation, mean, maximum, and minimum values were determined quantitatively. These values were qualitatively analysed by comparing with World Health Organisation (WHO), European Union (EU), United Kingdom (UK) permissible limits for indoor air quality.

Arithmetic mean was estimated to determine central tendency of the data obtained. The data obtained during this study were observed to have a non-skewed distribution (no value is greatly larger or smaller than the remaining set of numbers).

4. Results and Discussion

The results obtained at all six platforms over the period of study are shown in Table 1 below. The range of PM2.5 concentrations in µg m-3 are 89 - 120, 121 - 172, 144 - 180, 130 – 166, 131 – 147, 93 – 154 for Platform 1, 2, 3, 4, 5 and 6 respectively. The highest mean for PM2.5 was found in P3 with mean of 165 µg m-3.

Table 1. Showing Mean Concentrations of Study Area and Permissible Standards

Data	**Duration**	**Mean Concentrations (µg m^{-3})**
		$PM_{2.5}$
UK	Annual	25
	24hr	NA
EU	Annual	25
	24hr	20*ECO
WHO	Annual	5
	24hr	15
Scotland	Annual	12
	24hr	NA
Platform range	Hourly	103-165
Train range	Hourly	115-153
Realtime Ambient Data (aqicn.org)	24hr	27 (Range25-50)
Control	One off	3.5 (Range2-10)

* ECO-Exposure concentration obligation

The mean concentration PM2.5 measured outdoor above the ground was 3.5 µg m-3. The train data cover multiple rides between platforms when train was in tunnels including measurements when the train was not in motion. The range of PM2.5 concentrations in µg m-3 are 87 - 151, 99 - 168, 131 - 179, 119 – 166, 113 – 151, 82 –179 for Trains 1, 2, 3, 4, 5 and 6 respectively. The highest mean for PM2.5 was found in T3 with mean of 153 µg m-3.

The mean PM2.5 concentrations on the platforms ranged between 103 µg m-3and 165 µg m-3, for all the six platforms exceeding the control concentration as summarised in Figure 1 below. The control data were concentration data of the nearby outdoor streets obtained using the same handheld Aeroqual device. Comparing the PM2.5 range with reported Real time ambient values ranging between 25 and 50 µg m-3, the platform values were far greater. Monthly range of urban background mean reported for Northern UK, Central UK, Southern UK and London (England) were 6 to 21 µg m-3, 8 to 22 µg m-3, 9 to 20 µg m-3, and 9 to 22 µg m-3 respectively. The platform mean values exceeded the 25-µg m-3, 25 µg µg m-3, 5 µg m-3 PM2.5 permissible annual limit standards set by the EU, UK and WHO respectively. The concentrations for all the six platforms also exceeded the 20-µg m-3 and 15 µg m-3 PM2.5 permissible 24-hour limit standards set by the EU, and WHO respectively.

The enclosed nature of the platform limits the particles from dispersing and diluting with a larger atmosphere as the outdoor environment. This therefore creates a microenvironment with high concentration of particulate matter greater than ambient concentration [12]. There was no observable change in the concentration of PM2.5 with the arrival and number of passengers on the platform. However, the values increase on arrival of the incoming trains at all platforms which agrees with the "Piston effect" [16].

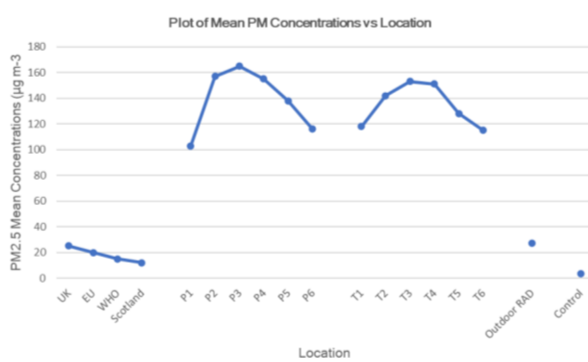

Figure 1. Showing Mean Concentrations of Study Area and Permissible Standards

The mean PM2.5 concentrations on the Train ranged between 115 µg m-3 and 153 µg m-3 exceeding the control concentration as summarised in Figure 1. The control data were concentration data of the nearby outdoor streets obtained using the same handheld Aeroqual device. Comparing the PM2.5 range with reported real time ambient values, the train values were far greater. The PM2.5 concentration also greatly exceeds the monthly mean urban ambient values range reported for Northern UK, Central UK, Southern UK, and London (England) which were 6 to 21 µg m-3, 8 to 22 µg m-3, 9 to 20 µg m-3, and 9 to 22 µg m-3 respectively. The train mean values exceeded the 25-µg m-3, 25 µgm-3, 5 µg m-3 PM2.5 permissible annual limit standards set by the EU, UK and WHO respectively. The concentrations for all the six platforms also exceeded the 20-µg m-3 and 15 µg m-3 PM2.5 permissible 24-hour limit standards set by the EU, and WHO respectively.

The enclosed nature of the platform limits the particles from dispersing and diluting with a larger atmosphere as the outdoor environment. This therefore creates a microenvironment with high concentration of particulate matter [13]. There was no observable change with the arrival and number of passengers in the train. However, the values increased when the door opened on arrival of the incoming trains at all platforms. This is due to PM being pushed from within the tunnel [16]. The train and platform concentrations agree with the subway concentrations reported across the world [44] including USA [14], London, New York, and Stockholm [15].

5. Recommendations

The following recommendations were made:

- A further study of underground train systems covering a longer period of exposure time (annual) and use of different methodologies (equipment) is strongly recommended.

- A monitoring station should be installed to monitor possible seasonal and diurnal variations.

- A more detailed assessment and monitoring of particulate matter should be carried out to determine the composition and sources.

- An efficient ventilation system should be introduced both in stations and in trains which will mitigate the high concentration levels.

- A policy that will ensure investigation, monitoring, and mitigation of particulate matter in microenvironments should be introduced.

- Such policy should establish an hourly permissible standard as a guide for short time exposure to complement the daily and annual standards.

6. Conclusion

Air particulate matter was assessed in selected UTS both on platforms and inside the train. The PM2.5 concentrations with aerodynamic size 2.5 µm was determined. The results revealed varying concentration for both PM2.5 in the sampled location employed in the study. The concentration of PM2.5 on platform and in train are influenced to a great extent by accumulated amount over a period of time and air pushed out from the tunnel. Mean PM2.5 concentrations were several times greater than mean concentrations in ambient outdoor air. Platform 3 recorded the highest concentration of both PM2.5 corresponding to high values obtain in the train around the platform which could be due to the presence of water body above ground. Levels of particulate matter PM2.5 were observed to exceed permissible limits set by regulatory bodies including UK DEFRA, EU Clean Air Directives and WHO.

Given the fact that there have been several research on particulate matter in UTS, the most of them have focused on monitoring variations in particulate matter concentration on platforms and in a limited number of stations. Little focus has been placed on determining the source and composition of particulate matter in form of speciation studies. Likewise, particulate matter in outdoor environment remains the major air quality focus by organisations, and government in the United Kingdom. As a result, comprehensive assessments of complete subway systems are required, spanning a wide range of lines, trains, and stations.

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