MS in Sustainability Science Program at Columbia University

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Measured Particulate Matter Concentrations in New York City's Subway System Suggest Exceedance of U.S. Environmental Protection

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Neighborhood-Scale Variation in Particulate Matter Pollution in the New York City Metropolitan Area

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Sustainability Science Program and Capstone Course

The Sustainability Science program at Columbia University supports students who wish to understand, address and solve environmental issues with a sound, technical science. The curriculum was developed by Columbia's Earth Institute and focuses on teaching students how to use cutting-edge scientific methods, instruments, and tools to help organizations address environmental issues with a distinct goal of addressing the University's Fourth Purpose, that of applying science to improving the world. Over the course of the program, students look at methods of earth observation and measurement, analysis and modelling of environmental conditions and impacts, scientific tools for responding to sustainability challenges, and policy and management.

The Sustainability Science Capstone course is a client-based workshop in which students collect and analyze data surrounding a particular sustainability problem and make recommendations for solving this issue. For the Fall 2021 semester, the main goals of the project was to use air quality sensors to monitor air quality in subways and subway platforms across New York City (NYC), and use that network to characterize environmental exposures associated with commuting in those subways to schools. We also strive to use this data to improve public health. Given the need to characterize air quality in these nontraditional settings, which are frequented by students most sensitive to excessive air pollution, we designed our experiments to measure air quality experienced by students commuting from Outward Bound schools.

Alongside the clients, New York City Outward Bound Schools and a network of science teachers are using these data to discuss environmental inequity, scientific data, statistics and environmental science. Based on the analysis of the data collected, it is clear that more effort is needed to understand air pollution in the subway.

Organization of Report

Our report is formatted as a scientific research publication that covers sensor deployment, sensor calibration, sensor output, and calculated human health exposures for students who commute on the subway.

Neighborhood-Scale Variation in Particulate Matter Pollution in the New York City Metropolitan Area

Abstract

An affordable and replicable process of accurately measuring particulate matter (PM2.5, PM <2.5 µm) concentration in the New York City subway system was conducted. The method uses PurpleAir monitoring devices calibrated with ultrasonic personal air sampler (UPAS) gravimetric filter data. Measurements from over 25 independent subway ride events across Manhattan, Staten Island, Queens, and Brooklyn, research found that the mean air quality in the New York City subway system, both on trains and on underground platforms, is often much higher than ambient air quality. During the sampling collected, mean air quality in the subway system was nearly fifteen times worse (approximately 105 $\mu g/m^3$) compared to the mean city ambient air quality over the same periods (6.55 $^{\mu g/m3}$). Concentrations differed considerably depending on train line, station and platform, with overall exposure being highest in local trains, deeper stations and crossing stations. High exposure sites are likely to disproportionately affect overall exposure to PM, suggesting that targeted remediation might effectively address much of this problem. It is suggested that the subway system install a network of air monitoring devices throughout the city's subway system to better understand users' potential exposure to particulate pollution.

Keywords: air pollution, subway, particulate matter, low-cost air quality monitoring

1. Introduction

The interest in using lower-cost air quality sensors to characterize urban and rural population exposure to fine particulate matter, particularly PM2.5, has recently gained momentum (Eilenberg et al., 2020; Kosmopoulos et al., 2020; Romero et al., 2020; Tryner et al., 2020). Given the emergence of a novel virus that exhibits higher rates of mortality for those with impaired lung health, there is increased concern about air pollution, especially PM2.5, and its linkage to a wide array of health effects, including heart and lung disease and premature mortality (Adhikari & Yin, 2020; Copat et al., 2020; Hendryx & Luo, 2020; Pope et al., 2019).

The New York City Community Air Survey (NYCCAS), led by the New York City Department of Health and Mental Hygiene (NYCDOH) and The Barry Commoner Center for Health and the Environment at Queens College, is the nation's largest ongoing urban air monitoring program, and is tasked with studying how pollutants from traffic, buildings, and other sources impact air quality across the city's many neighborhoods – particulate matter is one of the many pollutants measured by the program. Although New York City (NYC) air quality is improving, the most recent NYCDOH air pollution survey estimates that fine particle pollution alone caused an average of more than 2,000 deaths, approximately 1,500 hospital admissions for lung and heart conditions, and 5,000 emergency department admissions for asthma based on levels in 2009-11 (The New York City Community Air Survey: Neighborhood Air Quality 2008-2018, n.d.). In 2018, 78 locations were monitored routinely (80 percent of which were chosen at random by the NYCDOH to ensure representation in all types of neighborhoods, including residential, commercial, and industrial areas. The other, non-random, locations were selected because they are located near potentially high-emission sources, and include Times Square, the Port Authority Bus Terminal, and the entrance of the Holland Tunnel. This survey revealed considerable variation in contamination between sites, with the highest PM2.5 levels associated with high-traffic areas.

1.1 Subway Air Quality Monitoring

Subways represent a distinct and expansive indoor air environment. As of July 2021, no cities have implemented system-wide networks for air monitoring of indoor spaces, including transit services. The New York City subway system, one of the largest subway systems in the world, was responsible for transporting nearly 5.5 million passengers per weekday, pre-COVID lockdowns (MTA, 2020). However, since COVID-19 shutdowns were announced in late March 2020, people have been worried about using the system for commuting, and there has been increased interest in characterizing air pollution and improving ventilation systems of indoor space we utilize regularly (Bartzokas et al., 2021; Brazile, 2020; Goldbaum, 2020; Rivera-Rios et al., 2021).

Despite historically high ridership, there are relatively few studies of the particulate matter concentrations within the commuter system. One such study, Vicesimal et al. (2014), regarding air pollution in the city's subway system, found that particulate matter and black carbon concentrations were several times higher than ambient urban street levels of 9.5 µg/m3. Another found elevated levels of iron (Fe), manganese (Mn), and chromium (Cr), up to 100 times higher, in the subway system compared to aboveground (Chillrud et al., 2004).

More recently, a study of how various East Coast subway systems rank in terms of air pollution found that trapped polluted air is not a unique characteristic of NYC stations (Luglio et al., 2021). The study collected air quality data during morning and evening rush hours (pre-COVID) in 71 stations in Boston, New York City, Philadelphia, and Washington, D.C. Among the New York City subway stations measured, they found levels of hazardous metals and organic particles in the air over 20 times the measured concentrations of outside ambient air (Luglio et al., 2021). Of the study's four cities, New York City stations ranked as the first (PATH) and second (MTA) highest averaged PM2.5 concentrations, with individual observations reaching as high as 1,499 µg/m3 and 959 µg/m3, respectively, also making them the most hazardous to health (Luglio et al., 2021).

Historically, air pollution monitoring for a vast network, like the NYC subway, has been cost prohibitive. In recent years, new low-cost air quality monitors have entered the market, enabling so-called "citizen science" to fill in the gaps where government budgets have not been able to. One such low-cost monitor is PurpleAir. Continuing a partnership from a prior study with Outward Bound and the NYC Department of Education, we sought to develop and test a low-cost method to monitor PM2.5 concentrations in the city's subway system. In doing so, we hope to better understand and quantify the exposure of students, and other commuters, to particulate matter and prove that reliable air quality monitoring can be achieved with low-cost monitors, potentially providing the groundwork for a system-wide, publicly accessible subway air quality network.

2. Materials and Methods

A combination of the PA-II-SD (PurpleAir), the Ultrasonic Personal Air Sampler V2+ (UPAS) (Access Sensors), and a nephelometer (Temptop M2000C) for monitoring events (Figure 1). In addition, a 5V battery pack was utilized in the field to power the PurpleAir sensor.

2.1 PurpleAir

PurpleAir devices have proven to be precise and have built-in redundancy by utilizing dual Plantower laser particle counters to count suspended particles (Ardon-Dryer et al., 2020; Bi et al., 2020; Romero et al., 2020; Tryner et al., 2020). The PA-II-SD was selected because of its low cost ($279), utility for indoor and outdoor collection environments, and the integrated MicroSD slot, permitting both online and offline data collection. The device also has built-in pressure, temperature, and humidity sensors to assist the device in applying an algorithm to calculate the concentrations of PM1.0, PM2.5, and PM10 in $\mu g/m^3$ (PurpleAir PA-II-SD Specs, n.d.).

Figure 1: *PurpleAir in canteen pouch for portability and two UPAS devices (top), actively collecting air quality data on a subway platform, and the Temptop (bottom) monitoring air quality at the 86th Street A/B/C/D platform.*

2.2 Ultrasonic Personal Air Sampler (UPAS)

The filter-integrated UPAS uses a gravimetric pump with interchangeable PM size inlets to move air and particles through at a uniform rate. The device uses infrared light to count particles and provide real-time air quality information. It has built-in temperature, pressure, and relative humidity sensors, a GPS, and wireless connectivity that allow it to be monitored with an Apple iPhone.

2.3 Temtop Nephelometer

A Temtop air quality monitor to measure PM and CO2 concentrations in real-time as part of the sampling strategy. The nephelometer provides an instantaneous measurement of various air quality measurements, including PM2.5 and CO2, while also providing visual cues indicating the Air Quality Index (AQI) (Temptop M2000C Specs, n.d.).

2.4 Sampling Protocol

In the field, the utilization of a simple setup consisting of a small bag with an open top or mesh pocket, the PurpleAir was situated to expose it to air flow, and a 5V battery pack was used to power the unit. The UPAS was utilized in conjunction with the PurpleAir during collection events to establish a platform and train car average, which was utilized to calibrate the measurements of the PurpleAir. The nephelometer was used as an additional "visual" measure of real-time concentration data.

Measurements were done on numerous subway trains and platforms in the city using one of three separate PurpleAir monitors for a minimum of 1 h and a maximum of 8 h. Two distinct sampling strategies designed to: (a) sample a specific location for an extended period, and (b) during travel through the subway system, including trains, platforms, and stations. Most of the PurpleAir collection occurred between noon and 3pm, but no specific time of day was chosen as a baseline time of commute. Due to limited resources, it was uncommon for two PurpleAir devices to monitor in one location at the same time. However, separate measurements suggest that the PurpleAir devices are consistent with one another and show similar trends over short durations. In other words, their initial factory calibrations are similar and work well.

Despite there being no regimented design for sampling, monitoring was generally performed as a typical subway user would during their commute (i.e., wait on platform for train, board train, make transfers when necessary, exit train, and exit station when destination is reached). There may have been times when extended time on a platform may have occurred due to delays or "full" trains (i.e., trains that had a significant number of passengers, causing the field monitor to wait until the next arrival). Notations of the station and time were made when each of the "steps" of the commute occurred, so the measurements from the PurpleAir could be correlated with a location and time of day. When monitoring with a UPAS, the field collection event lasted at least two hours when the whole of the collection period was performed underground, as to allow for sufficient mass to be collected on the filter. When monitoring without a UPAS, train car and platform collection periods ranged from 20 minutes to 3 hours.

2.5 Sampling Site Selection

The train lines of primary focus for this study were the 1 Line ("the 1") and Staten Island Railroad (SIR). These primary train line sampling sites were selected based on proximity to Outward Bound and NYC Department of Education partner schools, the Washington Heights Expeditionary Learning School (WHEELS) (Manhattan), West End Secondary (Manhattan), and

Curtis High School (Staten Island) (Figure 2). In addition to these sites, train lines (2, 3, 7, A, B, C, D, E, F, L, Q, W) that connect to the 1 Line were selected because users of the system often have to transfer train lines in order to reach their final destinations (Moovit, n.d.).

Figure 2: *A map of NYC subway lines and partnered Outward Bound schools (orange hexagons).*

2.6 Data Analysis/Importation

The uncalibrated data collected by the PurpleAir can be exported by connecting the device's removable MicroSD card to a personal computer and downloading the respective day's comma separated values (CSV) file. The data was then organized according to local time collection. The values under the headers "current_temp", "current_humidity", "pm2_5_cf_1", and "p_2_5_um" were then calibrated according to the weighed UPAS filter (Romero et al., 2020; Tryner et al., 2020). These specific values were chosen for calibration based on the prior study by Romero et al. (2020) indicating that the "cf" value is indicative of concentrations for indoor environments, which in our study includes underground platforms and train cars.

2.7 Calibration with filter data

The PurpleAir sensors function via laser-counting, with reported mass concentration measurements being inferred based on an internal calibration for ambient air, which is distinct from subway air. In general, PurpleAir filters require recalibration based on a measured PM concentration relative to a reference measurement and adjusted for environmental conditions that influence calibration. Because of this, the raw data they produce require calibration in accordance with a Federal Reference or Federal Equivalency method. In other words, the data collected by PurpleAir needs to be calibrated either per a corresponding mass measurement, or per corresponding data that itself satisfies a Federal Reference Method.

Two calibration methods were used in this study based on the location of the collected data. Outdoor air quality measurements taken with the PurpleAir were calibrated by comparison with a station that satisfies a Federal Reference Method. This calibration was used for data collected indoors and outdoors, away from subway lines. This calibration was developed by comparing data collected from the fourth floor of the WHEELS school with data collected adjacent to it on the roof (10 m apart) by the New York State Department of Environmental Conservation (station IS 143), as well as temperature and humidity.

The composition of PM2.5 generated in the subways differs significantly from the profiles typically measured with the PurpleAir sensors. PurpleAir is designed to internally calibrate based on “expected” pollutants, mostly forms of hydrocarbons, and the ways they interact with other air quality factors, mainly temperature and humidity. PM2.5 in the subway systems, however, tends to be composed of various metals, which behave differently with regard to moisture in the air. Therefore, separate calibration was performed for data collected on platforms and trains. PurpleAir units are a promising tool for measuring PM2.5 concentrations and identifying relative concentration changes, as long as the PA-II-SD PM2.5 values can be corrected (Ardon-Dryer et al., 2020). For outdoor platforms and trains running aboveground, data was calibrated based on the average concentration reported by PurpleAir along the SIRR line, compared to UPAS filter data collected concurrently. For underground platforms and trains running underground, data was calibrated based on a regression of the entire set of UPAS filters collected during the study, compared to the corresponding PurpleAir averages during the respective time periods.

3. Results

A sample of calibration data on a platform can be seen in Figure 3 with data collected at the 116th St. platform over a two-hour period; it also shows both the PurpleAir calibration. The variation in the peaks over time is due sensor (in purple) and UPAS (in green) before and after the flow of subway traffic in the underground station. The fainter-colored lines depict the uncalibrated data, while the darker lines depict calibrated data. Both devices underestimate the real subway air concentration by four-fold, demonstrating how critical it is to calculate a calibration curve based on UPAS particulate weight data. PM2.5 calibrated concentrations from three different subway lines (A, L, and 3) are shown in Figure 4 from a daytime subway commute back and forth from Manhattan to Brooklyn. The area below the curve represents total exposure to PM2.5. Underground platforms are depicted as the area in blue, subway train cars in orange, and underground platforms in gray. Underground platforms in Manhattan had higher proportionate concentrations of PM2.5 (59th St. and 96th St.) compared to subway train cars and aboveground platforms.

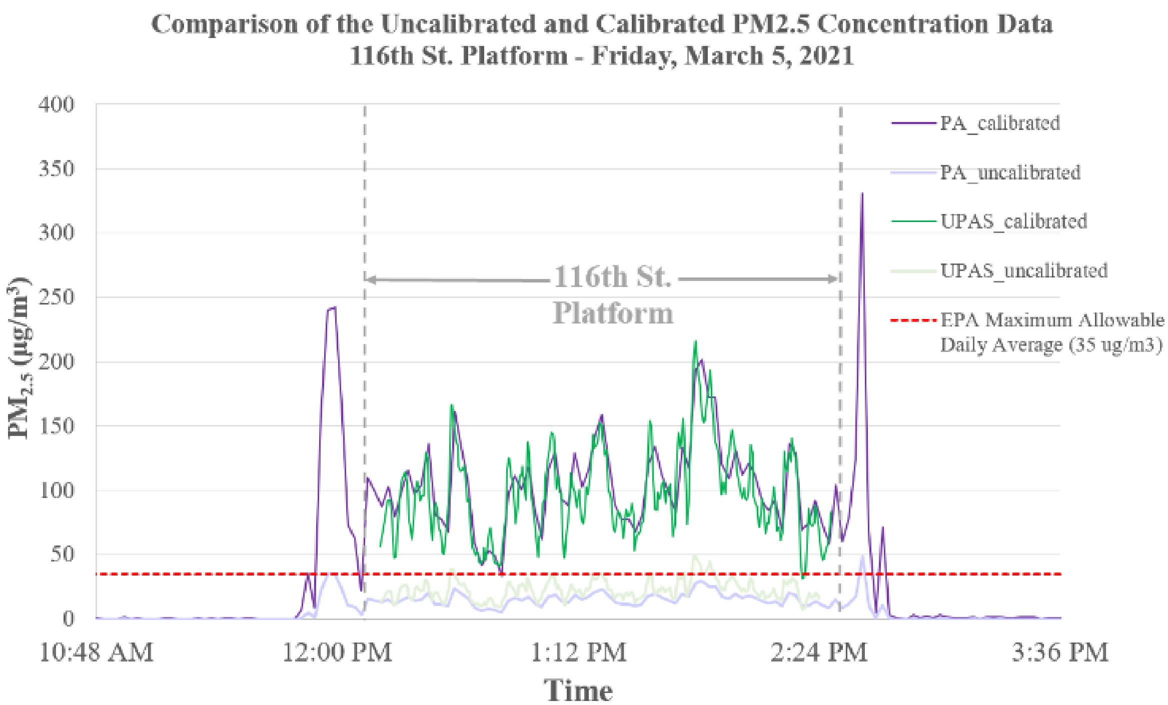

Figure 3 *The calibrated (dark) and uncalibrated (faded) PM2.5 data from the PurpleAir (purple) and UPAS device (green) plotted for the 116th St. platform. The U.S. EPA maximum allowable daily average (35 µg/m³) is shown in red. Calibrated PM2.5 data indicates concentrations exceeding EPA maximum.*

As illustrated in Figure 5, calibrations indicate that the raw data from the PurpleAir sensors tend to overestimate PM2.5 concentrations in locations with presumably typical PM2.5 compositions, and to heavily underestimate the PM2.5 concentrations underground. Train cars by a slight margin showed the highest variability out of our calibrated readings. As train cars have their own internal air filtering systems, real-time readings consistently showed PM2.5 concentrations lowering during transit and rising when doors opened onto an underground platform.

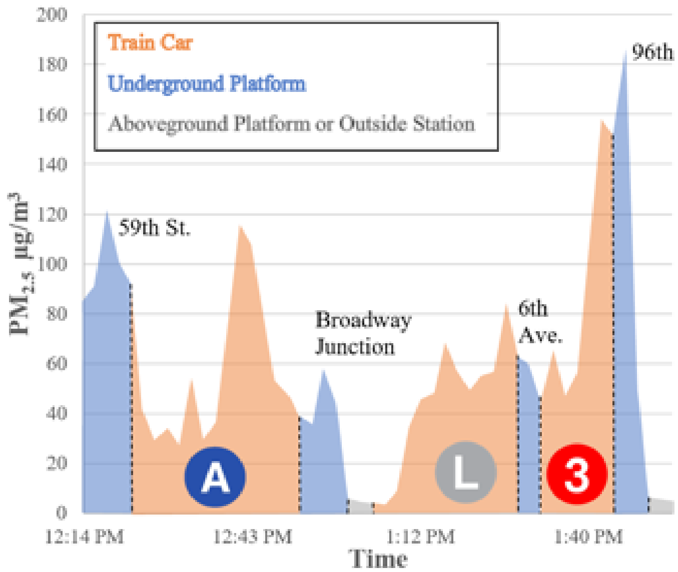

Figure 4 *Calibrated PM2.5 concentrations along different train lines on February 4, 2021. The different colors under the curve represent cumulative particulate matter exposure based on location of exposure.*

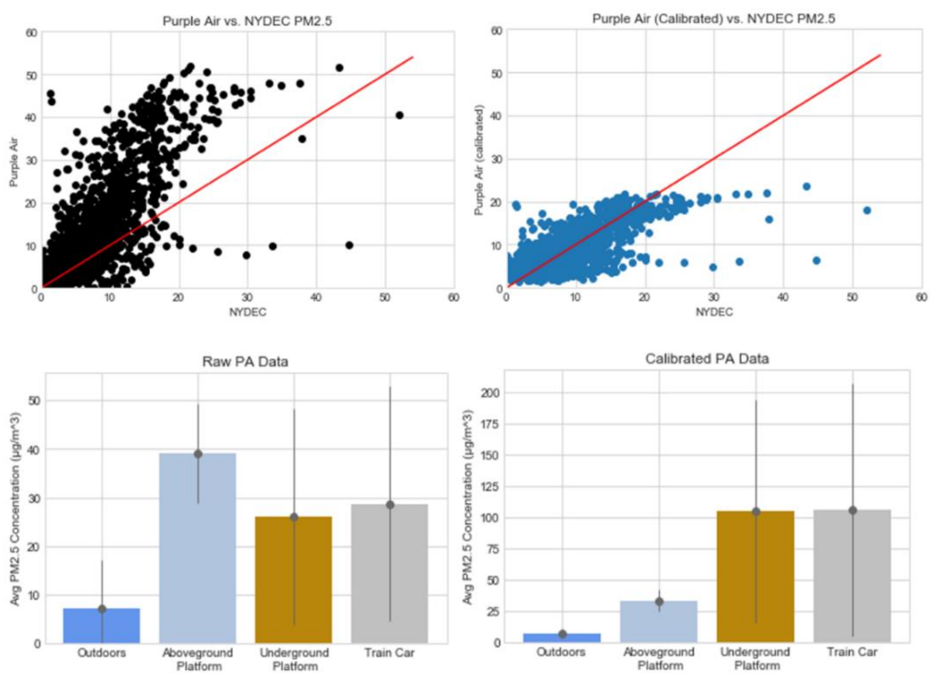

Figure 5 (Above): *The impact of calibration on outdoor/indoor data with "Typical" PM2.5 composition, illustrated against a 1:1 line.* ***(Below):*** *When calibrated against gravimetric UPAS filter data, measurements taken along the underground subway lines increase dramatically.*

Per Figure 6, the means of all samples collected on underground platforms and train cars were well above the EPA 24-hour standard of 35 µg/m3 (Figure 6). Most samples below this benchmark were collected on aboveground trains and platforms, the average PM2.5 concentrations continued to exceed the EPA's annual standard of 12 µg/m3.

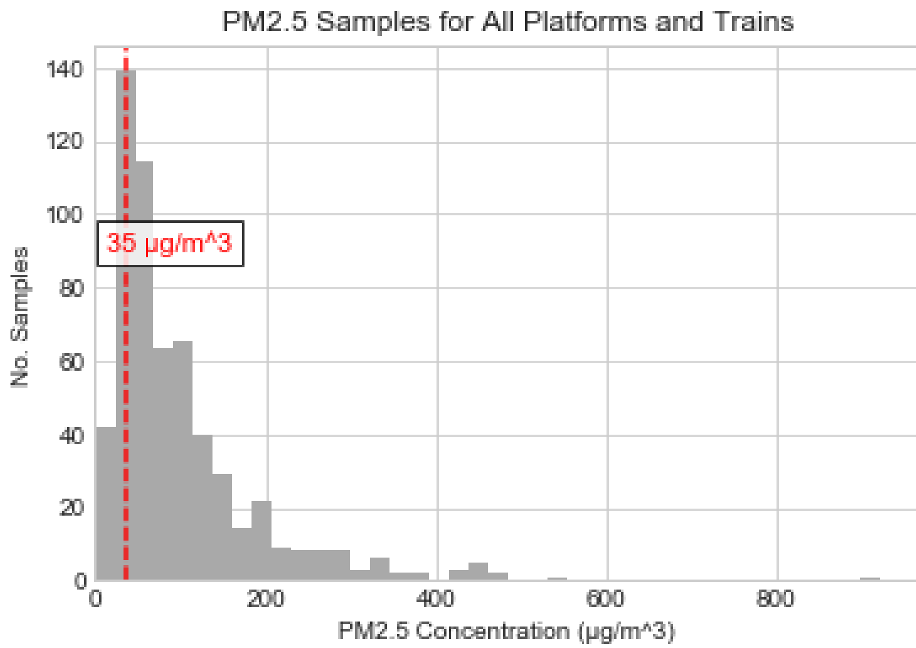

Figure 1 *Histogram of all calibrated samples taken on trains or train platforms, benchmarked against the EPA 24-hour standard of 35 µg/m^3*

4. Discussion

The elevated pollutant levels throughout the subway system are consistent with prior studies indicating above average background concentrations of PM2.5 in subway systems, particularly New York City's average of 6 µm/m3. The study found that outdoor ambient air concentration for NYC was 6.55 µm/m3 (Figure 7), compared to 105.44 µm/m3 for the average calibrated PM2.5 concentration of across all measured stations and trains.

4.1 Breakdown of Stations and Lines

The station with the worst average calibrated air quality was 2nd Avenue along the F line (407.88 µm/m3). The Lexington Ave-63rd station average concentration (113.19 µm/m3) was slightly above the total subway system's average for PM2.5 levels with no calibrated samples measured below the EPA standard. The 116th St-Columbia University station had better-than-average air quality (61.86 µm/m3), but most samples still showed PM2.5 levels higher than the EPA standard. The only train lines with average PM2.5 concentrations below the EPA standard, as seen in Figure 8, were the SIR, an aboveground line, and the W train, where many samples were collected from aboveground stops in Queens. All underground lines far exceed the EPA annual standard, with the F, 7, 1, and C lines showing the highest PM2.5 concentrations.

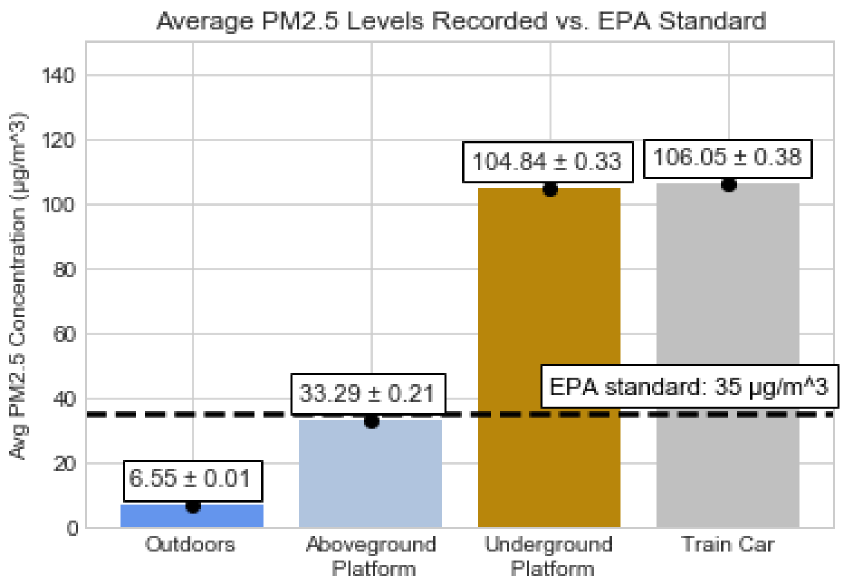

Figure 7 *Average calibrated PM2.5 levels recorded. The dashed line represents the EPA 24-hr standard*

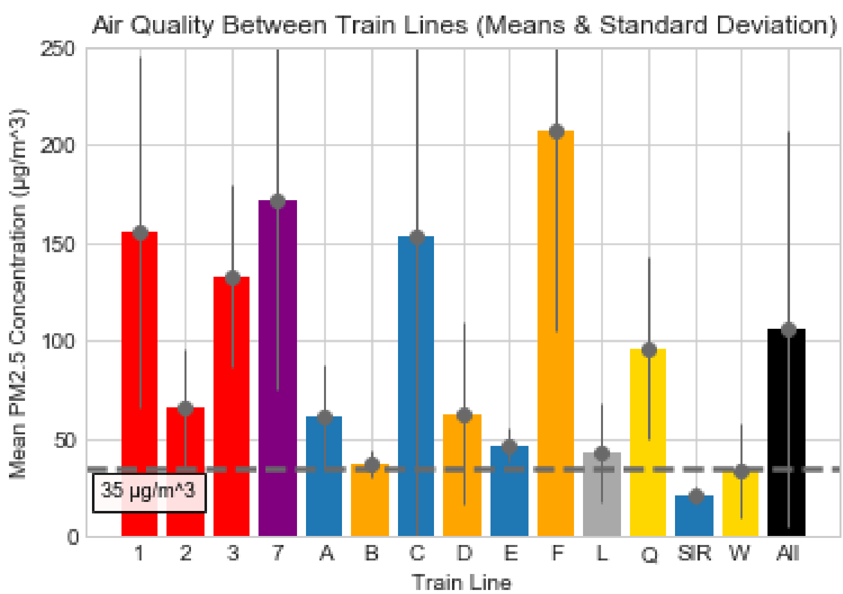

Figure 8 *Comparison of average PM2.5 concentration across all subway lines, as well as total average.*

While mean levels of PM2.5 on trains and underground platforms exceed the EPA 24-hour standard (and aboveground platforms exceed the annual PM2.5 standard of 12 µg/m^3), a person's average daily PM2.5 exposure depends on the amount of time in a day spent commuting, versus time spent aboveground. Given the scale of difference between outdoor air and underground air, exposure from time underground adds up quickly. Figure 9 shows that a two-hour commute will exceed the recommended EPA annual threshold, and a person spending all day underground exceeds the daily threshold.

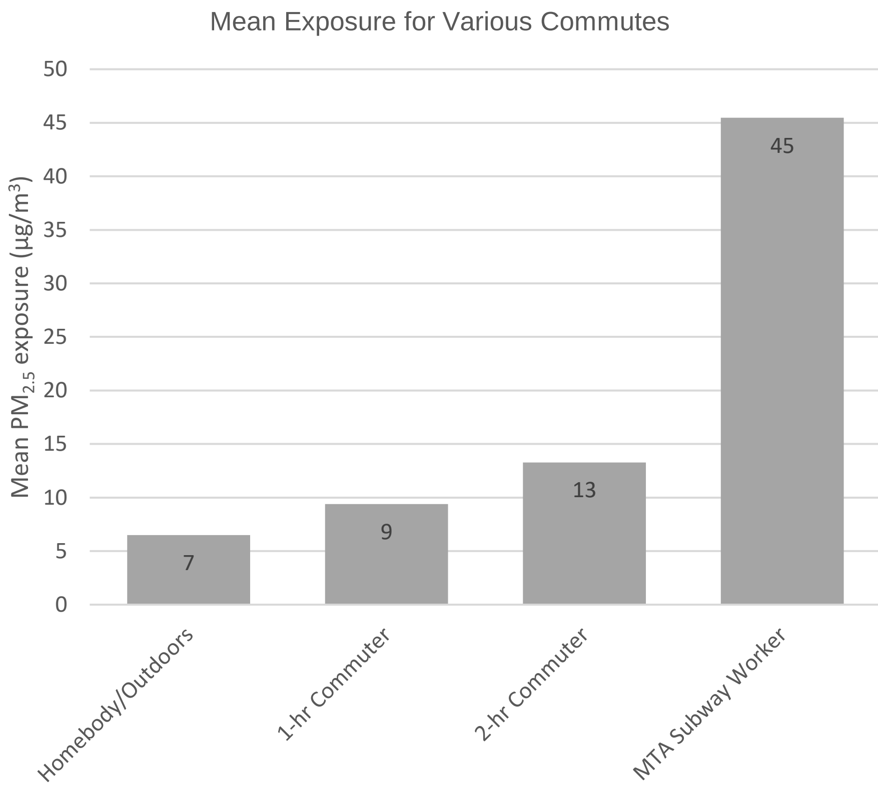

Figure 9 *Average PM2.5 levels for different location types along a commute, and the combined exposure for given commute times. The exposure of an MTA Subway Worker is more than 3 times that of a 2-hr Commuter, which could lead to heighted health risks*

4.2 Exposure & Health Implications

Studies have indicated that even modest exposure to PM2.5 increases the risk of developing serious respiratory ailments, such as asthma and lower lung function, and cardiovascular disease (Haley et al., 2009; Pope et al., 2019). It has also been shown that subway particles are more damaging to DNA and cause oxidative stress to lung cells (Grass et al., 2010).

Haley et al. (2009) found that older adults were significantly more susceptible to negative health impacts than their youth counterparts when exposed to short-term PM2.5 concentrations exceeding 5 µm/m3. Knowing this, the subway's average particulate matter concentrations are of particular concern for health.

The baseline average PM2.5 concentration in New York City is 6.5 µm/m3, meaning an older adult that does not utilize the city's subway system is already at a heightened health risk. The average commuter spends a little less than an hour commuting, resulting in about 64% of the daily maximum exposure from their train ride alone (Moovit, n.d.). As the commute reaches two hours, riders exceed maximum daily exposure by 19%, reaching 13 μm/m3. Of particular concern is the potential exposure for an MTA subway worker, compared to the 2-hr commuter. For an 8-hr workday in the subway, an MTA worker's exposure increases 246%, to 45 μm/m3.

4.3 Study Limitations

While the study has revealed important implications and next steps regarding the NYC subway system and has shown the efficacy of PurpleAir sensors as a cost-effective method of collecting data, there are several factors and questions that were unable to be addressed in the scope of this study. Many of these limitations could be addressed with additional data—with only four PurpleAir sensors and limited time to gather data, temporally-comprehensive profiles for the stations and train lines studied were unable to be built. As such, in-depth examination of the impact on PM2.5 levels from several factors, including time of day, day of the week, station depths, train car ages, and the effect of outdoor baseline PM2.5 levels on concentrations underground could not be completed. Furthermore, several train lines were characterized based on a low number of samples; with more comprehensive data collection, these profiles could be made much more robust.

There was additional uncertainty as to the best calibration method for data collected from aboveground platforms and trains running aboveground, given that the exact chemical composition of the PM2.5 in the samples taken during this study was could not be characterized in the available time. Superficially, the air sampled on aboveground stations and trains should bear similarities both to underground platforms (in the type of PM2.5 pollution presumably generated during operation), as well as outdoor air samples (in the amount of air exchange/ventilation at aboveground stations). We ultimately decided to calibrate aboveground platforms and trains in accordance with gravimetric data from a specific UPAS filter, collected during sampling along the SIRR train line.

This study has many important implications for further health and exposure studies that directly impact commuters, especially students and youth, the elderly, and subway workers. The average air quality of underground stations in the NYC subway system is above the EPA 24-hour standard. Therefore, we suggest that subway administrators should collaborate with researchers to devise and install a network of low-cost sensors to monitor underground platform air quality across subway stations. A long-term study that collects high frequency air quality data affordably, such as with PurpleAir devices, could help advise both the public and MTA workers of the conditions underground and alert certain stations when the level of pollution exceeds a certain threshold. Future studies may characterize particulate matter found in specific stations to help identify their sources, which may impact real-time decisions about which railcars to send on which tracks. Other studies may look at the inequalities and injustices that face certain communities which are disproportionately impacted based on their location and likely exposure to harmful air quality while commuting.

4.4 Future Study

This study suggests heterogeneity in time and space in exposures across many different stations, however, conducting a more representative portion of the trains, and with specific ride combinations, would better identify sources of contamination, characterize the dispersal of that contamination through the subway system, and the factors that are important in attenuating that contamination. Each of these data are critical to maintaining a healthy subway infrastructure. Furthermore, this process of utilizing low-cost sensors can also be applied to other indoor spaces in the city, such as buses, restaurants, offices, and schools.

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