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Particulate matter concentration and composition in the New York City subway system

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Abstract

This study investigated the concentration and composition of particulate matter ($PM_{2.5}$) in the New York City subway system. Realtime measurements, at a one-second cadence, and gravimetric measurements were performed inside train cars along 300 kilometers of nine subway lines, as well as on 333 platforms from 287 subway stations. The mean (±SD) $PM_{2.5}$ concentration on the underground platforms was 142 ± 69 μg/m^3 versus 29 ± 20 μg/m^3 for aboveground stations. The average Concentrations inside train cars were 88 ± 14 μg/m^3 when traveling through underground tunnels and platforms and 29 ± 31 μg/m^3 while on aboveground tracks. The particle composition analysis of filtered samples was done using X-ray fluorescence (XRF), revealing that iron made up approximately 43% of the total $PM_{2.5}$ mass on station platforms, around 126 times higher than the outdoor ambient iron concentration. Other trace elements include silicon, sulfur, copper, nickel, aluminum, calcium, barium, and manganese. Considering the very high iron content, the comparative analysis of the measured concentration versus the standards set by the Environmental Protection Agency (US EPA) is questionable since those limits are largely based on particulate matter from fossil fuel combustion. Health impact analysis of iron-based particles will complement the study results presented here.

Keywords

Air Pollution; Subway; Exposure; PM2.5; Particulate Matter

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Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

1. Introduction

$PM_{2.5}$ refers to airborne particles with an aerodynamic diameter equal to or less than 2.5 micrometers. From a health perspective, such particles are of great concern due to their small size and toxic constituents. Importantly, when inhaled, $PM_{2.5}$ can bypass the collection mechanisms of the upper respiratory tract and reach the gas exchange region in the lower lung and potentially enter the bloodstream (Feng et al., 2016; Martins and Graça, 2018). Exposure to ambient $PM_{2.5}$, especially those containing heavy metals from fossil fuel combustion, is one of the leading risk factors for disease burden, including respiratory, cardiovascular, metabolic, and neurological disorders (Jo et al., 2017; Ning et al., 2019; Peng et al., 2008; Polezer et al., 2018; Power et al., 2015; Roberts et al., 2019; Wang et al., 2017; Xie et al., 2019; Yan et al., 2020, Maciejczyk, et al, 2021). These particles have been associated with 3 million premature deaths (Lelieveld et al., 2015) and over 2.7 million preterm births per year, globally (Ghosh et al., 2021; Hamra et al., 2014; Huang et al., 2017).

A recent study evaluated $PM_{2.5}$ concentration in 78 subway stations in the Northeast US, including Boston, New York, Philadelphia, Washington DC, and found the average $PM_{2.5}$ concentration on underground stations and on-trains was 315 $\mu g/m^3$ and 194 $\mu g/m^3$, respectively. On average, particles in the sampled underground stations were found to be 52% iron and 31% carbon by mass (Luglio et al., 2021). One study of 30 stations in New York City (NYC) found that the concentration of black carbon (BC) in the underground stations was 2 to 7 times higher than street level values, and the $PM_{2.5}$ concentration was 3.5 to 20 times higher than at street level (Vilcassim et al., 2014). Another study collected air samples from highways, aboveground and underground stations, inside train cars, urban street-sides, and parks. $PM_{2.5}$ mass concentration was the highest on the subway platforms among all sampled categories (Wang and Oliver Gao, 2011). Furthermore, an earlier study examined teenagers' exposure to iron, manganese, and chromium with personal sampling techniques and identified the NYC subway system as their primary source of exposure to these chemical constituents (Chillrud et al., 2004). The NYC Subway, one of the largest subway systems in the world with 472 stations, accommodates approximately 5.5 million daily riders (MTA, 2020) and is reported to be heavily polluted with alarmingly high concentrations of $PM_{2.5}$ rich in iron, both on-platforms and in-train cars (Luglio et al., 2021; Vilcassim et al., 2014). However, to the best of our knowledge, studies that have been conducted so far rely on small samples, hence are unable to provide a complete characterization of the particulate matter exposure in the NYC subway systems. The study being reported here builds on our two previous studies (Luglio et al., 2021; Vilcassim et al., 2014), and extends the findings with a large number of samples of on-train and on-platform $PM_{2.5}$ measurements with two objectives. (1) investigating both on-platform (total = 333) and in-train car $PM_{2.5}$ concentrations for the entirety of nine subway lines, namely the #1, #3, #5, #6, B, C, F, M, and R lines. This large number of samples will provide a more reasonable understanding of $PM_{2.5}$ exposure of subway riders on a typical weekday. (2) identifying the chemical composition of $PM_{2.5}$ on-board and on-platform for these different subway lines.

2. Literature review

Studies of subway particulate matter have also been carried out in a number of cities. The Los Angeles (LA) metro system was found to be less polluted than NYC's; the average concentration on the underground stations in LA ranged from 9 to 130 μg/m^3 (Kam et al., 2011). The Mexico City subway system follows a similar pattern of concentrations of $PM_{2.5}$ as the one in LA, ranging between 60 μg/m^3 and 93 μg/m^3 (Mugica-Álvarez et al., 2012). However, because of the variation in measurement techniques and instruments, the results from the different studies are not always directly comparable (Nieuwenhuijsen et al., 2007). In Asia, one study sampled selected stations from three subway lines in Shanghai and found the average concentration of $PM_{2.5}$ ranged between 82.5 and 178 μg/m^3 (Guo et al., 2014). Similar concentration levels were found in the subway system of Tianjin (B. Q. Wang et al., 2016), Seoul (Park and Ha, 2008), Tehran (Kamani et al., 2014), and Taipei (Cheng et al., 2008). One study sampled four stations in Beijing and found the concentration of underground stations varied significantly (56 μg/m^3 – 291μg/m^3) on different days of the week (Pan et al., 2019). Furthermore, several studies have been carried out in European cities. For example, one study found that the deepest stations (>20 m under the ground) of the central subway line in London had significantly higher concentrations (~500 μg/m^3) than the stations located from 0 to 10 meters below the ground. Time-series measurements of one station in London for several days also exhibited a high correlation between $PM_{2.5}$ concentration and train frequency (Smith et al., 2020). Thus, it is likely that many varying factors contribute to the range of $PM_{2.5}$ concentrations measured in different subway systems throughout the globe.

The composition of subway particles is quite different from the PM composition in the urban outdoor ambient air, where particles created by the combustion of fossil fuels comprise the majority by mass (Davidson et al., 2007; Squizzato et al., 2018). Similar to the findings in NYC, some of the above subway studies included the analysis of the chemical composition of the particles in the subway air, concluding that iron (Fe) particles were the dominant element, accounting for over 40% by mass, where other transition metals include Cu, Ba, Cr, Si, Mn, and Zn (Guo et al., 2014; Loxham et al., 2013; Martins et al., 2016b; Moreno et al., 2015; Querol et al., 2012; Salma et al., 2007; Smith et al., 2020). The metal-rich particles in the subway systems are mostly generated from wear and friction processes at the intersection of rail–wheel–brake (Jung et al., 2012). Additionally, ambient air, ballast, electrification, diesel engines, and construction work in the tunnels could also be potential sources for the mineral particles (Aarnio et al., 2005). Other than the composition, contributing factors for the high particulate matter concentrations in subways include train frequency and station depth, ventilation system, ambient air quality, year of construction, etc. (Martins et al., 2016a; Wen et al., 2020).

While the adverse health impacts of exposure to ambient particles generated by fossil fuel combustion are well recognized (Maciejczyk et al., 2021), there is more uncertainty regarding exposure to iron-rich particulate matter, such as those experienced in subways. An available guidance level for exposure to iron-rich particulate matter is set by the Occupational Safety and Health Administration (OSHA), where the occupational exposure standard for welding fume (enriched with iron oxide) is limited to 5000 μg/m^3 for an

eight-hour work shift (NIOSH, 2011). Because subway PM concentrations would be below the occupational exposure limit set by OSHA, one might dismiss the health risks among subway workers and commuters. However, metals abundant in underground air have significant potential to contribute to oxidative stress by generating reactive oxygen species (ROS) (Figueroa-Lara et al., 2019). The co-presence of combustion-related sulfate with iron is of concern, as it is known to increase the solubility and oxidative stress from fine particle metal exposures (Fang et al., 2017). One study found that underground Mn, Zn, Ba, and especially Cu have more oxidative potential than Fe (Moreno et al., 2017a). The particles from a unit of magnetite (Fe_3O_4) rich air from the Stockholm subway is expected to be in the range of 40–80 times more genotoxic and 20–40 times more potent to induce oxidative stress as compared to air from a busy urban street (Karlsson et al., 2004). Another study found that PM sampled in the Paris Metro subway stations induced oxidative stress in macrophages *in vitro*, and lung homogenates *in vivo* (Bachoual et al., 2007). Additional research has found that employees who are highly exposed to airborne particles in the Stockholm underground system have higher concentrations of risk markers for cardiovascular diseases than employees with lower exposure (Bigert et al., 2008). Thus, there is burgeoning evidence that subway particles may have adverse effects on commuters and transit workers. Nonetheless, current studies rely on a limited number of samples that are inadequate for population-level exposure analysis. This study addresses the limitation of the existing body of knowledge by collecting real-time and gravimetric data on $PM_{2.5}$ concentrations and composition at a scale that has not been conducted before for New York City. The study provides a statistically informed place-based understanding of population exposure to air pollutants on public transit for a typical weekday and enables a number of areas for further research, particularly addressing the at-risk population.

3. Methods and data

3.1. Sampling strategy

Both real-time light scattering-based and gravimetric-based $PM_{2.5}$ measurements were collected on nine New York City subway lines, including both on-train and on-platforms. All the measurements for a particular line were completed within a day (except C train and #6 Train). In the morning, on-train concentration was measured by traveling in a subway car from one terminal end of the line to the other end. On the return trip, beginning around noon (except line #6), the investigators got off the train at every station along the subway line and sampled on-platform concentration until the arrival of the following train of the same line. The investigators stayed on each platform for 5 to 15 min before boarding the train to the next station. Due to technical problems in on-field equipment, on-train and on-platform measurement for lines #6 and C were conducted over two days. The date and time of the measurements are shown in Table 1.

3.2. Real-time and gravimetric measurements

Nephelometric-based DataRAM pDR 1500 (Thermo Fisher Scientific Inc.) units (pDR) with a 2.5 μm diameter cut point inlet cyclone were employed for real-time $PM_{2.5}$ measurements. This study used three pDR-1500 devices, and all pDR data were calibrated with gravimetric $PM_{2.5}$ concentrations (see Section 3.3). Real-time measurements were collected at one-

second intervals, and pDRs were zeroed with HEPA-filtered air before initiating each sampling run.

For gravimetric and elemental analysis of subway $PM_{2.5}$, and to allow a calibration of the real-time pDR mass measurements, a 2.5 μm cut Personal Environmental Monitor (PEM) (SKC, Eighty Four, PA) was employed to collect particles on 37 mm diameter Teflon (Pall, Ann Arbor, MI) filters with a Leland Legacy Pump (SKC, Eighty Four, PA) operating at 10 L/min. Filters were conditioned at 21°C ($^{+/-}$1°C) and 35% ($^{+/-}$5%) relative humidity (RH) for 24 hours pre- and post-sampling, and the mass concentration was calculated through standard gravimetric analysis using a micro-balance (Mettler MT5) in a temperature and humidity regulated laboratory. Two Teflon filters were used for each subway line (except R line), where the first filter collected on-train particles for 1 to 1.5 hours as the train moved from one terminus to the other. The second filter was used for sampling the air on all platforms of the subway line. Total sampling times for the latter ranged between four to eight hours. For the R line train, only one filter was used for the combined on-platform and on-train measurements, and so the elemental concentrations cannot be reported separately for on-train and on-platform on that R line.

A separate sampling was also conducted to collect ambient $PM_{2.5}$ with a Teflon and a quartz (Pall, Ann Arbor, MI) filter to compare particle compositions of the subway with ambient outdoor air. Ambient air was sampled near a busy urban roadway for eleven hours. In this case, total carbon (organic + elemental carbon) and the trace elements were quantified on both quartz and Teflon filters. However, only Teflon filters were used for sampling in subway systems. As a result, only the trace elements were quantified for on-platform and on-train samples.

3.3. Calibrating real-time measurements

The $PM_{2.5}$ concentrations were determined at a high temporal frequency of 1-second intervals using the three DataRAM pDR-1500 monitors. Although the monitors were factory calibrated, the output can be affected by particle composition, density, concentration, and water content (Halterman et al., 2018). Therefore, we adjusted real-time data with calibration curves (or factors) by comparing gravimetric measurements with co-located pDR instruments in the subways and ambient air (Howard-Reed et al., 2011; Wallace et al., 2010; Z. Wang et al., 2016). For the aboveground calibration, we sampled outside the Sutter Avenue Rutland Road station in Brooklyn for four hours, co-locating the gravimetric and all three real-time instruments. The aboveground gravimetric measurements indicated approximately twice the concentration as the real-time monitor pDR indirect measurements. For the three pDR instruments, we found the calibration coefficient for the aboveground station as 2.08, 1.97, and 2.01, respectively.

To calibrate pDR for the underground environment, we collected air samples by co-locating all three pDRs with a filter and pump system for one hour at five sites: 23rd Street, Nevis Street, 2nd Avenue, 168th Street, and Bergen Street stations. The Grubbs' outlier test indicated one extreme outlier observation that was excluded from the analyses. In addition to the specific calibration runs at the four underground stations, we also included the filter and real-time samples from the field campaign for the calibration curve. As mentioned in

Section 3.2, for each subway line, we used two filters for elemental analysis (except for line R), and each pDR was used to sample three lines, providing six additional data points to formulate the calibration curve function. As a result, a total of ten observations were used to calibrate pDR-1 and pDR-2. Here, pDR-1 was used to sample lines #3, #5, and #6, while pDR-2 was used for lines B, F, and M. Again, the third pDR (pDR-3) was used to take on-train and on-platform samples of lines #1, C, and R. Since a single filter was used in line R, discussed in section 3.2, a total of nine observations were available for pDR-3 calibration. We formulated a linear calibration function for underground measurements of each PDR instrument, which explains over 91% variance in data. (Figure 1).

3.4. Trace element analysis

The concentration of trace elements on Teflon filters (used in on-platform and on-train measurements) was determined with an energy dispersive X-ray fluorescence (XRF) spectrometer (Epsilon 5; PAN Analytical B.V.). Field and lab blank filters were incorporated to determine background filter levels for each element. Only concentrations three times the uncertainty were considered above the detection limit. The concentration of each trace element was adjusted by subtracting the mean blank value of the respective element. The concentration of organic (OC) and elemental (EC) carbon was determined with a Sunset Labs OCEC Analyzer (Subset instruments, inc.) and NIOSH 5040 method (Birch, 2003) using a quartz filter as described previously (Luglio et al., 2021).

4. Results

4.1. Concentration Measurements

Results of onboard and on-platform measurements of $PM_{2.5}$ concentration for the nine subway lines are graphically shown in Figures 2 and 3 and Tables 2 and 3. The mean concentration for each platform refers to the average value of measurements at each platform taken at 1 second intervals for 5 – 15 minutes, depending on the time the investigators stayed on the platform for sampling, generating around 300 to 900 data points to calculate the average. The on-train measurements for each link (on-cabin concentration between two stations) were taken from the moment the train doors closed at one station until they opened at the next. Typically, the travel time between consecutive stations ranges from 2 to 7 minutes. All real-time instruments were calibrated using co-located gravimetric measurements as described above. The mean (± SD) $PM_{2.5}$ concentration of the 271 sampled underground station platforms was 142 ± 69 $\mu g/m^3$. This was significantly greater than the mean concentration of 29 ± 20 $\mu g/m^3$ for the aboveground stations (n=62). Figure 3 (left) shows the histogram of the average $PM_{2.5}$ concentrations of 333 station platforms and Figure 3 (right) represents the histogram for on-train cabin measurements between stations. Table 2 shows that the mean $PM_{2.5}$ concentration was higher for underground conditions, both on-train and on-platform, compared to aboveground conditions for all subway lines. For line #3, during the sampling period, we observed heavy road construction under the train track of Saratoga Avenue, Rockaway Avenue and Junius Street station. It is likely that ground-level construction work caused a significant increase in aboveground on-train and on-station measurements. As a result, we excluded the concentration data from these

three stations when determining the average concentration of the entire line to eliminate the impact of this irregular occurrence.

We also observed spatial variation among the on-platform concentrations, whereas most of the stations located around the population/commercial and municipal centers in downtown and midtown Manhattan and downtown Brooklyn had much higher $PM_{2.5}$ concentrations than stations located in the city outskirts. Table 3 shows the on-platform concentration for the top 20 highest polluted stations, as well as the mean concentrations inside the train cabin during the train travel from these to neighboring stations. The mean concentrations of all sampled 333 station platforms are included in the supplementary materials (Figure S1 – Figure S9).

Figure 4 presents an example time series record of on-platform and on-train $PM_{2.5}$ concentrations for the M train, as the investigators rode from one terminal to the other. For this subway line, we started the on-train measurements from Fresh Pond Road station in Queens at 9:45 AM, and on-platform measurements were started from Forest Hills 71 Avenue station at noon. There are a number of aboveground stations on the M line (from Fresh Pond to Mercy Avenue). The mean (SD) onboard concentration of $PM_{2.5}$ was 95 ± 7 $\mu g/m^3$ when underground. The on-train concentrations rose above 130 $\mu g/m^3$ continuously between Broadway-Lafayette and 42 St-Bryant Park stations. The underground platforms of M also exhibit elevated levels of $PM_{2.5}$ concentrations of 122 ± 20 $\mu g/m^3$. Broadway-Lafayette station's M line platform turned out to be the most polluted on this line at 208 ± 30 $\mu g/m^3$. Other stations with high concentrations include West 4 Street-Washington Square (207 ± 27 $\mu g/m^3$), Lexington Avenue-53rd Street (205 ± 54 $\mu g/m^3$), and 34 Street-Herald Square (162 ± 17 $\mu g/m^3$). Similar time series graphs of real-time measurements of #1, #3, #5, #6, B, C, F and R lines are presented in the supplementary information section (Figure S1 – Figure S8).

In Table 4, we compared the average concentration of the NYC subway system with other studies worldwide. In our study, we collected samples from 333 platforms of 287 stations, around 61% of the total stations in the city (MTA, 2020). However, some studies in other cities have only sampled a few hand-picked stations, which may not represent the holistic understanding of an entire city, likely resulting in sampling bias. As a result, a direct comparison of the concentration of the NYC subway system from this study with other subway systems worldwide may not be straightforward. Nevertheless, the average $PM_{2.5}$ concentrations of NYC appears to be higher than many of the subway systems worldwide.

4.2. $PM_{2.5}$ Elemental analyses

We compared the trace element composition of ambient and in-subway $PM_{2.5}$. Figure 5 shows the composition of various elements as a percentage of the total $PM_{2.5}$ mass for both on-train and on-platform settings (for subway line R, one filter was used for both on-train and on-platform measurements and so separate on-train and on-platform data are not presented). On the station platforms, on average, iron constituted about 43% of total $PM_{2.5}$ mass, which is 126 times higher than in outdoor ambient air, where iron contributes only 0.34% of $PM_{2.5}$. Among the stations, the highest concentration (58%) of iron was found on the platforms of the #6 train, and the lowest concentration (35%) was found on

the C train platforms. In the on-train measurements, the contribution of iron particles was between 6% (#5 train) and 34% (#1 train). Although this iron contribution to $PM_{2.5}$ is low compared to on-platform measurements, it is still 18 – 100 times higher than its contribution to ambient outdoor concentrations of 0.34%. Among other trace elements, silicon was the second-most abundant metal in the subway environment. Amongst all samples, the largest contribution (4.2%) of silicon was found on-board of the #5 train, which was over nine times more than in the outdoor environment. On average, silicon constituted about 2% of total subway $PM_{2.5}$. Furthermore, copper and nickel, two critical trace metals for oxidative stress, were found to contribute to a 44- and 5-times higher share of subway particles than in outdoor particles, respectively. Additionally, manganese, another transition metal associated with oxidative stress (Moreno et al., 2017a), was on average 20 times higher in the air inside train cars and 36 times higher in the air of station platforms than in ambient outdoor air. Furthermore, a small percentage of other elements, such as aluminum (<1%), calcium (0.5% – 1.5%), barium (<1.2%), and chromium (<0.3%) were measured both on platforms and on the train. These elements were below detection in the outdoor sample.

In the outdoor environment, the most dominant chemical species was OC (70%), followed by EC (5.5%). Because of the sole use of Teflon filters in the sampling within the underground subway systems, carbon concentrations were not specifically quantified in the subway particles, and its contribution falls under the unexplained category (Figure 5). Carbon likely makes up a sizeable fraction of the unexplained, as seen by (Luglio et al., 2021). In addition, oxygen is likely to compose much of the rest of the unexplained fraction. As shown in previous studies, Fe is likely to be found in oxide forms such as Fe_2O_3, Fe_3O_4, etc. (Lu et al., 2015; Querol et al., 2012; Sheikh et al., 2022). If it is assumed that all the Fe is in the common hematite form, then the mass concentration of Fe-containing particles will increase by a factor of 1.43. Currently, work is being conducted on the speciation (i.e., oxidation state and mineralogy) of iron and other elements on subways in the Northeastern United States (unpublished work). The preliminary results indicate that Fe can be found in a few different oxide forms. In addition, elements such as Na, Mg, Cr, Sr, etc., were detected by XRF, but are not presented individually in Figure 5. The ‘other’ category in Figure 5 demonstrates the summed percent contribution of these elements. The normalized trace element concentrations (μg element/mg $PM_{2.5}$) for on-train, on-platform, and outdoor measurements are shown in the supplementary material (Table S10).

5. Discussion

Concerning determinants for on-train $PM_{2.5}$ concentrations, past studies have found that particles penetrate the train cabin from the platform when the door opens, making the on-train concentration rise (J. Wang et al., 2016). While this explains how concentrations may change as trains enter a station, it does not explain how they change when riding through tunnels. Understanding how air circulates within the subway car is essential to analyze these dynamics. It is reported that at any given time, 75% of the air inside the NYC subway cabin is recycled, and the remaining 25% is pulled from outside (Gröndahl et al., 2020). The inside cabin air is constantly pulled, cooled, and filtered during the recycling process, while being simultaneously mixed with filtered outside air, before being pushed back into the cabin. With this process, the inside train car air theoretically gets entirely replaced by

outside subway air every three to four minutes. Often, subway cars use MERV-7 category filters to filter out the particles (Gröndahl et al., 2020). Experiments identifying $PM_{2.5}$ filter efficiency found that these MERV-7 category filters only remove between 2% and 21% of particles, whereas higher category filters such as MERV-16 and HEPA can remove upwards of 96% – 100% (Azimi et al., 2014; Zhao et al., 2015). Therefore, the filtrated air that is dispensed into the cabin is likely to possess a significant concentration of tunnel particles. Focusing on real-time measurements can provide insight into how the particle concentration changes in the subway train car while traveling through a tunnel.

Regarding on-platform concentrations, possible strategies to reduce $PM_{2.5}$ concentrations on subway platforms include the installation of platform screen doors (PSD), filtration devices, improved ventilation, and increased tunnel cleaning, as demonstrated in other studies (Chang et al., 2021). Since the particles are likely to be generated mostly by the friction between rail, wheel, and brakes, replacing the metal component of the friction surface, such as introducing a rubber-tired rail system, could reduce the production of heavy metal particles (Cartenì and Cascetta, 2018). In NYC, most subway stations and tunnels lie deep underground, making underground air and ambient exchange difficult. In such cases, forced mechanical tunnel ventilation could effectively reduce $PM_{2.5}$ concentrations (Moreno et al., 2014). Again, when a train approaches the station, piston wind is generated, which pushes air and particles from the tunnels to the platform (J. Wang et al., 2016). This piston wind is considered the main driver of high PM concentrations on platforms (He et al., 2018). Separating rail tracks from the platform with barriers such as PSDs could be an effective measure for controlling particle concentration on the platforms as they can block the tunnel wind from entering the platforms (Han et al., 2015; Martins et al., 2016b, 2015; Moreno et al., 2017b). Importantly, although PSDs can reduce on-platform pollution, a study suggested that they may increase on-train particle concentrations (Son et al., 2014). To mitigate this potential effect, the concentration inside the train cabin can be reduced with filters or subway cabin purifiers, as discussed above. Ultimately, however, reductions in the on-platform concentrations will be required to minimize in-cabin concentrations.

The alarmingly high concentrations of $PM_{2.5}$ observed in this study raise concerns about the potential impact on a subway rider or worker's cardiopulmonary health. A few studies, conducted around the world, have examining human health endpoints after subway exposures, and found mixed results (Bigert et al., 2008; Klepczyńska Nyström et al., 2010; Liu et al., 2015; Sauvain et al., 2022). The subway system in New York City, however, is among the most polluted in the world (Xu and Hao, 2017), and generally exceeds those observed in these other studies. As such, it is important to investigate the potential health effects of commuting or working in this subway environment with extreme $PM_{2.5}$ exposure.

Although the study presented here offers a representation of the particulate matter scenario in the NYC subway system for a typical weekday, it is important to note that the study has certain limitations. While on-train and on-platform data were collected within the same season, the overall impact of seasonal changes on subway air quality is still unknown. Additionally, the concentration of particulate matter can vary within a day, with train frequency being a major determinant of subway PM concentration. Although we were not able to capture the temporal variability of concentration within a day, we did perform

on-train measurements during peak hours to minimize bias and included the sampling time for all station measurements (Tables S1–S9) as a part of comprehensive data reporting. The results of this study may be limited by the shorter sampling time used to sample each platform, and capturing a larger number of stations with longer sampling times would require a more extensive campaign that should be considered for future work.

6. Conclusions

- Among the sampled platforms, the 271 underground station platforms had an average $PM_{2.5}$ concentration of 142 ± 69 μg/m^3, while the 62 above-ground platforms had an average concentration of 29 ± 20μg/m^3. Therefore, $PM_{2.5}$ in underground stations was found to be roughly 5 times higher than in the aboveground stations.
- The majority of stations located in the population/commercial and municipal centers, such as midtown and downtown Manhattan and downtown Brooklyn were heavily polluted. 181st Street station in uptown Manhattan was found to be the highest polluted station within the MTA system, with an average $PM_{2.5}$ concentration of 600 ± 84 μg/m^3.
- Elemental composition analysis found that iron constitutes about 43% of total $PM_{2.5}$ mass. Inside train cars, iron constitutes 21% of $PM_{2.5}$ mass. This contribution of iron in subway particles is much higher than that of ambient air, where iron contributes only 0.34% of $PM_{2.5}$. Other trace elements measured in the NYC subway system include sulfur (<1%), silicon (2%), copper (<1%), nickel (<1%), aluminum (<1%), calcium (1%), barium (<1.2%), Manganese (<1%) and chromium (<0.3%).
- Short-term $PM_{2.5}$ concentrations in New York's underground stations were found to be roughly four times higher than the U.S. EPA's 24-h average ambient air standard of 35 μg/m^3 for outdoor air. The $PM_{2.5}$ composition of these particles, however, was found to differ greatly from ambient outdoor particles, and riders do not spend 24 hours per day in the subways, both of which create uncertainties in comparing the subway $PM_{2.5}$ mass concentrations with ambient air quality standards. Therefore, the health implications of these underground particle exposures likely differ from the typical outdoor combustion particle exposures regulated by the EPA, and the potential health effects of such elevated exposures need direct investigation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

Aarnio P, Yli-Tuomi T, Kousa A, Mäkelä T, Hirsikko A, Hämeri K, Räisänen M, Hillamo R, Koskentalo T, Jantunen M, 2005. The concentrations and composition of and exposure to fine particles (PM2.5) in the Helsinki subway system. Atmos Environ 39, 5059–5066. 10.1016/J.ATMOSENV.2005.05.012

Adams HS, Nieuwenhuijsen MJ, Colvile RN, Mcmullen MAS, Khandelwal P, 2001. Fine particle PM personal exposure levels in 2.5 transport microenvironments, London, UK, The Science of the Total Environment. 10.1016/S0048-9697(01)00723-9

Azimi P, Zhao D, Stephens B, 2014. Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. Atmos Environ 98, 337–346. 10.1016/J.ATMOSENV.2014.09.007

Bachoual R, Boczkowski J, Goven D, Amara N, Tabet L, On D, Leçon-Malas V, Aubier M, Lanone S, 2007. Biological Effects of Particles from the Paris Subway System. Chem Res Toxicol 20, 1426–1433. 10.1021/TX700093J [PubMed: 17883261]

Bigert C, Alderling M, Svartengren M, Plato N, de Faire U, Gustavsson P, 2008. Blood markers of inflammation and coagulation and exposure to airborne particles in employees in the Stockholm underground. Occup Environ Med 65, 655–658. 10.1136/OEM.2007.038273 [PubMed: 18178587]

Birch ME, 2003. Monitoring of diesel particulate exhaust in the workplace. NIOSH Manual of Analytical Methods (NMAM) 2154.

Cartenì A, Cascetta F, 2018. Particulate matter concentrations in a high-quality rubber-tyred metro system: the case study of Turin in Italy. International Journal of Environmental Science and Technology 15, 1921–1930. 10.1007/s13762-017-1566-x

Cartenì A, Cascetta F, Campana S, 2015. Underground and ground-level particulate matter concentrations in an Italian metro system. Atmos Environ 101, 328–337. 10.1016/J.ATMOSENV.2014.11.030

Chang L, Chong WT, Wang X, Pei F, Zhang X, Wang T, Wang C, Pan S, 2021. Recent progress in research on PM2.5 in subways. Environ Sci Process Impacts 23, 642–663. 10.1039/D1EM00002K [PubMed: 33889885]

Cheng YH, Lin YL, Liu CC, 2008. Levels of PM10 and PM2.5 in Taipei Rapid Transit System. Atmos Environ 42, 7242–7249. 10.1016/J.ATMOSENV.2008.07.011

Chillrud SN, Epstein D, Ross JM, Sax SN, Pederson D, Spengler JD, Kinney PL, 2004. Elevated Airborne Exposures of Teenagers to Manganese, Chromium, and Iron from Steel Dust and New York City's Subway System. Environ Sci Technol 38, 732–737. 10.1021/ES034734Y [PubMed: 14968857]

Cusack M, Talbot N, Ondráček J, Minguillón MC, Martins V, Klouda K, Schwarz J, Ždímal V, 2015. Variability of aerosols and chemical composition of PM10, PM2.5 and PM1 on a platform of the Prague underground metro. Atmos Environ 118, 176–183. 10.1016/j.atmosenv.2015.08.013

Davidson CI, Phalen RF, Solomon PA, 2007. Airborne Particulate Matter and Human Health: A Review. Aerosol Science and Technology 39, 737–749. 10.1080/02786820500191348

Fang T, Guo H, Zeng L, Verma V, Nenes A, Weber RJ, 2017. Highly Acidic Ambient Particles, Soluble Metals, and Oxidative Potential: A Link between Sulfate and Aerosol Toxicity. Environ Sci Technol 51, 2611–2620. 10.1021/ACS.EST.6B06151 [PubMed: 28141928]

Feng S, Gao D, Liao F, Zhou F, Wang X, 2016. The health effects of ambient PM2.5 and potential mechanisms. Ecotoxicol Environ Saf 128, 67–74. 10.1016/J.ECOENV.2016.01.030 [PubMed: 26896893]

Figueroa-Lara JJ, Murcia-González JM, García-Martínez R, Romero-Romo M, Torres Rodríguez M, Mugica-Álvarez V, 2019. Effect of platform subway depth on the presence of Airborne PM2.5, metals, and toxic organic species. J Hazard Mater 377, 427–436. 10.1016/J.JHAZMAT.2019.05.091 [PubMed: 31176078]

Ghosh R, Causey K, Burkart K, Wozniak S, Cohen A, Brauer M, 2021. Ambient and household PM2.5 pollution and adverse perinatal outcomes: A meta-regression and analysis of attributable global burden for 204 countries and territories. PLoS Med 18, e1003718. 10.1371/JOURNAL.PMED.1003718 [PubMed: 34582444]

Gröndahl M, Goldbaum C, White J, 2020. What Happens to Viral Particles on the Subway - The New York Times. URL https://www.nytimes.com/interactive/2020/08/10/nyregion/nyc-subway-coronavirus.html (accessed 3.11.22).

Guo L, Hu Y, Hu Q, Lin J, Li C, Chen J, Li L, Fu H, 2014. Characteristics and chemical compositions of particulate matter collected at the selected metro stations of Shanghai, China. Science of The Total Environment 496, 443–452. 10.1016/J.SCITOTENV.2014.07.055 [PubMed: 25105755]

Halterman A, Sousan S, Peters TM, 2018. Comparison of Respirable Mass Concentrations Measured by a Personal Dust Monitor and a Personal DataRAM to Gravimetric Measurements. Ann Work Expo Health 62, 62–71. 10.1093/ANNWEH/WXX083

Hamra GB, Guha N, Cohen A, Laden F, Raaschou-Nielsen O, Samet JM, Vineis P, Forastiere F, Saldiva P, Yorifuji T, Loomis D, 2014. Outdoor Particulate Matter Exposure and Lung Cancer: A Systematic Review and Meta-Analysis. Environ Health Perspect 122, 906–911. 10.1289/EHP/1408092 [PubMed: 24911630]

Han H, Lee JY, Jang KJ, 2015. Effect of platform screen doors on the indoor air environment of an underground subway station. Indoor and Built Environment. 24, 672–681. 10.1177/1420326X14528731

He S, Jin L, Le T, Zhang C, Liu X, Ming X, 2018. Commuter health risk and the protective effect of three typical metro environmental control systems in Beijing, China. Transp Res D Transp Environ 62, 633–645. 10.1016/J.TRD.2018.04.015

Howard-Reed C, Rea AW, Zufall MJ, Burke JM, Williams RW, Suggs JC, Sheldon LS, Walsh D, Kwok R, 2011. Use of a Continuous Nephelometer to Measure Personal Exposure to Particles During the U.S. Environmental Protection Agency Baltimore and Fresno Panel Studies. J Air Waste Manage Assoc 50, 1125–1132. 10.1080/10473289.2000.10464150

Huang F, Pan B, Wu J, Chen E, Chen L, Huang F, Pan B, Wu J, Chen E, Chen L, 2017. Relationship between exposure to PM2.5 and lung cancer incidence and mortality: A meta-analysis. Oncotarget 8, 43322–43331. 10.18632/ONCOTARGET.17313 [PubMed: 28487493]

Jo EJ, Lee WS, Jo HY, Kim CH, Eom JS, Mok JH, Kim MH, Lee K, Kim KU, Lee MK, Park HK, 2017. Effects of particulate matter on respiratory disease and the impact of meteorological factors in Busan, Korea. Respir Med 124, 79–87. 10.1016/J.RMED.2017.02.010 [PubMed: 28284326]

Johansson C, Johansson A, 2003. Particulate matter in the underground of Stockholm. Atmos Environ 37, 3–9. 10.1016/S1352-2310(02)00833-6

Jung HJ, Kim BW, Malek MA, Koo YS, Jung JH, Son YS, Kim JC, Kim HK, Ro CU, 2012. Chemical speciation of size-segregated floor dusts and airborne magnetic particles collected at underground subway stations in Seoul, Korea. J Hazard Mater 213–214, 331–340. 10.1016/J.JHAZMAT.2012.02.006

Kam W, Cheung K, Daher N, Sioutas C, 2011. Particulate matter (PM) concentrations in underground and ground-level rail systems of the Los Angeles Metro. Atmos Environ 45, 1506–1516. 10.1016/J.ATMOSENV.2010.12.049

Kamani H, Hoseini M, Seyedsalehi M, Mahdavi Y, Jaafari J, Safari GH, 2014. Concentration and characterization of airborne particles in Tehran's subway system. Environmental Science and Pollution Research 21, 7319–7328. 10.1007/S11356-014-2659-4 [PubMed: 24573466]

Karlsson HL, Nilsson L, Möller L, 2004. Subway Particles Are More Genotoxic than Street Particles and Induce Oxidative Stress in Cultured Human Lung Cells. Chem Res Toxicol 18, 19–23. 10.1021/TX049723C

Klepczyńska Nyström A, Svartengren M, Grunewald J, Pousette C, Rödin I, Lundin A, Sköld CM, Eklund A, Larsson BM, 2010. Health effects of a subway environment in healthy volunteers. European Respiratory Journal 36, 240–248. 10.1183/09031936.00099909 [PubMed: 20032018]

Lee Y, Lee YC, Kim T, Choi JS, Park D, 2018. Sources and characteristics of particulate matter in subway tunnels in seoul, korea. Int J Environ Res Public Health 15. 10.3390/ijerph15112534

Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A, 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature 2015 525:7569 525, 367–371. 10.1038/NATURE15371

Li TT, Bai YH, Liu ZR, Li JL, 2007. In-train air quality assessment of the railway transit system in Beijing: A note. Transp Res D Transp Environ 12, 64–67. 10.1016/J.TRD.2006.11.001

Liu W, te, Ma CM, Liu IJ, Han BC, Chuang HC, Chuang KJ, 2015. Effects of commuting mode on air pollution exposure and cardiovascular health among young adults in Taipei, Taiwan. Int J Hyg Environ Health 218, 319–323. 10.1016/J.IJHEH.2015.01.003 [PubMed: 25638696]

Loxham M, Cooper MJ, Gerlofs-Nijland ME, Cassee FR, Davies DE, Palmer MR, Teagle DAH, 2013. Physicochemical characterization of airborne particulate matter at a mainline underground railway station. Environ Sci Technol 47, 3614–3622. 10.1021/ES304481M [PubMed: 23477491]

Lu S, Liu D, Zhang W, Liu P, Fei Y, Gu Y, Wu M, Yu S, Yonemochi S, Wang X, Wang Q, 2015. Physico-chemical characterization of PM2.5 in the microenvironment of Shanghai subway. Atmos Res 153, 543–552. 10.1016/J.ATMOSRES.2014.10.006

Luglio DG, Katsigeorgis M, Hess J, Kim R, Adragna J, Raja A, Gordon C, Fine J, Thurston G, Gordon T, Vilcassim MJR, 2021. PM2.5 Concentration and Composition in Subway Systems in the Northeastern United States. Environ Health Perspect 129. 10.1289/EHP7202

Maciejczyk P, Chen LC, Thurston G, 2021. The Role of Fossil Fuel Combustion Metals in PM2.5 Air Pollution Health Associations. Atmosphere 2021, Vol. 12, Page 1086 12, 1086. 10.3390/ATMOS12091086

Martins NR, Graça GC da, 2018. Impact of PM2.5 in indoor urban environments: A review. Sustain Cities Soc 42, 259–275. 10.1016/J.SCS.2018.07.011

Martins V, Moreno T, Mendes L, Eleftheriadis K, Diapouli E, Alves CA, Duarte M, de Miguel E, Capdevila M, Querol X, Minguillón MC, 2016a. Factors controlling air quality in different European subway systems. Environ Res 146, 35–46. 10.1016/J.ENVRES.2015.12.007 [PubMed: 26717078]

Martins V, Moreno T, Minguillón MC, Amato F, de Miguel E, Capdevila M, Querol X, 2015. Exposure to airborne particulate matter in the subway system. Science of The Total Environment 511, 711–722. 10.1016/J.SCITOTENV.2014.12.013 [PubMed: 25616190]

Martins V, Moreno T, Minguillón MC, van Drooge BL, Reche C, Amato F, de Miguel E, Capdevila M, Centelles S, Querol X, 2016b. Origin of inorganic and organic components of PM2.5 in subway stations of Barcelona, Spain. Environmental Pollution 208, 125–136. 10.1016/J.ENVPOL.2015.07.004 [PubMed: 26189044]

Mohsen M, Ahmed MB, Zhou JL, 2018. Particulate matter concentrations and heavy metal contamination levels in the railway transport system of Sydney, Australia. Transp Res D Transp Environ 62, 112–124. 10.1016/j.trd.2018.02.015

Moreno T, Kelly FJ, Dunster C, Oliete A, Martins V, Reche C, Minguillón MC, Amato F, Capdevila M, de Miguel E, Querol X, 2017a. Oxidative potential of subway PM2.5. Atmos Environ 148, 230–238. 10.1016/J.ATMOSENV.2016.10.045

Moreno T, Kelly FJ, Dunster C, Oliete A, Martins V, Reche C, Minguillón MC, Amato F, Capdevila M, de Miguel E, Querol X, 2017b. Oxidative potential of subway PM2.5. Atmos Environ 148, 230–238. 10.1016/J.ATMOSENV.2016.10.045

Moreno T, Martins V, Querol X, Jones T, BéruBé K, Minguillón MC, Amato F, Capdevila M, de Miguel E, Centelles S, Gibbons W, 2015. A new look at inhalable metalliferous airborne particles on rail subway platforms. Science of The Total Environment 505, 367–375. 10.1016/J.SCITOTENV.2014.10.013 [PubMed: 25461038]

Moreno T, Pérez N, Reche C, Martins V, de Miguel E, Capdevila M, Centelles S, Minguillón MC, Amato F, Alastuey A, Querol X, Gibbons W, 2014. Subway platform air quality: Assessing the

influences of tunnel ventilation, train piston effect and station design. Atmos Environ 92, 461–468. 10.1016/J.ATMOSENV.2014.04.043

MTA, 2020. subway and bus ridership for 2019. URL https://new.mta.info/agency/new-york-city-transit/subway-bus-ridership-2019 (accessed 9.21.20).

Mugica-Álvarez V, Figueroa-Lara J, Romero-Romo M, Sepúlvea-Sánchez J, López-Moreno T, 2012. Concentrations and properties of airborne particles in the Mexico City subway system. Atmos Environ 49, 284–293. 10.1016/J.ATMOSENV.2011.11.038

Nieuwenhuijsen MJ, Gómez-Perales JE, Colvile RN, 2007. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. Atmos Environ 41, 7995–8006. 10.1016/J.ATMOSENV.2007.08.002

Ning X, Ji X, Li G, Sang N, 2019. Ambient PM2.5 causes lung injuries and coupled energy metabolic disorder. Ecotoxicol Environ Saf 170, 620–626. 10.1016/J.ECOENV.2018.12.028 [PubMed: 30579162]

NIOSH, 2011. 1988 OSHA PEL Project - Welding Fumes. URL https://www.cdc.gov/niosh/pel88/welding.html (accessed 2.21.22).

Pan S, Du S, Wang X, Zhang X, Xia L, Liu J, Pei F, Wei Y, 2019. Analysis and interpretation of the particulate matter (PM10 and PM2.5) concentrations at the subway stations in Beijing, China. Sustain Cities Soc 45, 366–377. 10.1016/J.SCS.2018.11.020

Park DU, Ha KC, 2008. Characteristics of PM10, PM2.5, CO2 and CO monitored in interiors and platforms of subway train in Seoul, Korea. Environ Int 34, 629–634. 10.1016/J.ENVINT.2007.12.007 [PubMed: 18262270]

Peng RD, Chang HH, Bell ML, McDermott A, Zeger SL, Samet JM, Dominici F, 2008. Coarse Particulate Matter Air Pollution and Hospital Admissions for Cardiovascular and Respiratory Diseases Among Medicare Patients. JAMA 299, 2172–2179. 10.1001/JAMA.299.18.2172 [PubMed: 18477784]

Polezer G, Tadano YS, Siqueira H. v., Godoi AFL, Yamamoto CI, de André PA, Pauliquevis T, Andrade M, de F, Oliveira A, Saldiva PHN, Taylor PE, Godoi RHM, 2018. Assessing the impact of PM2.5 on respiratory disease using artificial neural networks. Environmental Pollution 235, 394–403. 10.1016/J.ENVPOL.2017.12.111 [PubMed: 29306807]

Power MC, Kioumourtzoglou MA, Hart JE, Okereke OI, Laden F, Weisskopf MG, 2015. The relation between past exposure to fine particulate air pollution and prevalent anxiety: observational cohort study. BMJ 350. 10.1136/BMJ.H1111

Querol X, Moreno T, Karanasiou A, Reche C, Alastuey A, Viana M, Font O, Gil J, de Miguel E, Capdevila M, 2012. Variability of levels and composition of PM 10 and PM 2.5 in the Barcelona metro system. Atmos Chem Phys 12, 5055–5076. 10.5194/ACP-12-5055-2012

Raut JC, Chazette P, Fortain A, 2009. Link between aerosol optical, microphysical and chemical measurements in an underground railway station in Paris. Atmos Environ 43, 860–868. 10.1016/j.atmosenv.2008.10.038

Ren J, He J, Kong X, Xu W, Kang Y, Yu Z, Li H, 2022. A field study of CO2 and particulate matter characteristics during the transition season in the subway system in Tianjin, China. Energy Build 254. 10.1016/j.enbuild.2021.111620

Roberts S, Arseneault L, Barratt B, Beevers S, Danese A, Odgers CL, Moffitt TE, Reuben A, Kelly FJ, Fisher HL, 2019. Exploration of NO2 and PM2.5 air pollution and mental health problems using high-resolution data in London-based children from a UK longitudinal cohort study. Psychiatry Res 272, 8–17. 10.1016/J.PSYCHRES.2018.12.050 [PubMed: 30576995]

Salma I, Weidinger T, Maenhaut W, 2007. Time-resolved mass concentration, composition and sources of aerosol particles in a metropolitan underground railway station. Atmos Environ 41, 8391–8405. 10.1016/J.ATMOSENV.2007.06.017

Sauvain JJ, Hemmendinger M, Suárez G, Creze C, Hopf NB, Jouannique V, Debatisse A, Pralong JA, Wild P, Canu IG, 2022. Malondialdehyde and anion patterns in exhaled breath condensate among subway workers. Part Fibre Toxicol 19, 1–13. 10.1186/S12989-022-00456-Z [PubMed: 34983569]

Shakya KM, Saad A, Aharonian A, 2020. Commuter exposure to particulate matter at underground subway stations in Philadelphia. Build Environ 186, 107322. 10.1016/J.BUILDENV.2020.107322

Sheikh HA, Tung PY, Ringe E, Harrison RJ, 2022. Magnetic and microscopic investigation of airborne iron oxide nanoparticles in the London Underground. Scientific Reports 2022 12:1 12, 1–10. 10.1038/s41598-022-24679-4

Smith JD, Barratt BM, Fuller GW, Kelly FJ, Loxham M, Nicolosi E, Priestman M, Tremper AH, Green DC, 2020. PM2.5 on the London Underground. Environ Int 134, 105188. 10.1016/J.ENVINT.2019.105188 [PubMed: 31787325]

Son YS, Jeon JS, Lee HJ, Ryu IC, Kim JC, 2014. Installation of platform screen doors and their impact on indoor air quality: Seoul subway trains. J Air Waste Manage Assoc 64, 1054–1061. 10.1080/10962247.2014.923350

Squizzato S, Masiol M, Rich DQ, Hopke PK, 2018. A long-term source apportionment of PM2.5 in New York State during 2005–2016. Atmos Environ 192, 35–47. 10.1016/J.ATMOSENV.2018.08.044

Vilcassim MJR, Thurston GD, Peltier RE, Gordon T, 2014. Black carbon and particulate matter (PM2.5) concentrations in New York city's subway stations. Environ Sci Technol 48, 14738–14745. 10.1021/ES504295H [PubMed: 25409007]

Wallace LA, Wheeler AJ, Kearney J, van Ryswyk K, You H, Kulka RH, Rasmussen PE, Brook JR, Xu X, 2010. Validation of continuous particle monitors for personal, indoor, and outdoor exposures. Journal of Exposure Science & Environmental Epidemiology 2011 21:1 21, 49–64. 10.1038/jes.2010.15

Wang BQ, Liu JF, Ren ZH, Chen RH, 2016. Concentrations, properties, and health risk of PM2.5 in the Tianjin City subway system. Environmental Science and Pollution Research 23, 22647–22657. 10.1007/S11356-016-7444-0 [PubMed: 27557967]

Wang J, Yin Q, Tong S, Ren Z, Hu M, Zhang H, 2017. Prolonged continuous exposure to high fine particulate matter associated with cardiovascular and respiratory disease mortality in Beijing, China. Atmos Environ 168, 1–7. 10.1016/J.ATMOSENV.2017.08.060

Wang J, Zhao L, Zhu D, Gao HO, Xie Y, Li H, Xu X, Wang H, 2016. Characteristics of particulate matter (PM) concentrations influenced by piston wind and train door opening in the Shanghai subway system. Transp Res D Transp Environ 47, 77–88. 10.1016/J.TRD.2016.05.006

Wang XR, Oliver Gao H, 2011. Exposure to fine particle mass and number concentrations in urban transportation environments of New York City. Transp Res D Transp Environ 16, 384–391. 10.1016/J.TRD.2011.03.001

Wang Z, Calderón L, Patton AP, Sorensen Allacci MA, Senick J, Wener R, Andrews CJ, Mainelis G, 2016. Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building. J Air Waste Manag Assoc. 66, 1109–1120. 10.1080/10962247.2016.1201022 [PubMed: 27333205]

Wen Y, Leng J, Shen X, Han G, Sun L, Yu F, 2020. Environmental and Health Effects of Ventilation in Subway Stations: A Literature Review. International Journal of Environmental Research and Public Health 2020, Vol. 17, Page 1084 17, 1084. 10.3390/IJERPH17031084

Xie J, Teng J, Fan Y, Xie R, Shen A, 2019. The short-term effects of air pollutants on hospitalizations for respiratory disease in Hefei, China. Int J Biometeorol 63, 315–326. 10.1007/S00484-018-01665-Y [PubMed: 30680626]

Xu B, Hao J, 2017. Air quality inside subway metro indoor environment worldwide: A review. Environ Int 107, 33–46. 10.1016/J.ENVINT.2017.06.016 [PubMed: 28651166]

Yan R, Ku T, Yue H, Li G, Sang N, 2020. PM2.5 exposure induces age-dependent hepatic lipid metabolism disorder in female mice. Journal of Environmental Sciences 89, 227–237. 10.1016/J.JES.2019.10.014

Zhao D, Azimi P, Stephens B, 2015. Evaluating the Long-Term Health and Economic Impacts of Central Residential Air Filtration for Reducing Premature Mortality Associated with Indoor Fine Particulate Matter (PM2.5) of Outdoor Origin. International Journal of Environmental Research and Public Health 2015, Vol. 12, Pages 8448–8479 12, 8448–8479. 10.3390/IJERPH120708448

Highlights

- $PM_{2.5}$ concentration and composition in the NYC subway system were measured.
- Underground platform concentrations averaged 142 ± 69 μg/m^3.
- Underground on-cabin concentrations averaged 88 ± 14 μg/m^3.
- The $PM_{2.5}$ samples had high iron content, approximately 43% of the total mass.

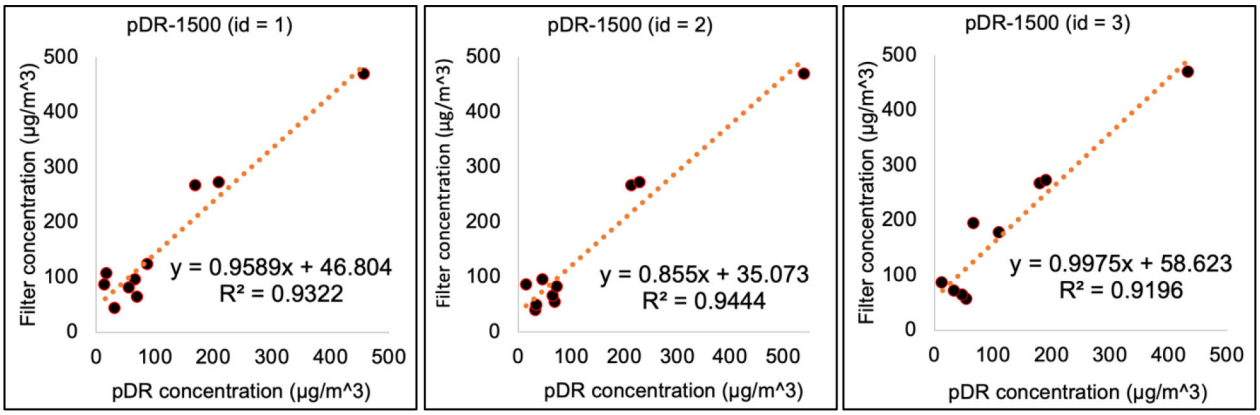

Figure 1:

Calibration curves for individual real-time monitors: (left) pDR-1500 (id = 1) was used to sample #3, #5, and #6 subway lines, (middle) pDR-1500 (id = 2) used in B, F, and M lines, (right) pDR-1500 (id = 3) measured lines #1, C, and R.

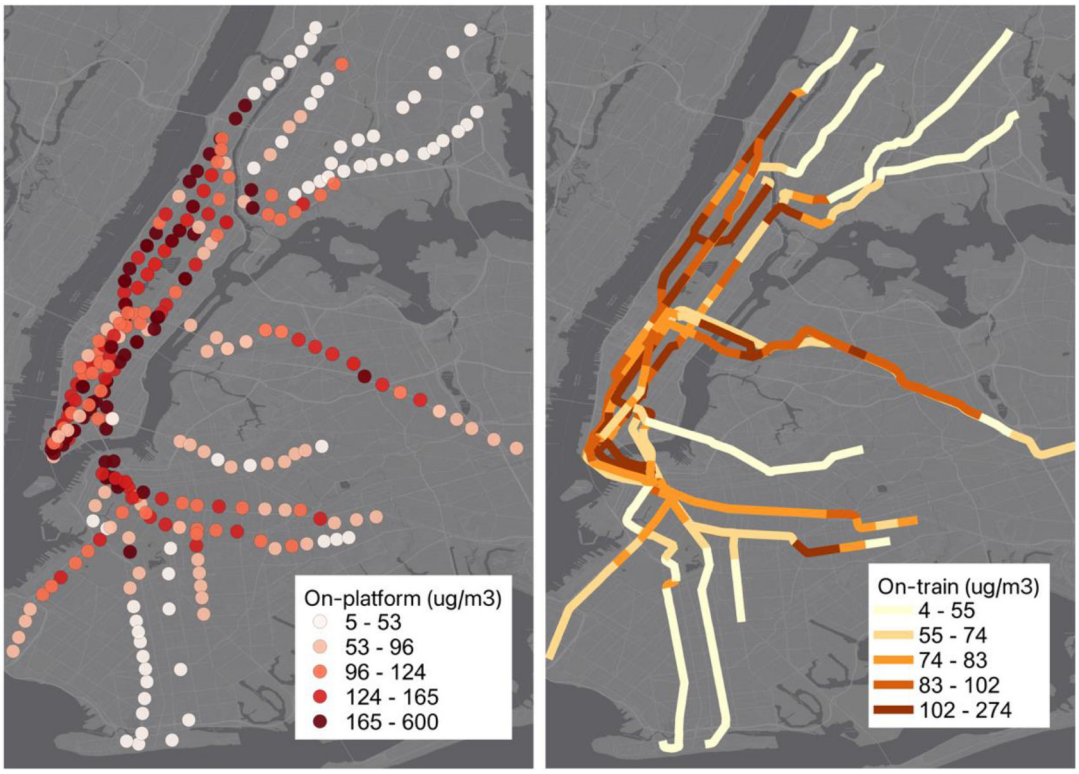

Figure 2:
(left) Average PM2.5 concentration on station platforms and (right) inside train cars between stations. (right).

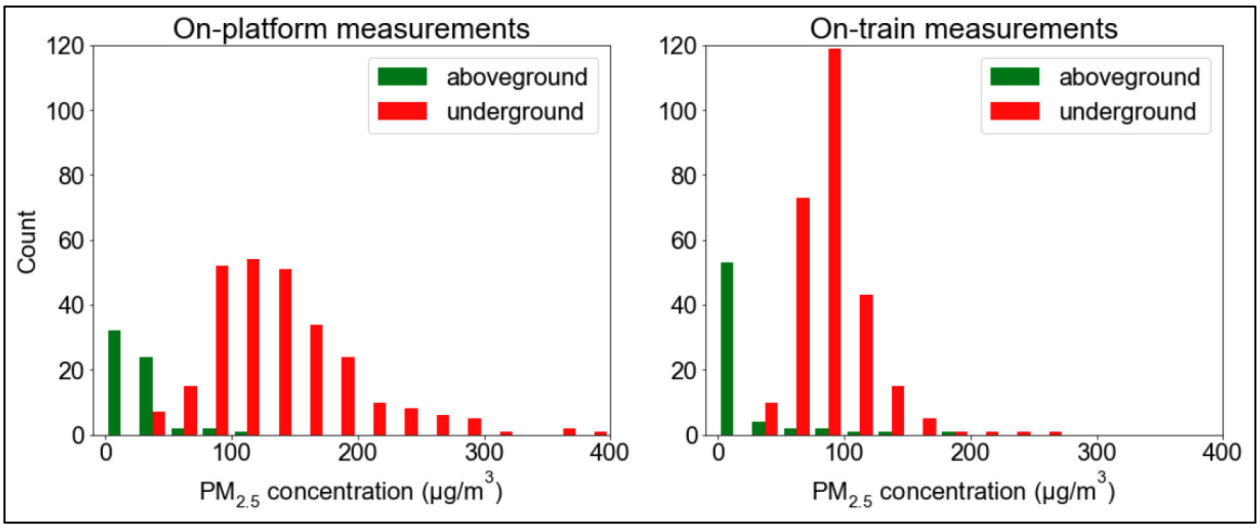

Figure 3:

Histogram of average (left) on-platform and (right) on-train samples for lines #1, #3, #5, #6, B, C, F, M, R. Aboveground and underground measurements are indicated in green and red color, respectively.

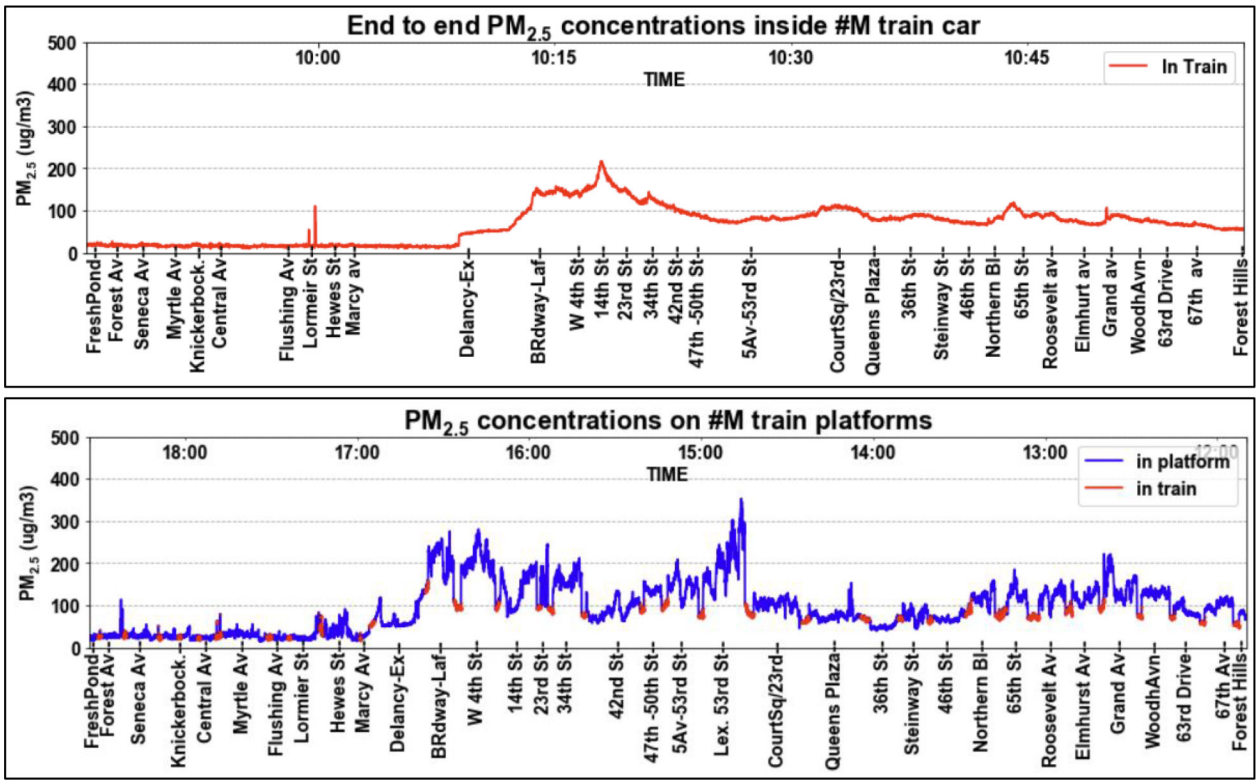

Figure 4:

(Top) PM2.5 concentrations inside the train car for an end-to-end trip of a M train. Measurements started from Fresh Pond Avenue at 9:45 AM. (Bottom) PM2.5 concentrations on the platforms (blue color) and inside the train between stations (red color) of the #M train. Sampling started from Forest Hills in Queens from 12:00 PM. Note that the direction of time is inverted for the on-platform chart.

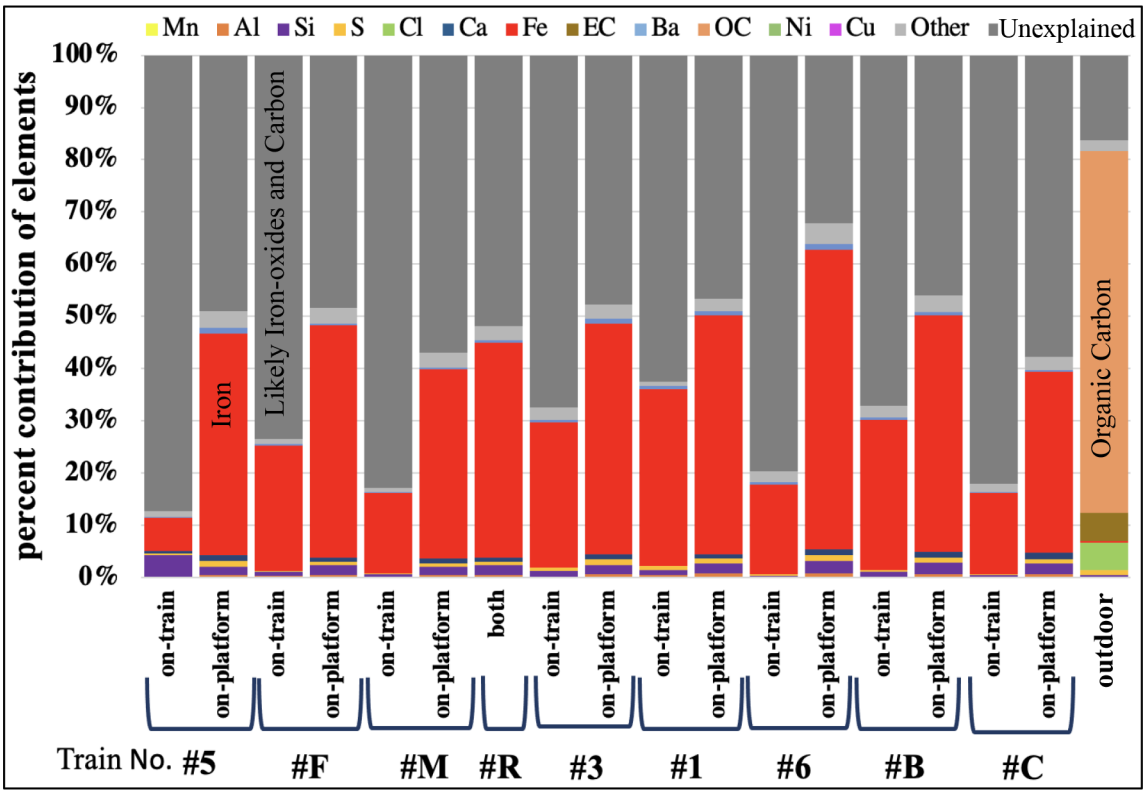

Figure 5:

Percent contribution of elemental constituents to the total mass of PM2.5. collected on filters in on-train, on-platform, and outdoor samples. Several elements, such as Na, Mg, Cr, Sr, etc., are included in the “other” category and are listed in Table S10. The unexplained category for the subway samples is likely a mix of carbon and oxygen, which were not analyzed in the samples.

Table 1.

Date and time for sampling

	On-train measurements		On-platform measurements	
Subway line	**Date**	**Time**	**Date**	**Time**
#1	10 Dec 2021	11:45 am – 12:44 pm	10 Dec 2021	2:07 pm – 6:34 pm
#3	10 Dec 2021	09:10 am – 10:20 am	10 Dec 2021	11:57 am – 5:07 pm
#5	11 Oct 2021	10:27 am – 12:02 pm	11 Oct 2021	12:57 pm – 7:02 pm
#6	7 Dec 2021	05:15 pm – 6:20 pm	8 Dec 2021	08:34 am – 11:28 am
B	7 Dec 2021	09: 50 am – 11:14 am	7 Dec 2021	12:14 pm – 06:16 pm
C	8 Dec 2021	05:12 pm – 06:28 pm	7 Dec 2021	12:15 pm – 06:52 pm
F	11 Oct 2021	10:06 am – 11:50 am	11 Oct 2021	01:20 pm – 08:40 pm
M	11 Oct 2021	09:45 am – 11:00 am	11 Oct 2021	11:50 am – 06:33 pm
R	10 Dec 2021	09:40 am – 11:10 am	10 Dec 2021	12:00 pm – 08:27 pm

Table 2.

Mean (SD) on-train and on-platform real-time PM2.5 concentrations for each subway line.

	Number of Sampled platforms		On-Train concentration		On-Platform concentration	
Subway line	**Aboveground**	**Underground**	**Aboveground (μg/m^3)**	**Underground (μg/m^3)**	**Aboveground (μg/m^3)**	**Underground (μg/m^3)**
#1	7	30	35 ± 8	111 ± 7	46 ± 12	195 ± 27
#3	6	25	59 ± 33	102 ± 7	59 ± 17	146 ± 20
#5	13	22	10 ± 5	71 ± 5	16 ± 5	162 ± 28
#6	9	27	8 ± 3	89 ± 7	12 ± 6	159 ± 18
B	4	32	20 ± 5	84 ± 8	38 ± 31	119 ± 17
C	0	39	-	91 ± 8	-	146 ± 23
F	13	30	13 ± 5	54 ± 7	23 ± 6	123 ± 28
M	10	23	17 ± 3	95 ± 7	28 ± 7	122 ± 19
R	0	43	-	83 ± 4	-	121 ± 18

Table 3.

On-platform and on-train mean (SD) real-time concentrations for 20 highest polluted stations

Station Name	Line	On-platform $PM_{2.5}$ concentration ($\mu g/m^3$)	On-train	
			On-train PM2.5 concentration ($\mu g/m^3$)	Train bound direction
181st street	#1	600 ± 84	238 ± 17	Bronx
168th street	#1	557 ± 70	273 ± 49	Bronx
Bowling Green	#5	384 ± 43	110 ± 11	Bronx
Broadway-Lafayette	B	367 ± 75	132 ± 21	Bronx
High Street	C	360±132	155 ± 8	Manhattan
Borough Hall	#3	311 ± 41	132 ± 6	Manhattan
Lafayette Avenue	C	295 ± 47	83 ± 5	Manhattan
Fulton Street	C	290±108	151 ± 13	Manhattan
WTC Cortlandt	#1	290 ± 33	88 ± 2	Bronx
Bleecker Street	#6	282 ± 20	128 ± 8	Bronx
34th St-Herald Sq	B	279 ± 30	206 ± 23	Bronx
2nd Avenue	F	273 ± 32	120 ± 11	Queens
125 Street	#5	256 ± 20	73 ± 4	Bronx
East Broadway	F	253 ± 65	77 ± 5	Queens
42nd Grand Central	#6	253 ± 23	84 ± 4	Bronx
72nd Street	#3	252 ± 25	118 ± 5	Manhattan
145th street	#1	252 ± 46	99 ± 16	Bronx
York Street	F	246 ± 41	74 ± 10	Queens
Canal Street	#6	246 ± 29	89 ± 6	Bronx
14th Union Square	#6	240 ± 31	99 ± 5	Bronx

Table 4:

Comparison of $PM_{2.5}$ concentrations (μg/m^3) measured from NYC with worldwide subway systems.

City (Study year)	Station Sampled	On platform concentration (μg/m^3)				On train concentration (μg/m^3)				Reference
		Underground		Aboveground		Underground		Aboveground		
		Avg	±SD (Min-Max)	Avg	±SD (Min-Max)	Avg	±SD (Min-Max)	Avg	±SD (Min-Max)	Reference
New York City (2021)	287	142	± 69	29	± 20	88	±14	29	±31	Current study
Los Angeles (2011)	13	57	(9 – 130)	29	(4 – 77)	24	(11 – 62)	14	(3 – 38)	(Kam et al., 2011)
Philadelphia (2019)	12	45	±27	–	–	–	–	–	–	(Shakya et al., 2020)
Barcelona (2011)	4	125	(102–148)	–	–	21	(16 – 26)	–	–	(Querol et al., 2012)
Naples (2015)	17	52	±4 (45–58)	10	±1 (8–11)	29	±5 (21–36)	13	±4 (8–18)	(Carteni et al., 2015)
Sydney (2018)	16	41	12	17	±7	38	±23	15	±13	(Mohsen et al., 2018)
Seoul(2017)	13	78	±8	–	–	–	–	–	–	(Lee et al., 2018)
Seoul(2008)	89	105	±14	115	±9	117	±14	121	±16	(Park and Ha, 2008)
Taipei (2008)	5	44	±12 (22–91)	33	±23 (7–94)	40	10 (20–68)	28	±14 (8–67)	(Cheng et al., 2008)
Helsinki (2004)	3	50	(37–87)	–	–	21	(17–45)	–		(Aarnio et al., 2005)
Stockholm (2000)	1	199	±104	–	–	–	–	–	–	(Johansson and Johansson, 2003)
London (2020)	375	105	(45–885)	10	(2–95)	–	–	–	–	(Smith et al., 2020)
London (1999)	–	–	–	–	–	247	(105–371)	29	(12–42)	(Adams et al., 2001)
Beijing (2005)	–	–	–	–	–	113	±43	37	±19	(Li et al., 2007)
Tianjin (2021)	–	43	±6	–	–	23	±7	–	–	(Ren et al., 2022)
Paris (2006)	1	93	±34	–	–	–	–	–	–	(Raut et al., 2009)
Prague (2013)	1	108	±24	–	–	–	–	–	–	(Cusack et al., 2015)