



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

Shams Azad^a, David G. Luglio^b, Terry Gordon^b, George Thurston^b, Masoud Ghandehari^{a,*}

^a Department of Civil and Urban Engineering, New York University, Tandon School of Engineering, Brooklyn, New York, USA

^b Department of Medicine, New York University Langone Health, New York, USA

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ABSTRACT

In this study we investigated the concentration and composition of particulate matter (PM_{2.5}) in the New York City subway system. Realtime measurements, at a 1-s cadence, and gravimetric measurements were performed inside train cars along 300 km of nine subway lines, as well as on 333 platforms on 287 subway stations. The mean (\pm SD) PM_{2.5} concentration on the underground platforms was $142 \pm 69 \mu\text{g}/\text{m}^3$ versus $29 \pm 20 \mu\text{g}/\text{m}^3$ for aboveground stations. The average concentrations inside train cars were $88 \pm 14 \mu\text{g}/\text{m}^3$ when traveling through underground tunnels and platforms and $29 \pm 31 \mu\text{g}/\text{m}^3$ 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, approximately 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 not appropriate since those limits are largely based on particulate matter from fossil fuel combustion. Health impact analysis of inhalation of iron-based particles is needed to contextualize the results presented here.

1. Introduction

PM_{2.5} refers to airborne particles with an aerodynamic diameter equal to or less than 2.5 μm . 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 $315 \mu\text{g}/\text{m}^3$ and $194 \mu\text{g}/\text{m}^3$, 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 2–7 times higher than street level values, and the PM_{2.5} concentration was 3.5–20 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).

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* Corresponding author.

E-mail addresses: shams.azad@nyu.edu (S. Azad), David.Luglio@nyulangone.org (D.G. Luglio), Terry.Gordon@nyulangone.org (T. Gordon), george.thurston@nyu.edu (G. Thurston), mg3081@nyu.edu (M. Ghandehari).

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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 $\mu\text{g}/\text{m}^3$ (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 $\mu\text{g}/\text{m}^3$ and 93 $\mu\text{g}/\text{m}^3$ (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 $\mu\text{g}/\text{m}^3$ (Guo et al., 2014). Similar concentration levels were found in the subway system of Tianjin (Wang et al., 2016a), 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 $\mu\text{g}/\text{m}^3$ – 291 $\mu\text{g}/\text{m}^3$) 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 $\mu\text{g}/\text{m}^3$) than the stations located from 0 to 10 m 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 $\mu\text{g}/\text{m}^3$ for an 8-h 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 (Fe₃O₄) 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 5–15 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 1-s intervals, and pDRs were zeroed with HEPA-filtered air before initiating each sampling run.

Table 1
Date and time for sampling.

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

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% ($\pm 5\%$) relative humidity (RH) for 24 h 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 1–1.5 h 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 8 h. 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 11 h. 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-s 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; Wang et al., 2016c). For the aboveground calibration, we sampled outside the Sutter Avenue Rutland Road station in Brooklyn for 4 h, 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 1 h 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. (Fig. 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 Figs. 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 s intervals for 5–15 min, 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 min. All real-time instruments were calibrated using co-located gravimetric measurements as described above.

The mean (\pm SD) PM_{2.5} concentration of the 271 sampled underground station platforms was $142 \pm 69 \mu\text{g}/\text{m}^3$. This was significantly greater than the mean concentration of $29 \pm 20 \mu\text{g}/\text{m}^3$ for the aboveground stations ($n = 62$). Fig. 3 (left) shows the histogram of the average PM_{2.5} concentrations of 333 station platforms and Fig. 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

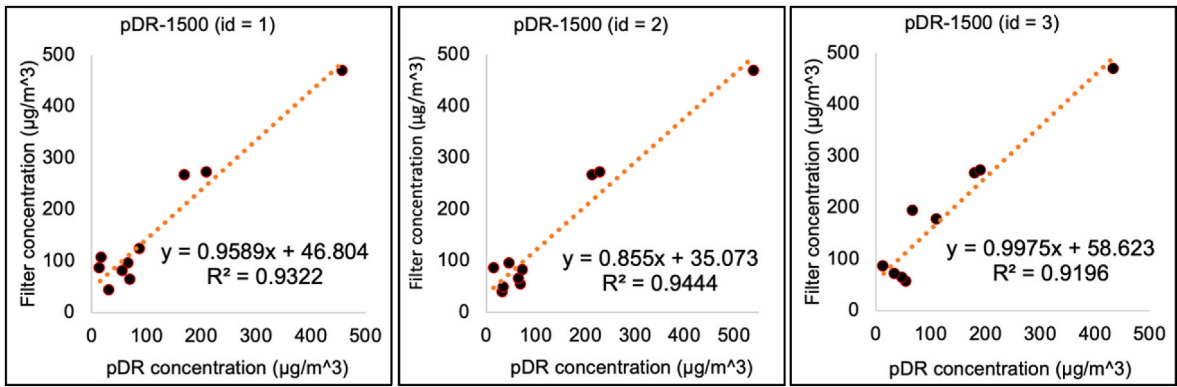


Fig. 1. Calibration curves for individual real-time monitors: (left) pDR-1500 (id = 1) was used to sample #3, #5, and #6 subway lines, (middle) pDR-1500 (id = 2) used in B, F, and M lines, (right) pDR-1500 (id = 3) measured lines #1, C, and R.

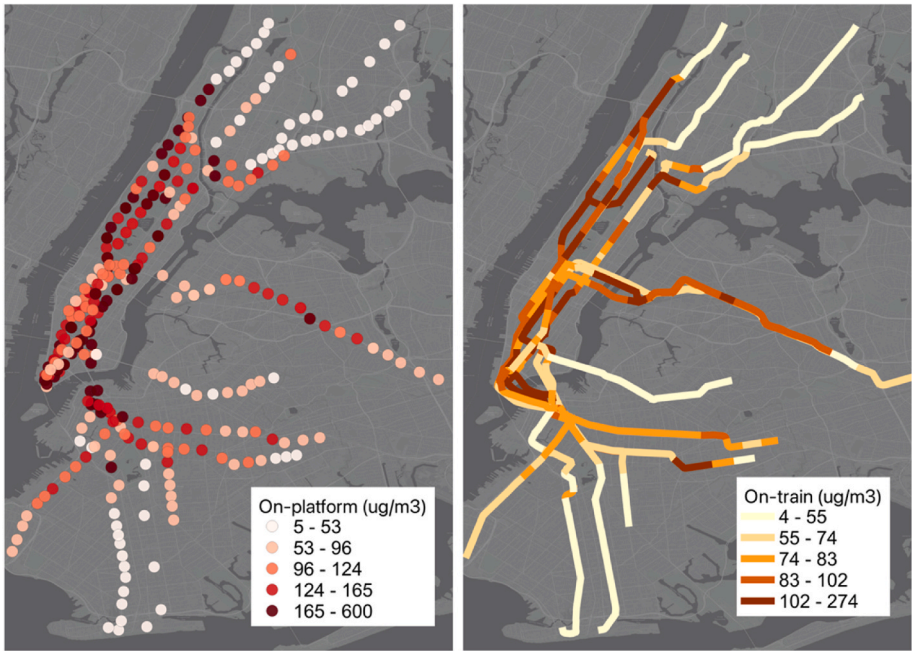


Fig. 2. (Left) Average $\text{PM}_{2.5}$ concentration on station platforms and (right) inside train cars between stations.

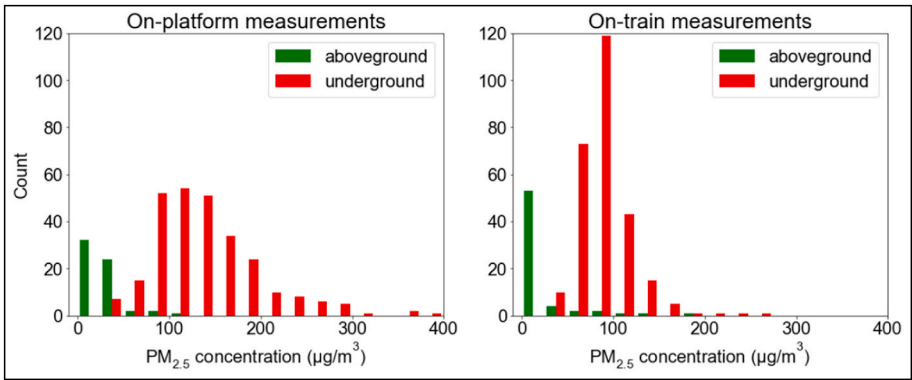


Fig. 3. Histogram of average (left) on-platform and (right) on-train samples for lines #1, #3, #5, #6, B, C, F, M, R. Aboveground and underground measurements are indicated in green and red color, respectively.

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 $\text{PM}_{2.5}$ concentrations than stations located in the city outskirts. Table 3 shows the on-platform

Table 2Mean (SD) on-train and on-platform real-time PM_{2.5} concentrations for each subway line.

Subway line	Number of Sampled platforms		On-Train concentration		On-Platform concentration	
	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 (µg/m ³)	On-train	
			On-train PM _{2.5} concentration (µg/m ³)	Train bound direction
181th 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

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 – Fig. S9).

Fig. 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 a.m., 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 µg/m³ when underground. The on-train concentrations rose above 130 µg/m³ 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 µg/m³. Broadway-Lafayette station's M line platform turned out to be the most polluted on this line at 208 ± 30 µg/m³. Other stations with high concentrations include West 4 Street-Washington Square (207 ± 27 µg/m³), Lexington Avenue-53rd Street (205 ± 54 µg/m³), and 34 Street-Herald Square (162 ± 17 µg/m³). 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 – Fig. 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}. Fig. 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 (Fig. 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 Fe₂O₃, Fe₃O₄, etc. (Lu et al., 2015; Querol et al., 2012; Sheikh et al., 2022). If it is assumed that all the

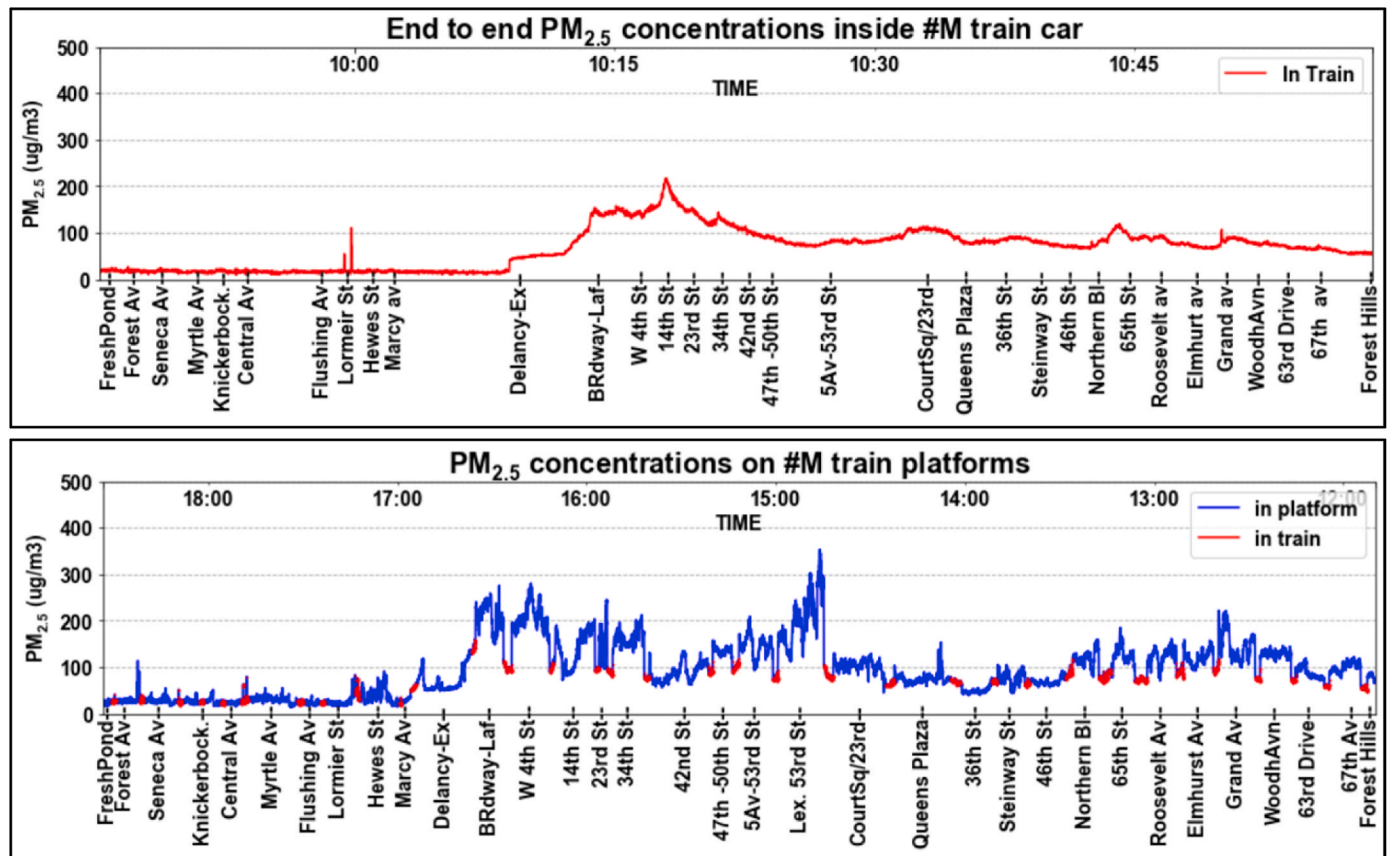


Fig. 4. (Top) $PM_{2.5}$ concentrations inside the train car for an end-to-end trip of a M train. Measurements started from Fresh Pond Avenue at 9:45 a.m. (Bottom) $PM_{2.5}$ concentrations on the platforms (blue color) and inside the train between stations (red color) of the M train. Sampling started from Forest Hills in Queens from 12:00 p.m. Note that the direction of time is inverted for the on-platform chart.

Table 4

Comparison of $PM_{2.5}$ concentrations ($\mu g/m^3$) 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)

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 Fig. 5. The 'other' category in Fig. 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

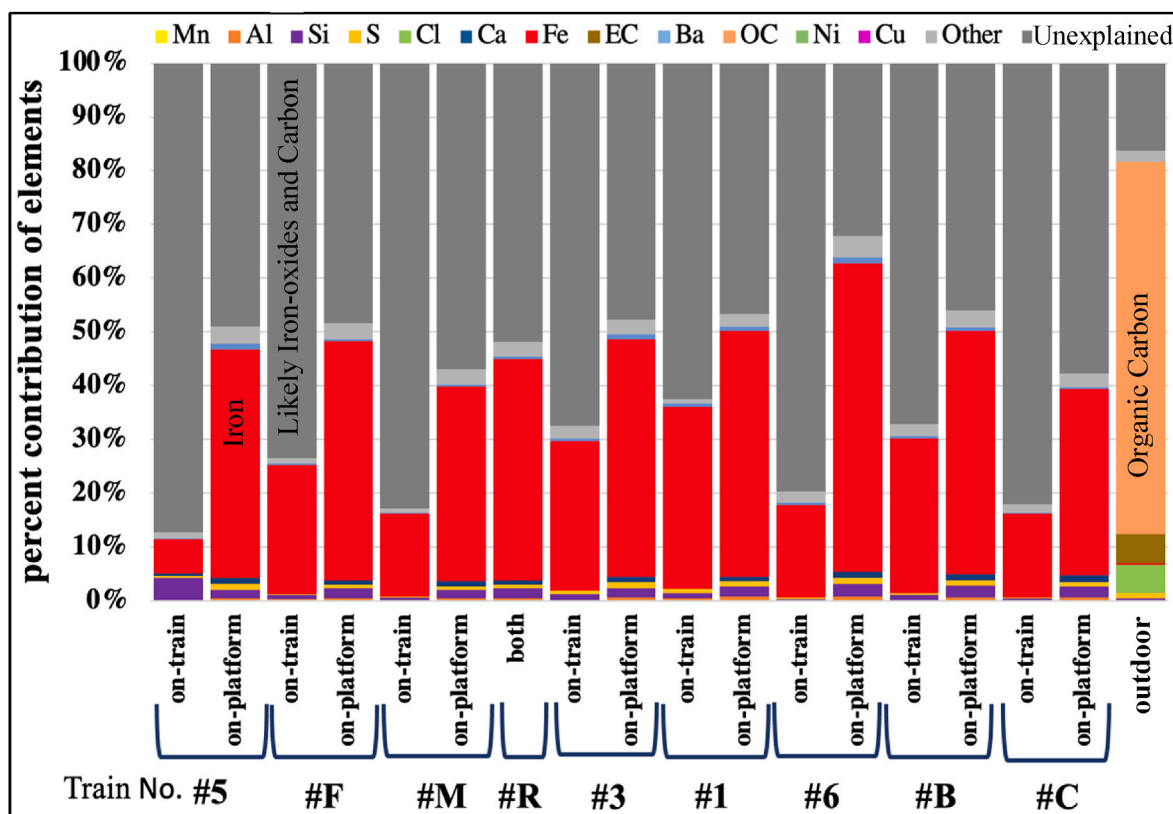


Fig. 5. Percent contribution of elemental constituents to the total mass of $PM_{2.5}$. Collected on filters in on-train, on-platform, and outdoor samples. Several elements, such as Na, Mg, Cr, Sr, etc., are included in the “other” category and are listed in Table S10. The unexplained category for the subway samples is likely a mix of carbon and oxygen, which were not analyzed in the samples.

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 (Wang et al., 2016b). 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 4 min. 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 (Carteni and Caschetta, 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 (Wang et al., 2016b). 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., 2015, 2016b; 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 examined 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 $142 \pm 69 \mu\text{g}/\text{m}^3$, while the 62 above-ground platforms had an average concentration of $29 \pm 20 \mu\text{g}/\text{m}^3$. 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. 181th 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 $600 \pm 84 \mu\text{g}/\text{m}^3$.
- 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 $35 \mu\text{g}/\text{m}^3$ 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 h 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.

Credit author statement

Shams Azad: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Visualization, Writing – original draft. David Luglio: Conceptualization, Methodology, Formal analysis, Data curation, Investigation, Writing – review & editing. Terry Gordon: Conceptualization, Methodology, Resources, Supervision, Investigation, Writing – review & editing. George Thurston: Conceptualization, Methodology, Resources, Supervision, Investigation, Writing – review & editing. Masoud Ghandehari: Conceptualization, Methodology, Resources, Supervision, Project administration, Investigation, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apr.2023.101767>.

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