A Comprehensive Analysis of the Air Quality in the NYC Subway System

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16. Abstract

We have carried out a study analyzing the concentrations of particulate matter in the New York City subway system. Realtime and gravimetric measurements were made inside train cars along the full length of 9 subway lines, as well as real-time measurements on 341 platforms from 287 stations, all at one-second intervals that the mean (±SD) PM2.5 concentrations on the underground platforms was 216 ± 82 μg/m3 versus 29 ± 27 μg/m3 for aboveground stations. Other trace elements measured in the NYC subway system include silicon, copper, nickel, aluminum, calcium, barium, Manganese, and chromium. Results also suggest that when train cars are at stations with doors open, mixing of air between the platform and cars results in a rapid increase of PM concentrations in the cars.

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A Comprehensive Analysis of the Air Quality in the NYC Subway System

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Executive Summary

We have carried out a study analyzing the concentrations of particulate matter in the New York City subway system. Realtime and gravimetric measurements were made inside train cars along the full length of 9 subway lines, as well as real-time measurements on 341 platforms from 287 stations, all at one-second intervals that the mean (±SD) PM2.5 concentrations on the underground platforms was 216 ± 82 µg/m3 versus 29 ± 27 µg/m3 for aboveground stations. Concentrations inside train cars were 148 ± 51 µg/m3 when traveling through underground tunnels and platforms, and 22 ± 44 µg/m3 while on aboveground tracks. US EPA's standards limit the allowable daily average PM2.5 mass concentration at 35 µg/m3. Using particle element analysis, we found that the concentration of iron particles in subway stations was 140 times higher than ambient outdoor levels. Other trace elements measured in the NYC subway system include silicon, copper, nickel, aluminum, calcium, barium, Manganese, and chromium. Results also suggest that when train cars are at stations with doors open, mixing of air between the platform and cars results in a rapid increase of PM concentrations in the cars.

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Introduction

PM2.5 refers to airborne particles that have 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 toxicity. Importantly, when inhaled, PM2.5 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 [1], [2]. Exposure to ambient PM2.5, especially those containing heavy metals from combustion, is one of the leading risk factors for disease burden, including respiratory, cardiovascular, metabolic, and neurological disorders [3]–[11]. These particles are responsible for over 3 million premature deaths [12] and over 2.7 million preterm births per year, globally [13], [14] [15].

Literature Review

A recent study looked at PM2.5 concentration in 78 subway stations in the Northeast US, including Boston, New York, Philadelphia, Washington DC, and found the average PM2.5 concentration on underground stations and on-trains was 315 µg/m3 and 194 µg/m3, respectively. On average, particles on the sampled underground stations were found to be 52% iron and 31% carbon by mass [16]. One study of 30 stations in 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 PM2.5 concentration was 3.5 to 20 times higher than on street level [17]. Another study collected air samples from highways, aboveground and underground stations, inside train cars, urban street-sides and parks. PM2.5 mass concentration was the highest on the subway platforms, amongst all sampled categories [18]. Furthermore, an earlier study examined teenagers' exposure to iron, manganese, and chromium with personal sampling techniques, and identified that the NYC subway system was their primary source of exposure to these chemical constituents [19].

Studies of subway particulate matter have also been carried out in number of other cities. The Los Angeles (LA) metro system was found to be less polluted than New York's; the average concentration on the underground stations in LA ranged from 9 to 130 µg/m3 [20]. The Mexico City subway system follows similar pattern of concentrations of PM2.5 as the one in Los Angeles, ranging between 60 µg/m3 and 93 µg/m3 [21]. However, because of the variation in measurement techniques and instruments, the results from the different studies are not always directly comparable [22]. In Asia, one study sampled selected stations from three subway lines

in Shanghai and found the average concentration of PM2.5 ranged between 82.5 and 178 µg/m3 [23]. Similar concentration levels were found in the subway system of Tianjin [24], Seoul [25], Tehran [26], and Taipei [27]. One study sampled four stations in Beijing and found the concentration of underground stations varied significantly (56 µg/m3 – 291µg/m3) on different days of the week [28]. 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/m3) than the stations located from 0 to10 meters below the ground. Time-series measurements of one station in London for several days also exhibited a high correlation between PM2.5 concentration and train frequency [29].

The composition of subway particles is quite different from the PM composition in the outdoor ambient air, where organic carbon particles created by combustion of fossil fuels comprise the majority by mass [30], [31]. Similar to the findings in NYC, some of the above studies included 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 includes Cu, Ba, Cr, Si, Mn, and Zn [23], [29], [32]–[36]. The metal-rich particles in the subway systems are mostly generated from wear and friction processes at the intersection of rail–wheel–brake [37]. Additionally, ambient air, ballast, and construction work in the tunnels could also be potential sources for the mineral particles [38]. Other than the composition, contributing factors for the above high particulate matter concentrations in subways include train frequency and station depth, ventilation system, ambient air quality, year of construction, etc. [39], [40].

While the adverse health impacts of exposure to ambient particles generated by fossil fuel combustion is well recognized [41], there is more uncertainty regarding the health effects of exposure to iron-rich particulate matter, such as experienced in subways. An available guidance level for exposure to iron-rich particulate matter is set by the American Conference of Governmental Industrial Hygienists (ACGIH), based on the proposal of Occupational Safety and Health Administration (OSHA), where the occupational exposure standard for welding fume (enriched with iron oxide) is limited to 5000 µg/m3 for an eight-hour work shift [42]. 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. Metals abundant in

underground air, however, have significant potential to contribute to oxidative stress by generating reactive oxygen species (ROS) [43]. One study found that underground Mn, Zn, Ba, and especially Cu have more oxidative potential than Fe [44]. 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 [45]. A study on the biological effects of PM sampled in Paris subway stations found that PM induced oxidative stress in macrophages in vitro, and lung homogenates in vivo [46]. Another study found that employees who are highly exposed to airborne particles in the Stockholm underground have higher concentrations of risk markers for cardiovascular diseases than employees with lower exposure [47]. For Seoul metro subway stations, incremental lifetime cancer risks were identified for the commuters [48] although another study did not find any evidence of elevated risk of lung cancer for subway drivers [49].

Materials and Methods

Sampling strategy

Both real-time, light scattering-based, and gravimetric-based PM$_{2.5}$ measurements were collected on nine subway lines, including both on-train and on-platforms. All measurements for one subway line were conducted in a single day (except train #C and #6). In the morning, on-train concentration was measured by traveling in a subway car from one end of the line to the other end. On the return trip, beginning around noon (except train #6), the investigators got off from the train at every station along the subway line and sampled the real-time on-platform concentration until the arrival of the following train of the same line. Thus, the investigators stayed on each platform for 5 to 10 min before the boarding train to the next station.

Real-time and gravimetric measurements

A nephlometric-based real-time DataRAM PDR 1500 [51] with a 2.5 μm diameter cut point inlet cyclone was used for real-time PM2.5 measurements. In this study, we used three PDR-1500 devices, and all PDR data were calibrated with gravimetric PM2.5 concentrations (see section 2.3). 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 PM2.5, and to allow a calibration of the real-time pDR mass measurements, a 2.5 µm cut Personal Environmental Monitor (PEM) [52] was employed to collect particles on 37 mm diameter Teflon filters with a Leland Legacy Pump [53] operating at 10 L/min. In addition to sampling subway air, we sampled ambient outdoor air quality separately with both a Teflon filter and a prebaked quartz (Pall) filter to analyze trace metals and carbon in ambient outdoor PM. Filters were conditioned at 21 oC (+/- 1 oC) 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 #6 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 ranged for the latter from four to eight hours. For line #R, only one filter was used for the on-platform, and the on-train measurements and the elemental concentration cannot be reported separately for on-train and on-platform.

To compare particle compositions of the subway with ambient air, separate sampling was also done to collect ambient PM2.5 with a Teflon and a quartz filter. For eleven hours, ambient air was sampled near a busy urban roadway. 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 subway systems. As a result, only the trace elements were quantified for on-platform and on-train samples.

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 [54]. 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 [55]–[57]. For the above-ground 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. We found that the gravimetric measurements showed around twice as much concentration as real-time measurements from all monitors. The mean ratio of gravimetric to

real-time was 2.03, which was used as the calibration factor for the above-ground environment. For the underground calibration, we collected air samples at five sites, namely, 181st Street station, Borough Hall, Nevis Street, 2nd Avenue, and Bowling Green stations. We formulated a non-linear underground calibration function for each of the PDR instruments (Figure 1).
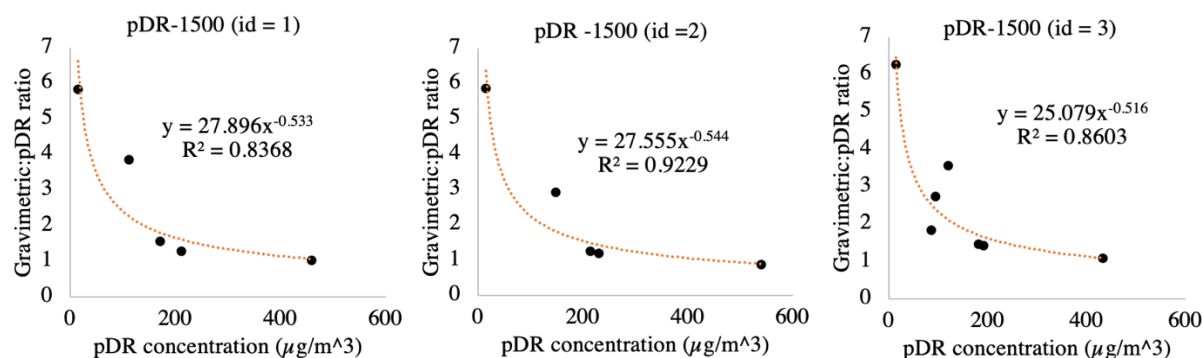
Figure 1: Calibration curves for individual real-time monitors

(left) pDR-1500 (id = 1) is 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

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 (model: 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 [16]. The concentration of organic (OC) and elemental (EC) carbon was determined with a Sunset Labs OCEC Analyzer (Subset instruments, inc.) and NIOSH 5040 method [58] using a quartz filter.

Concentration Measurements

Results of onboard and on-platform measurements of PM$_{2.5}$ concentration for the nine subway lines are shown in Figures 2 and 3 and Tables 1 and 2. The mean concentration for each platform refers to the average value of measurements at each platform taken at 1 second intervals for 5 – 10 minutes. The mean on-train concentration indicates the average concentration inside the train cabin when it moves through the track sections between consecutive stations. All real-time instruments were calibrated using co-located gravimetric measurements as described above.
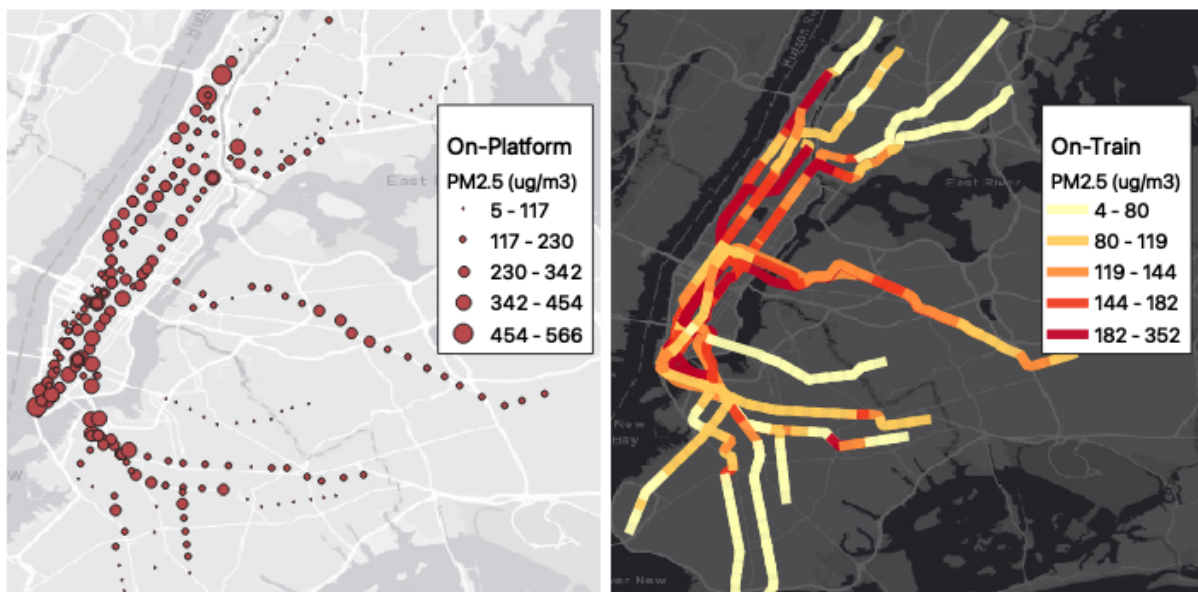
Figure 2: Average PM$_{2.5}$ concentration in station platforms (left) and inside train car between stations

The mean PM$_{2.5}$ concentration of 275 sampled underground station platforms was 216 ± 82 µg/m^3. This is much higher than the concentration of aboveground stations (n=66), where the mean concentration was 29 ± 27 µg/m^3.

Figure 3 shows the histogram of the average PM$_{2.5}$ concentrations of 341 station platforms and on-train cabin measurements along the section tracks between stations. The histogram shows a bimodal distribution, where the left pick shows measurements for aboveground and right pick

for underground environments, with some overlap in concentrations for the on-platform and on-train.

Table 1 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. Again, the concentrations of on-train measurements are lower than that of on-platform samples.
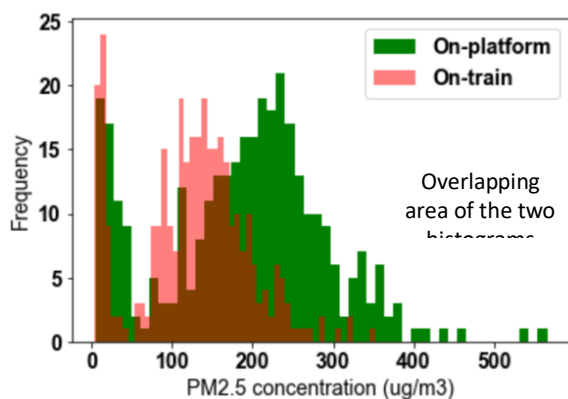
Figure 3: Histogram of average on-platform and on-train measurements

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 2 shows the on-platform concentration for the top 20 highest polluted stations and the mean concentrations inside train cabin during the train travels from these and neighboring stations.

Table 1: Mean (SD) on-train and on-platform PM2.5 concentrations for each sampled subway line

Subway line	Number of Sampled platforms Aboveground	Number of Sampled platforms Underground	On-Train concentration Aboveground ($\mu g/m^3$)	On-Train concentration Underground ($\mu g/m^3$)	On-Platform concentration Aboveground ($\mu g/m^3$)	On-Platform concentration Underground ($\mu g/m^3$)
#1	7	31	40 ± 29	164 ± 62	46 ± 12	268 ± 106
#3	7	25	97 ± 127	186 ± 38	75 ± 54	239 ± 68
#5	13	23	9 ± 12	120 ± 38	16 ± 9	257 ± 105
#6	10	27	7 ± 5	162 ± 36	9 ± 8	262 ± 69

#B	5	32	19 ± 6	158 ± 65	34 ± 35	184 ± 87
#C	0	40	-	131 ± 39	-	194 ± 70
#F	14	30	14 ± 11	142 ± 45	22 ± 8	221 ± 77
#M	10	23	16 ± 4	188 ± 47	29 ± 10	227 ± 67
#R	0	44	-	115 ± 30	-	183 ± 56

Table 2: On-platform and on-train mean (SD) concentrations for top 20 highest polluted stations

Station Name	Line	On-platform PM2.5 concentration ($\mu g/m^3$)	On-train	
			On-train PM2.5 concentration ($\mu g/m^3$)	Train bound direction
181st street	#1	566 ± 46	322 ± 16	Bronx
168th street	#1	543 ± 41	351 ± 41	Bronx
Bowling Green	#5	460 ± 31	202 ± 18	Bronx
Broadway–Lafayette	#B	439 ± 58	243 ± 16	Bronx
High Street	#C	410 ± 103	234 ± 10	Manhattan
Borough Hall	#3	408 ± 34	244 ± 21	Bronx
Bleecker Street	#6	386 ± 17	227 ± 11	Bronx
34th St–Herald Sq	#B	382 ± 23	227 ± 11	Bronx
2nd Avenue	#F	377 ± 29	321 ± 21	Bronx
Lafayette Avenue	#C	368 ± 39	114 ± 12	Bronx
WTC Cortlandt	#1	366 ± 33	128 ± 5	Bronx
125 Street	#5	364 ± 20	130 ± 9	Bronx
42nd Grand Central	#6	361 ± 22	154 ± 7	Bronx
East Broadway	#F	358 ± 53	164 ± 9	Queens
Canal Street	#6	355 ± 26	165 ± 12	Bronx
Fulton Street	#C	355 ± 102	229 ± 16	Manhattan
York Street	#F	355 ± 37	157 ± 18	Queens
14th Union Square	#6	350 ± 28	184 ± 8	Bronx
149 Street	#5	347 ± 30	143 ± 9	Bronx
72nd Street	#3	343 ± 23	227 ± 6	Bronx

Figure 4 presents an example time series record of on-platform and on-train PM2.5 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 of the #M line (from Fresh Pond to Mercy Avenue). The average onboard concentration of $PM_{2.5}$ was 188 ± 47 $\mu g/m^3$ when underground. In fact, on-train concentrations rose above 200 $\mu g/m^3$ continuously between Broadway-Lafayette and 42 St-Bryant Park stations. The underground platforms of #M also exhibit elevated levels of $PM_{2.5}$ concentrations, with an average of 227 ± 67 $\mu g/m^3$. Broadway-Lafayette station's #M line platform turned out to be the most polluted among all, with an

average concentration of 332 ± 27 µg/m^3. Other stations with high concentrations include West 4 Street-Washington Square (330 ± 24 µg/m^3), Lexington Avenue-53rd Street (326 ± 48 µg/m^3), and 34 Street-Herald Square (288 ± 18 µg/m^3). Please see the Appendix for similar real-time measurements of #1, #3, #5, #6, #B, #C, #F and #R lines.
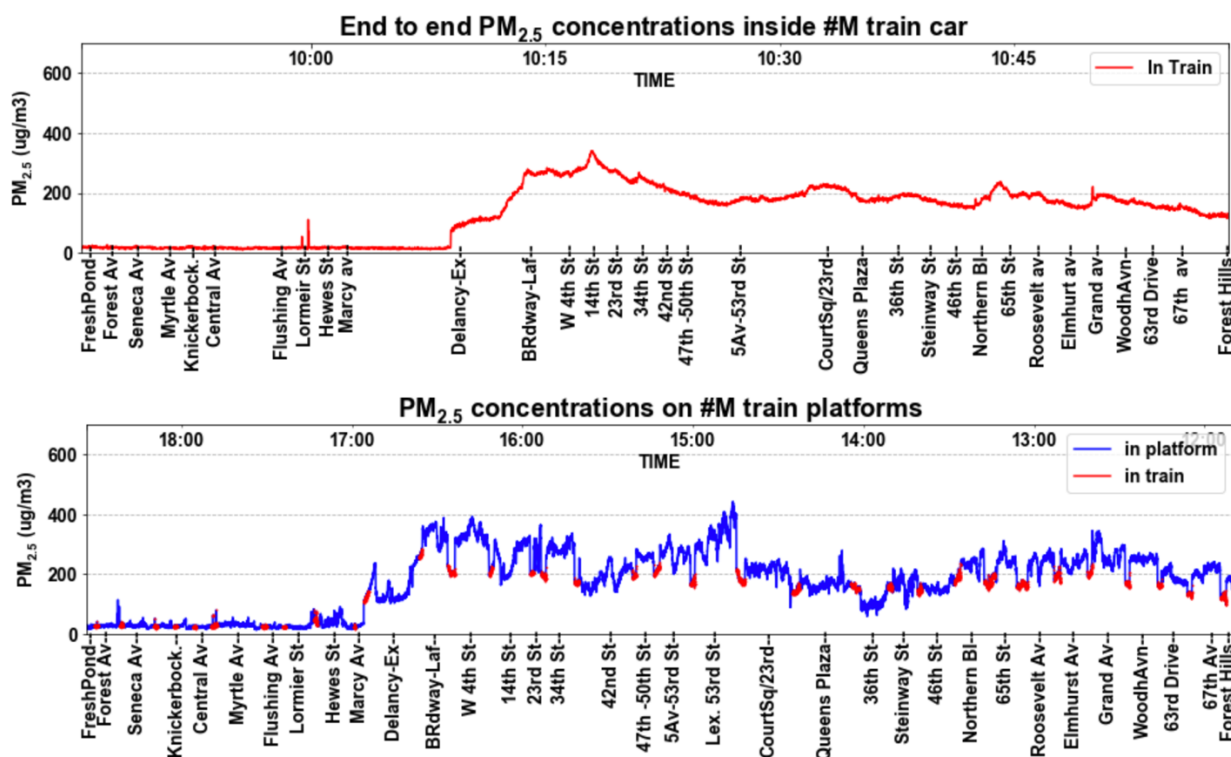
Figure 4: (Top) PM$_{2.5}$ concentrations inside the train car for a end-to-end trip of a #M train

Measurements started from Fresh Pond Avenue at 9:45 AM. (Bottom) PM2.5 concentrations on the platforms (blue color) 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.

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 percent 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 is found between 6% (#5 train) and 34% (#1 train). Although this contribution 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 is over nine times more than in the outdoor environment. On average, silicon constituted about 2% of total $PM_{2.5}$. Furthermore, copper and nickel, two critical trace metals for oxidative stress, were found to contribute to a 44- and 5-times higher share in subway particles than in outdoor particles, respectively. Additionally, manganese, another transition metal associated with oxidative stress [44], 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 not detected in the outdoor sample, however.

In the outdoor environment, the most dominant species was OC (70%), followed by EC (5.5%). Because of the sole use of Teflon filters in subway systems, carbon concentrations were not specifically quantified in the subway particles, and its contribution falls under the unknown category (Figure 1). Looking at the unknowns for each sample, we find the unknowns constitute on average 47% for on-platform, 74% for on-train, and only 16% for the outdoor measurements.
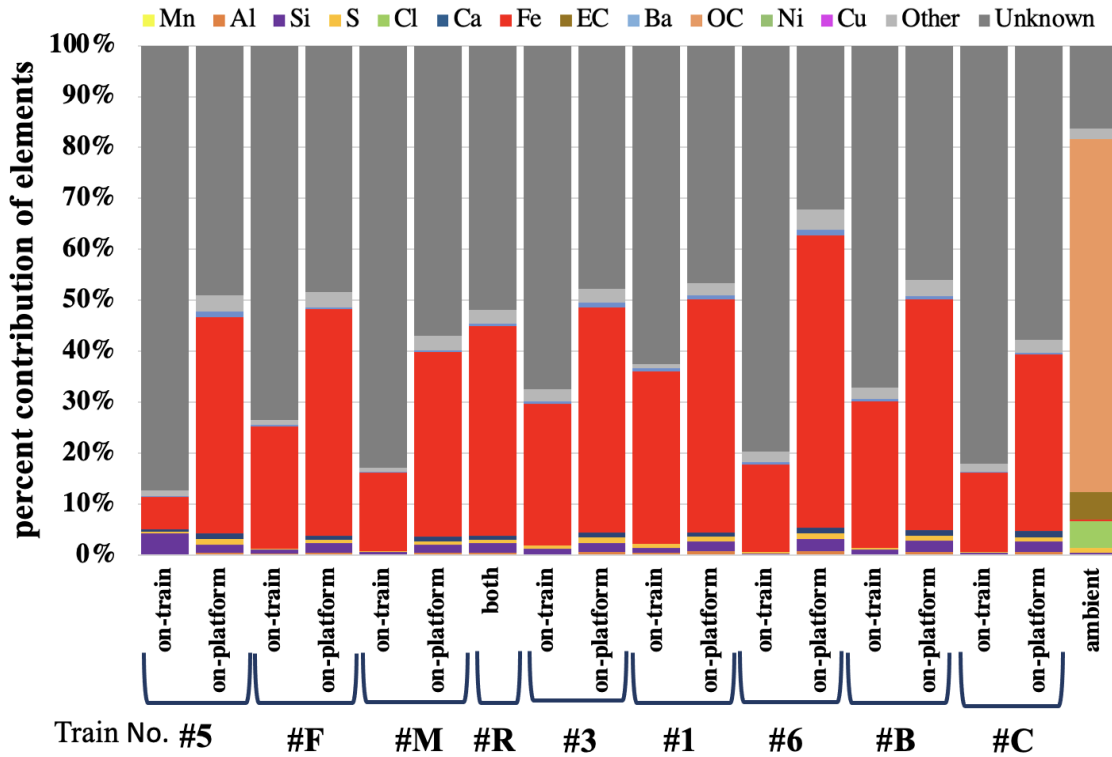
Figure 5: Percent contribution of elemental constituents to total mass of PM2.5 collected on filters in on-train, on-platform, and outdoor samples

Discussion

Concerning determinants for on-train PM2.5 concentration, past studies have found that particles rush into the train cabin from the platform when the door opens, making the on-train concentration rise [59]. 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 rest 25% of is pulled from outside [60]. 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 gets entirely replaced by outside subway air every three minutes and twenty seconds. Specifically, subway cars use MERV-7 category filters to filter out the particles [60]. Experiments identifying PM2.5 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% [61], [62]. Therefore, the filtrated air that is dispensed into the cabin is likely to still possess a significant concentration of particles.

Focusing on an example of real-time measurements provides insights into how the concentration changes in the subway train car while traveling through a tunnel. Figure 6 shows the on-train concentration of the #M train when it moves from the Delancey Street-Essex Street station to the Broadway-Lafayette Street station. The average on-platform PM2.5 concentration of Essex St station is 152 ± 45 μg/m3, whereas Broadway-Lafayette Street has a concentration of 332 ± 27 μg/m3. During the end-to-end on-train sampling, the train idled in the Delancey St station for approximately 70 seconds. During that period, the on-train concentration measurement increased from 70 μg/m3 to 97 μg/m3. This increase is likely the result of gradual particle-laden air transport from the platform into the train through its open doors. The onboard concentration continued to rise at the same rate after the train left the station until it reached point A (figure 6), where the train started an approximately 45-degree turn along its track. From this point, the on-train concentration started to rise at a higher rate and continued to rise until it reached Broadway-Lafayette Street station. This increase of on-board concentration can possibly be explained by the infiltration of high PM2.5 concentration air from the tunnels into the car.

The observation of an increase in onboard particle concentration when the train traveled through the tunnels is indicative of the limitations of the car filtration system. As the train ventilation system pulls in the tunnel air, the filters poorly capture the particles or are entirely bypassed. Improving the quality of in-car filters may further mitigate this issue.
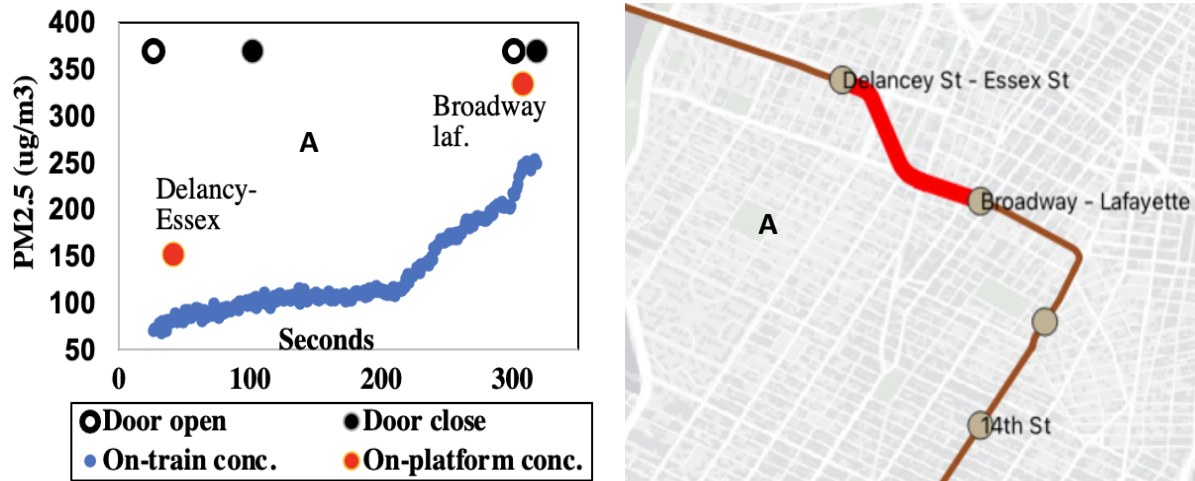
Figure 6: (Left) Blue dots represents the on-train PM$_{2.5}$ concentration of #M train when it moves from Delancey street (Essex Street) to Broadway-Lafayette Street station

Red dots show the on-platform concentration and with black dots indicates when door opened and closed in those stations during sampling

Possible strategies to reduce PM2.5 concentrations on subway platforms include the installment of platform screen doors (PSD), filtration devices, proper ventilation, and increased tunnel cleaning, as demonstrated in other studies [63]. Since the particles are likely to be mostly generated by the friction of 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 [64]. 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 PM2.5 concentrations [65]. Again, when a train approaches the station, piston wind is generated, which pushes air and particles from the tunnels to the platform [59]. This piston wind is considered the main driver/cause of high of PM concentrations on platforms [66]. Separating rail tracks from the platform with glass barriers such as PSD could be an effective measure for controlling particle concentration of the platforms, since they can block the tunnel wind from entering the platforms [67]–[71]. Even though PSD can reduce on-platforms pollution, a study suggested that it may increase on-train particle concentrations [72]. To mitigate this potential effect, the concentration inside the train cabin can be reduced with filters or subway cabin purifiers, as discussed above [70].

Conclusions

- Among the sampled platforms, the 275 underground station platforms had an average PM2.5 concentration of 216 ± 82 μg/m3; while the 66 above-ground platforms had an average concentration of 29 ± 27 μg/m3. Therefore, PM2.5 in underground stations were found to be roughly 7.5 times higher than on 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, where PM2.5 ranged between 300 μg/m3 and 450 μg/m3. 181st street station in uptown Manhattan was found to be the highest polluted station in the city, with an average PM2.5 concentration of 566 ± 46 μg/m3.

- On-train real-time PM2.5 concentrations were the highest when the train was operating underground. We observed that the PM2.5 concentration on the train gradually rises as the train sits at a platform. This is likely due to the transport of the particles from the platform onto the train through the train's open doors. In addition, while operating through the tunnels, the train's ventilation systems draw the tunnel air and dispenses it into the cabin. During this process, tunnel particles bypass or fail to be captured by the system's filters and mix with the cabin air.

- Elemental composition analysis found that iron constitutes about 43% of total PM2.5 mass. Inside train cars, iron constitutes 21% of PM2.5 mass. This contribution of iron in subway particles is much higher than that of in ambient air, where iron contributes only 0.34% of PM2.5. Other trace elements measured in the NYC subway system include silicon (2%), copper (<1%), nickel (<1%), aluminum (<1%), calcium (1%), barium (<1.2%), Manganese (<1%) and chromium (<0.3%).

- Short-term PM2.5 concentrations in New York's underground stations were found to be roughly six times higher than the U.S. EPA's 24-h average ambient air standard of 35μg/m3 for outdoor air. But the PM2.5 composition of these particles were found to differ greatly from ambient outdoor particles, and riders do not spend 24 hours per day in the subways. Therefore, the health implications of these particle exposures may differ greatly from the typical outdoor combustion particle exposures regulated by the EPA. The potential health effects of such elevated exposures need direct investigation.

- **Outputs**
- This study resulted in a data product containing the spatial distribution of particulate matter on all platforms and on-board trains on all subway lines in the NYC subway

system. The 1 second temporal cadence of data collection and the spatial coverage of the PM2.5 concentrations and composition resulted in information at a scale that has not been done before. A data Visualization dashboard has been developed, and the manuscript outlining the finding is nearly complete.

- **Impacts**
- The resulting data products of this study can serve as a tool for agencies and owners to prioritize systems upgrades and capital improvements. These may include isolation of selected subway stations from rails (as has been done in many stations of the London Underground), or upgrade to the subway car ventilation system, where the prioritization for these interventions will be based on level of exposure determined through the study results statistics.
- **Outcomes**
- One proposal is out for review. Manuscript has not been published, so the number of views and citations is not available. We are currently preparing to engage with interested stakeholders.

Appendix

Line#1: Among all nine lines, the #1 line has the most polluted stations, where the average on-platform concentration of its 37 stations (30 underground and 7 aboveground stations) was 226 ± 129 µg/m^3. The average concentrations of the platforms of underground (South Ferry to 191 Street station) and aboveground stations (Dyckman Street to 242 Street station) were 268 ± 106 µg/m^3 and 46 ± 12 µg/m^3, respectively. With this train, end-to-end travel takes around one hour, where riders are exposed to on average 140 ± 76 µg/m^3 PM$_{2.5}$ onboard. The concentration varies quite significantly inside train car throughout the travel, as well as in the platforms. #1 train's platform of 181st street station in uptown Manhattan was found to be the most polluted station in the NYC subway system, with an average concentration of 566 ± 46 µg/m^3. The next station, 168th street station, was the second polluted station the concentration of 543 ± 41 µg/m^3. During crossing these stations, the onboard PM$_{2.5}$ concentration also reaches its highest level of 443 µg/m^3 (average= 335 ± 34 µg/m^3).
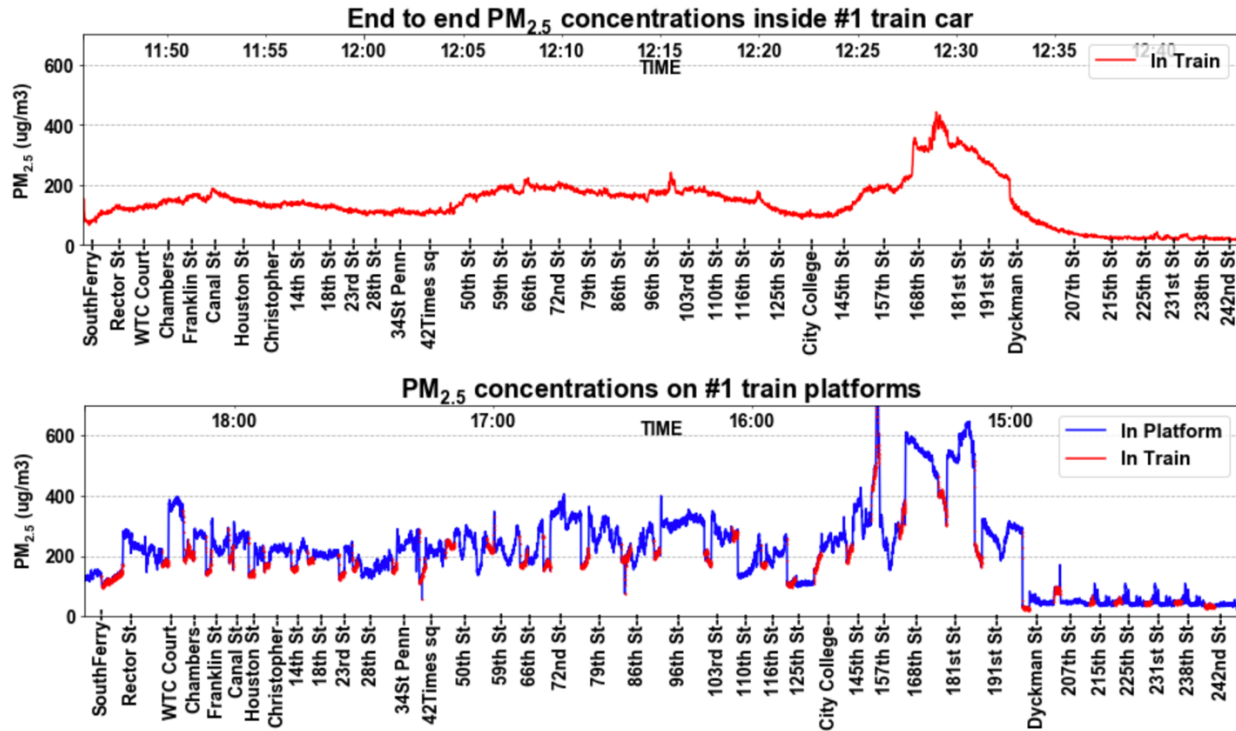
Figure 7: (top) PM2.5 concentration inside train car for the end-to-end trip of a #1 train

Measurements started from South Ferry station at 11:45 AM. (bottom) PM2.5 concentration on the platforms (blue color) of the #1 train. The red color in the plot represents the on-train samples while traveling between stations. Sampling started from 242nd Street station at 2:00 PM

Line #3: We started on-train measurements during the morning rush from New Lots Avenue, and from noon we started on-platform measurements from 148th Station. The onboard concentration of the express subway line #3 is also relatively high, with an average of 173±69 $\mu g/m^3$. The onboard concentration inside the train peaks when it approaches stations, such as Borough Hall (245±21 $\mu g/m^3$), Wall Street (240±20 $\mu g/m^3$), 96th street (232±24 $\mu g/m^3$), Hoyt Street (228±7 $\mu g/m^3$). Looking at the on-platform concentrations, Borough Hall was found to be the most polluted station of this line, where the average concentration was 407±33 $\mu g/m^3$, followed by 72nd street (343±22 $\mu g/m^3$), Hoyt Street (341±11 $\mu g/m^3$), 96th Street (324±15 $\mu g/m^3$), and Wall Street (308±12 $\mu g/m^3$). The average concentration on the platforms of underground stations of line #3 was (239±68 $\mu g/m^3$). Surprisingly, both the on-board and on-platform concentrations were high for aboveground stations, between New Lots Avenue and Sutter Ave-Rutland Road. This may cause by the heavy on-road construction works below the stations that took place during the time of sampling.
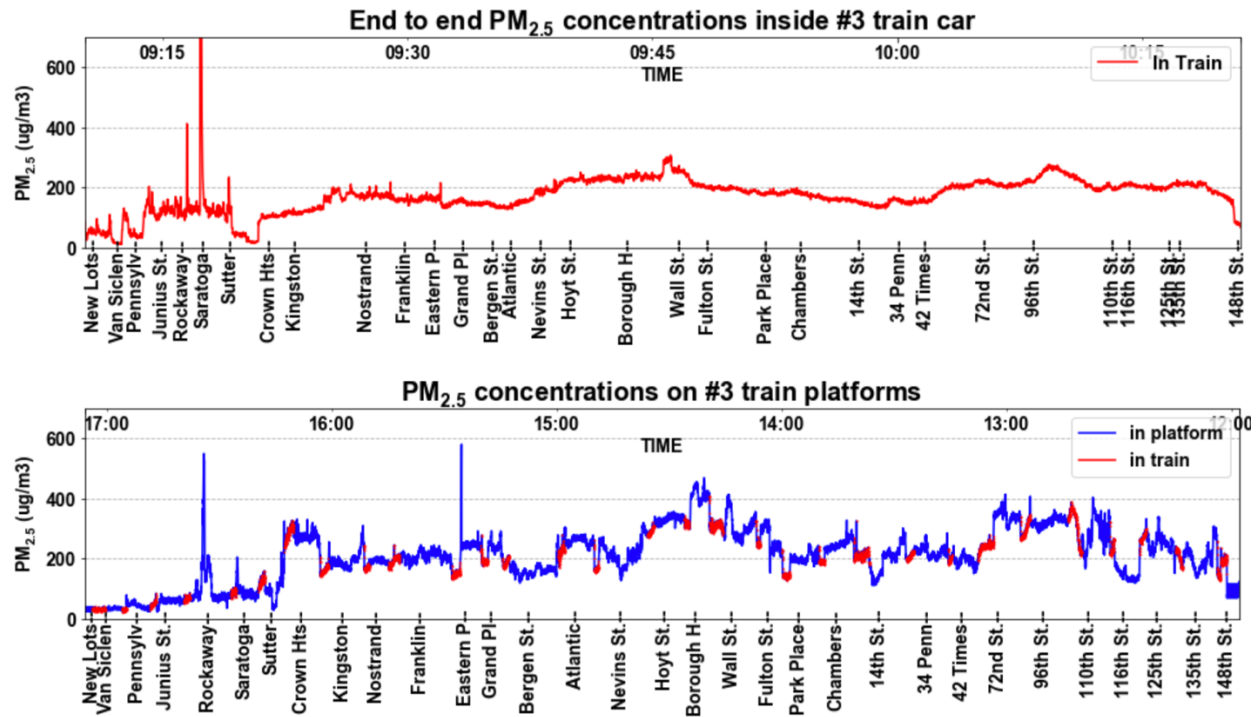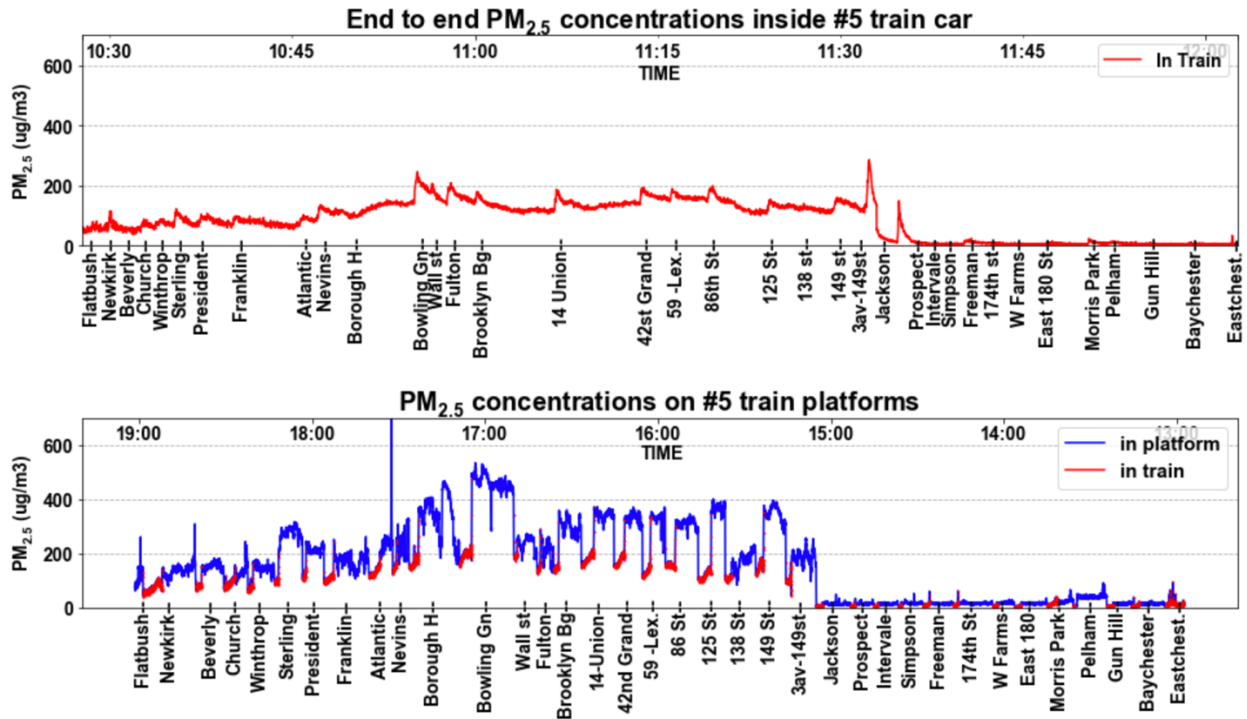
Figure 8: (top) PM2.5 concentration inside train car for the end-to-end trip of a #3 train

Measurements started from New Lots Avenue station at 9:10 AM. (bottom) PM2.5 concentration on the platforms (blue color) of the #3 train. The red color in the plot represents the on-train samples while traveling between stations. Sampling started from 148th Street station at 12:00 PM.

Line #5: the on-train and on-platform measurements were initiated from Flatbush and Eastchester Dyre Avenue, respectively. This line has a total of thirty-six stations, thirteen of which are elevated stations (from Jackson Avenue to Eastchester Dyre Avenue station), and the rest twenty-three are underground stations (from Flatbush Avenue to 3 Av-149 Street station). The average PM$_{2.5}$ concentration for the elevated stations is 16 ± 9 µg/m^3, but for the underground stations, the average is 257 ± 105 µg/m^3. Among the stations, the Bowling Green was found to be most polluted, with an average concentration of 460 ± 30 µg/m^3. Other polluted stations include 125th Street (364 ± 20 µg/m^3) and 149th Street (347 ± 30 µg/m^3). For a Bronx-bound #5 train, the onboard concentration starts to elevate after it crosses Atlantic Avenue station, and it remains high until the train reaches the aboveground stations in Bronx. The average onboard concentration for an end-to-end trip is 85 ± 60 µg/m^3. However, during rush hours, the train usually remains at capacity throughout its entire path in Manhattan, where the average onboard concentration is 146 ± 25 µg/m^3.

Figure 9: (top) PM$_{2.5}$ concentration inside train car for the end-to-end trip of a #5 train

Measurements started from Flatbush Avenue station at 10:30 AM. (bottom) PM2.5 concentration on the platforms (blue color) of the #5 train. The red color in the plot represents the on-train samples while traveling between stations. Sampling started from Eastchester – Dyre Avenue at 1:00 PM.

Line #6: Samples were collected in two days, where both on-train and on-platform measurements show the concentration during morning rush hours. Measurements were initiated from Brooklyn Bridge City Hall station. This line has ten aboveground stations (from Whitlock Avenue station to Pelham Bay Park), with an average concentration of 8.5±7 $\mu g/m^3$. Compared to the aboveground stations, this line's twenty-seven underground stations, from Brooklyn Bridge City Hall in Lower Manhattan and Hunts Point in Bronx, has significantly high concentration averaging 262 ± 69 $\mu g/m^3$. The highest concentration was found in Bleecker Street station (386 ± 17 $\mu g/m^3$), followed by Canal Street (355 ± 26 $\mu g/m^3$), Astor Place (326 ± 16 $\mu g/m^3$). Onboard concentration during train running underground is (162 ± 36 $\mu g/m^3$), and aboveground is (7.5 ± 6 $\mu g/m^3$).
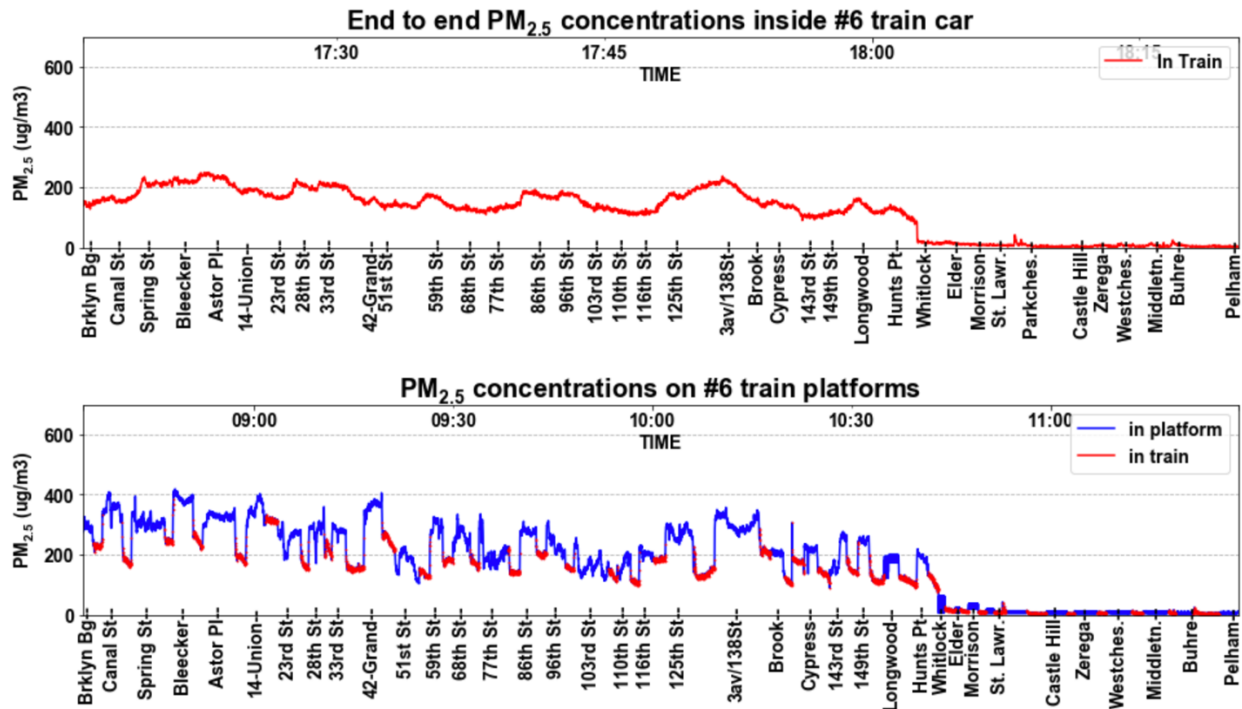
**Figure 10: For #6 train, samples were collected in two days, where both on-train and on-platform measurements show the concentration during morning rush hours**

(top) the On-train PM$_{2.5}$ concentration for end-to-end trip of #6 train. Measurements were initiated from Brooklyn Bridge City Hall station. (bottom) PM2.5 concentration on the platforms (blue color) of the #6 train. Sampling was done on the following day from Brooklyn Bridge Station at 8:30 AM.

Line #B operates between Brighton Beach in Brooklyn (starting point for on-train samples) and Bedford Park Boulevard in Bronx (starting point for on-station samples). This line has five aboveground stations, from Brighton Beach to Church Avenue. Similar to other lines, the average on-train concentration of PM$_{2.5}$ is 131 ± 80 µg/m^3, and 159 ± 65 µg/m^3 when the train runs underground. However, extraordinary spikes in onboard concentration (300 ± 46 µg/m^3) were found when the train passed the tunnel between W4 Street Washington Square and 42nd Street–Bryant Park stations. Looking at the on-platform measurements, we find the concentration on the #B train platforms are considerably lower than its counterparts, averaging 166 ± 89 µg/m^3 (only underground stations = 184 ± 87 µg/m^3). The highest concentration was found in Broadway–Lafayette station (440 ± 58 µg/m^3), followed by 34th Street–Herald Square (382 ± 23 µg/m^3), 42nd Street–Bryant Park (293 ± 19 µg/m^3), 7th Avenue 53rd Street (290 ± 12 µg/m^3).
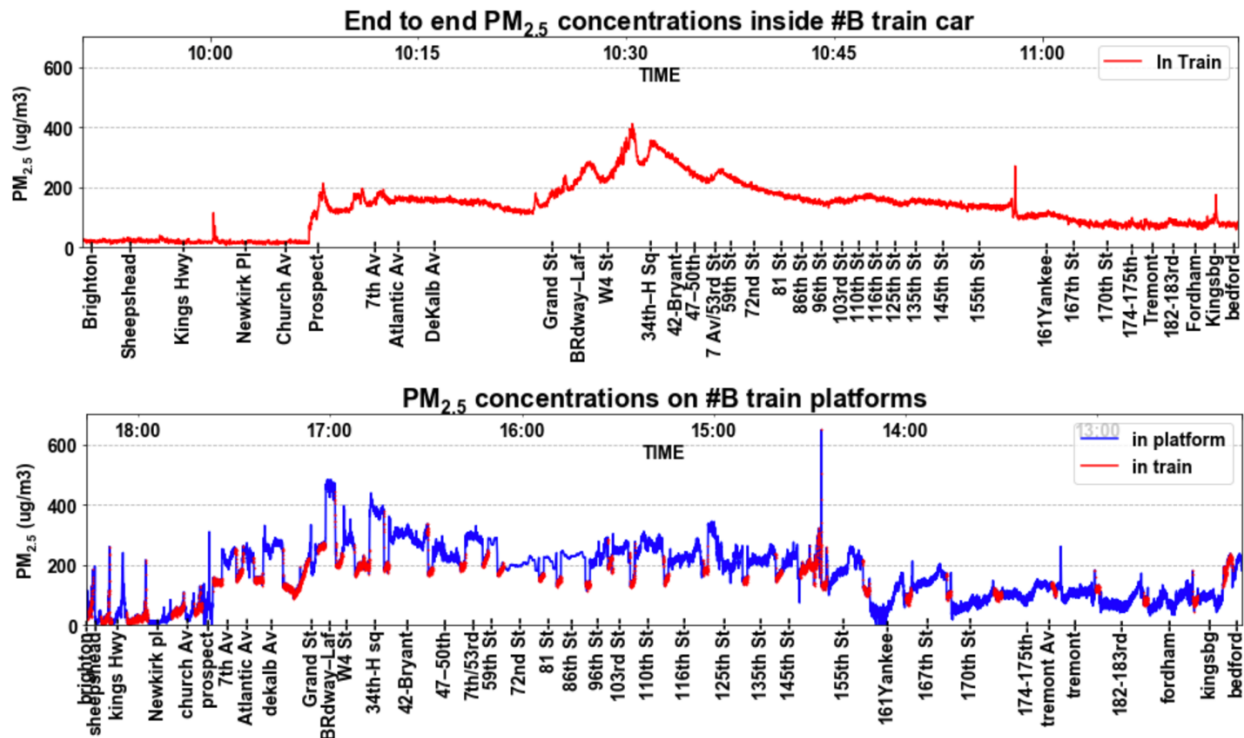
Figure 11: (top) PM2.5 concentration inside train car for the end-to-end trip of a #B train

Measurements started from Brighton Beach in Brooklyn at 9:45 AM. (bottom) PM2.5 concentration on the platforms (blue color) of the #B train. The red color in the plot represents the on-train samples while traveling between stations. Sampling started from Bedford Park Boulevard in Bronx at 1:00 PM.

Line #C runs fully underground from Euclid Avenue in Brooklyn to 168th Street in upper Manhattan. Measurements for this line are done in two days. On the first day, onboard concentration was measured during the evening rush starting from Euclid Avenue. On the following day, starting at noon, on-platform measurement was conducted from 168th Street station. During the entire run from the first station to the last, we observed a consistently high concentration of $PM_{2.5}$ inside the train car, averaging (131 ± 40 μg/m³). The highest concentration inside the train was found when the train moved through the tunnels between Jay Street MetroTech and Fulton Street. During this period, the average onboard concentration was 198 ± 45 μg/m³. The average on-platform concentration of PM2.5 of the #C line is similar to what we found earlier on the #B line. Averaging all stations, the on-platform measurement was found to be (194 ± 70 μg/m³). Top five stations of #B line with highest $PM_{2.5}$ concentrations are: High Street (410 ± 103 μg/m³), High Street (410 ± 103 μg/m³), Lafayette Avenue (410 ± 103

µg/m^3), Fulton Street (355 ± 102 µg/m^3), 59th Street (290 ± 16 µg/m^3), and Jay Street MetroTech (285 ± 45 µg/m^3).
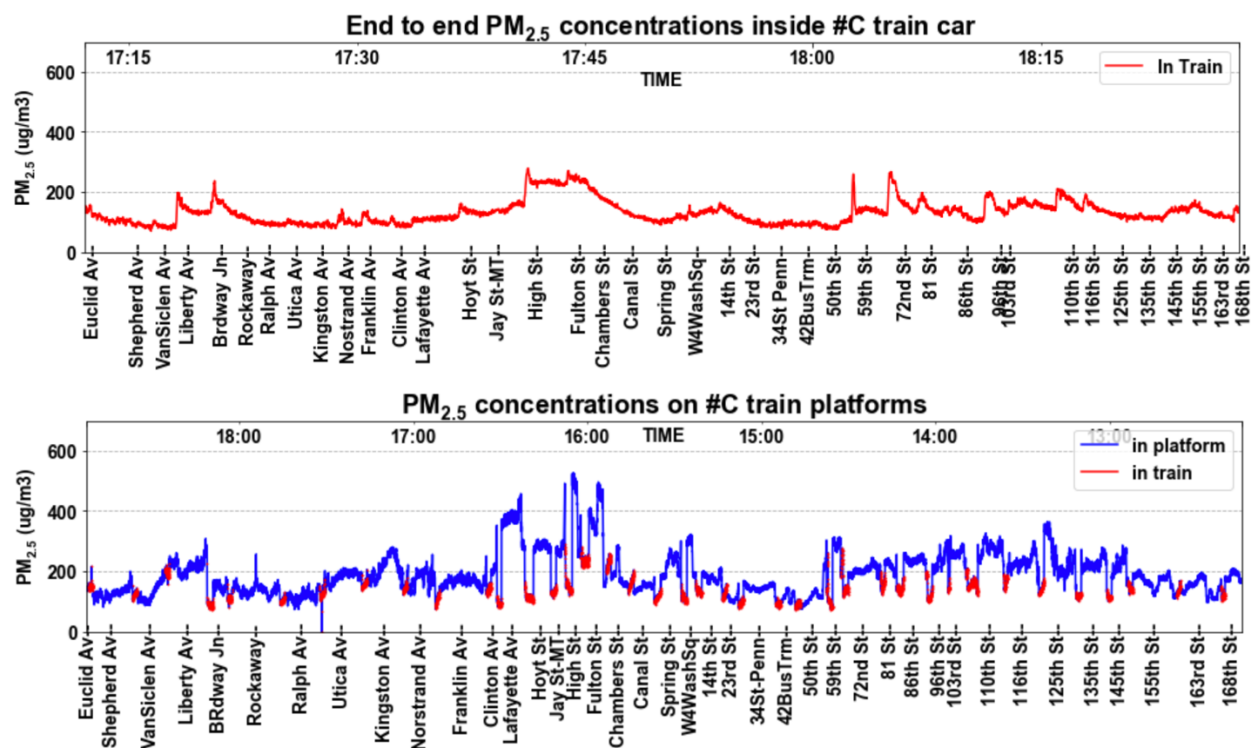
Figure 12: Measurements for #C line done in two days

On the first day, onboard concentration was measured during the evening rush starting from Euclid Avenue. On the following day, starting at noon, on-platform measurement was conducted from 168th Street station. (top) shows the on-train and (bottom) shows the on-platform measurements

Line #F: we started the on-train measurements from Coney Island in Brooklyn from 10:00 am and on-platform samples from 169th Street station in Queens from around 1:30 pm of the same day. There are 15 aboveground stations and 30 underground stations on this line. One complete run from start to end station takes around 110 minutes, where passengers are exposed to an average of 110 ± 68 µg/m^3 PM$_{2.5}$ inside train cars. Onboard concentration is much higher when the train moves underground through Manhattan. During this period, the train usually remains overcrowded; the average concentration onboard remains high (194 ± 35 µg/m^3). Again, we have observed substantial variation in concentration for different stations regarding on-platform measurement. Like other lines, the aboveground stations of #F have low PM$_{2.5}$ with an average of   22 ± 8 µg/m^3. However, the average for underground stations is 221 ±

77 μg/m³. Among all stations of #F train, the platform of the 2nd Avenue station provided the highest concentration value of 377 ± 29 μg/m³. Several stations also showed high concentrations, such as, East Broadway (358 ± 53) μg/m³, York Street (355 ± 36) μg/m³, W4 Street-Washington Square (307 ± 47) μg/m³.
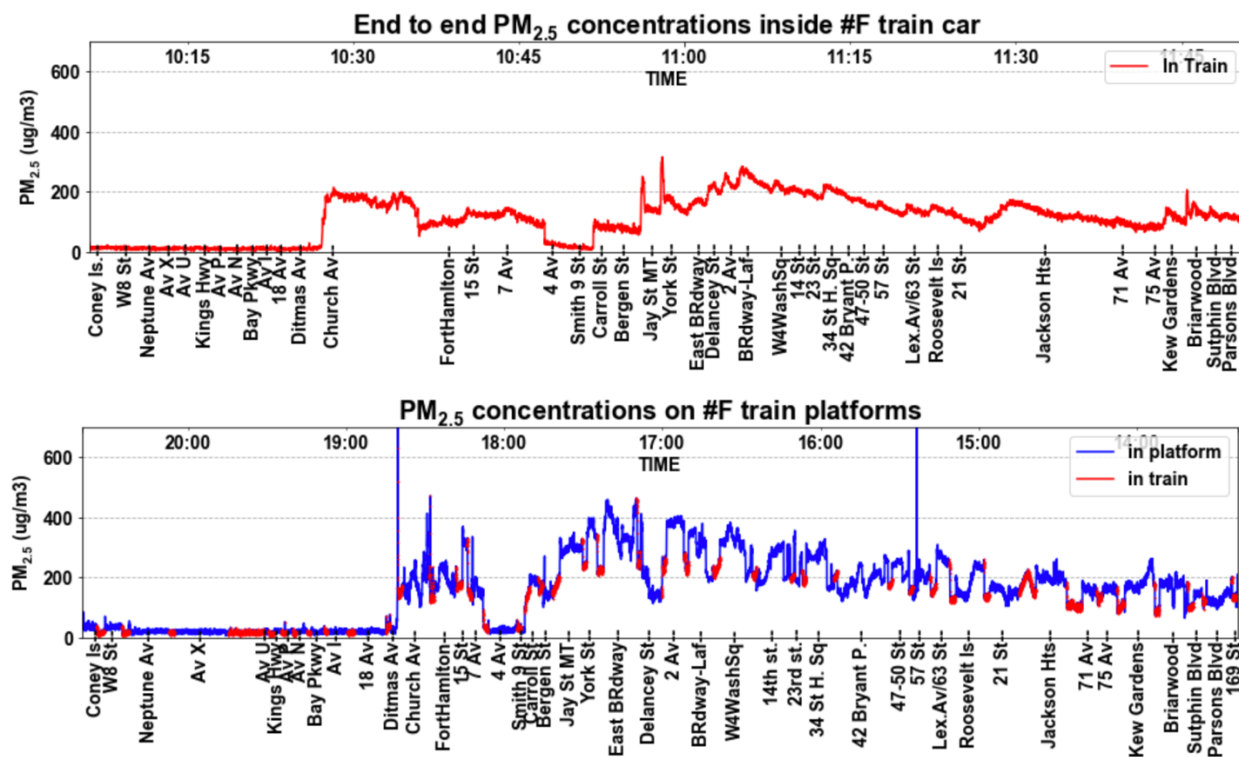
Figure 13: (top) PM₂.₅ concentration inside train car for the end-to-end trip of a #F train

Measurements started from Coney Island in Brooklyn at 10:00 AM. (bottom) PM₂.₅ concentration on the platforms (blue color) of the #F train. The red color in the plot represents the on-train samples while traveling between stations. Sampling started from 169th Street station in Queens at 1:30 PM.

Line #R: we sampled both the on-train (starting from Bay Ridge 95th Street) and the on-station (from Forest Hills) measurements on a single day. #R line operates completely underground, and we observed a constant level of PM₂.₅ concentration for on-train measurements. The average concentration inside the train car was 115 ± 30 μg/m³. On the contrary, the average concentration on #R train station platforms was found to be 183 ± 56 μg/m³. In Whitehall Street station, the highest concentration was observed (264 ± 48 μg/m³).
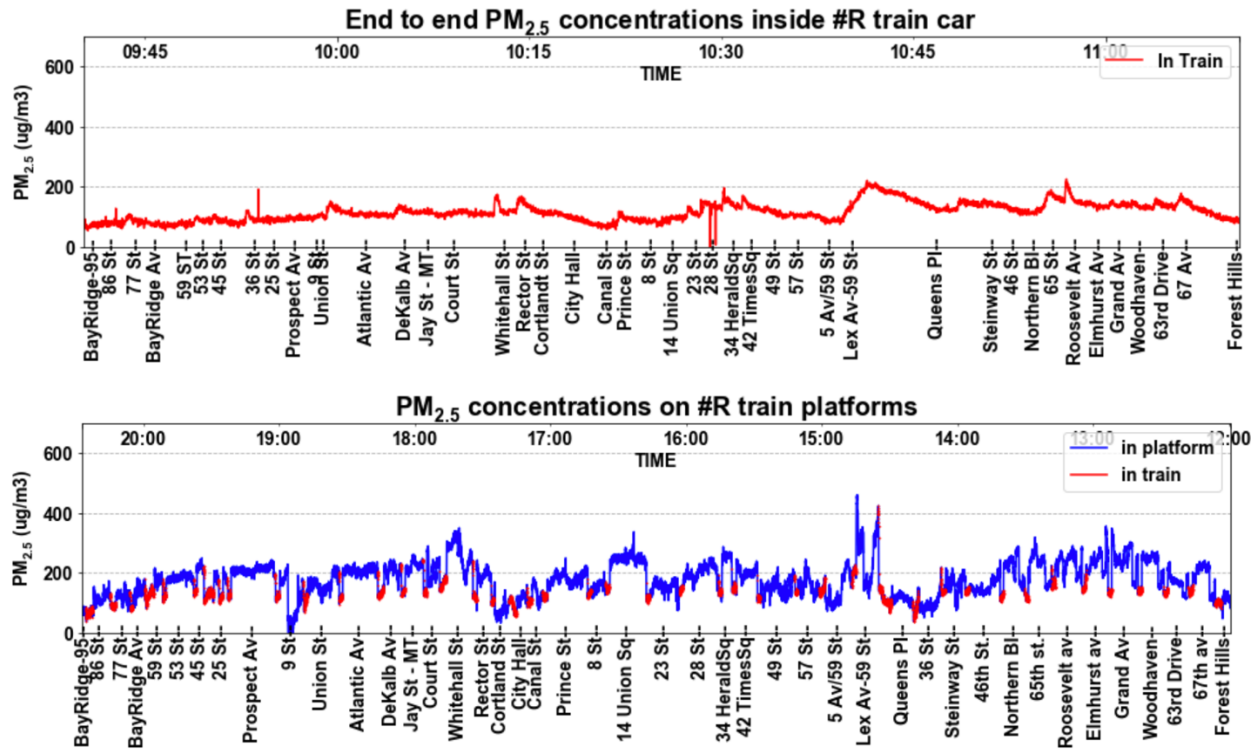
Figure 14: (top) PM$_{2.5}$ concentration inside train car for the end-to-end trip of a #R train

Measurements started from Bay Ridge 95th Street in Brooklyn at 9:40 AM. (bottom) PM2.5 concentration on the platforms (blue color) of the #R train. The red color in the plot represents the on-train samples while traveling between stations. Sampling started from Forest Hills Street station in Queens at 1:30 PM.

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