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Black Carbon and Particulate Matter ($PM_{2.5}$) Concentrations in New York City's Subway Stations

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Supporting Information

ABSTRACT: The New York City (NYC) subway is the main mode of transport for over 5 million passengers on an average weekday. Therefore, airborne pollutants in the subway stations could have a significant impact on commuters and subway workers. This study looked at black carbon (BC) and particulate matter ($PM_{2.5}$) concentrations in selected subway stations in Manhattan. BC and $PM_{2.5}$ levels were measured in real time using a Micro-Aethalometer and a PDR-1500 DataRAM, respectively. Simultaneous samples were also collected on quartz filters for organic and elemental carbon (OC/EC) analysis and on Teflon filters for gravimetric and trace element analysis. In the underground subway stations, mean real time BC concentrations ranged from 5 to 23 $\mu g/m^3$, with 1 min average peaks >100 $\mu g/m^3$, while real time $PM_{2.5}$ levels ranged from 35 to 200 $\mu g/m^3$. Mean EC levels ranged from 9 to 12.5 $\mu g/m^3$. At street level on the same days, the mean BC and $PM_{2.5}$ concentrations were below 3 and 10 $\mu g/m^3$, respectively. This study shows that both BC soot and PM levels in NYC's subways are considerably higher than ambient urban street levels and that further monitoring and investigation of BC and PM subway exposures are warranted.

INTRODUCTION

Transportation in NYC mainly comprises private vehicles, taxis, and a large network of public transportation that includes aboveground trains, the subway system, and buses. Of these, the NYC subway is a preferred mode of transport for many commuters. On an average weekday, over 5 million commuters use the subway for transportation.[1] Therefore, the air quality conditions in the subway stations may have a significant impact on a large population of commuters as well as subway workers.

Over the years, many studies in cities that have subways have found that air pollutant concentrations in subways are several times higher than aboveground levels.[2−4] $PM_{2.5}$ concentrations in the London and Stockholm subway systems were approximately 10 times higher than aboveground.[2,5] Health effects of ambient fine particulate matter ($PM_{2.5}$) have been studied in detail, and epidemiological studies have established that $PM_{2.5}$ pollution is a major risk to human health.[6,7] One of the earliest of such studies, the Harvard Six Cities Study, showed that long-term exposure to particulate matter air pollution resulted in an adjusted mortality rate ratio of 1.26 per range of 11.0 to 29.6 $\mu g/m^3$ (95% confidence interval, 1.08−1.47) with fine particulate matter.[8] Short-term exposure to increasing levels of $PM_{2.5}$ is also associated with acute effects that lead to respiratory and cardiovascular problems, thereby causing increased hospitalization as seen in recent studies.[9,10]

Since 2004, NYC subway studies have shown levels of PM2.5, iron, manganese and chromium to be several times higher than aboveground levels.[11−13] These studies showed that steel dust is the primary source of iron, manganese, and chromium exposure in teenage students and workers who participated in the studies. These PM levels and composition in the NYC subway system can be partially explained by the fact that, during operation, friction results in the release of particles from the metal-to-metal contact between the car wheels and the rail.

It is important to note, however, that other factors can affect air quality in the subway system, such as the exchange of air between the road level and subway, as well as the use of a variety of operational equipment in the subway system. Upon preliminary investigation, we determined that the NYC subway system uses diesel-powered locomotives/cars for maintenance work at night. The use of diesel engines can inevitably lead to the release of diesel soot, including BC, but the levels of BC in the subways have not been previously examined.

The main goal of this study was to monitor the exposure levels of BC and $PM_{2.5}$ in the subway system in NYC, with a focus on Manhattan, the most populous area, and assess if these levels are in the range that may cause adverse health concern. Specific objectives of the study included: (1) measuring levels of BC in selected subway stations along subway lines in Manhattan; (2) simultaneously measuring levels of $PM_{2.5}$ in the

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Table 1. Mean and Standard Deviation Concentrations of $BC_{2.5}$ at All Stations Sampled[a]

line	station/platform	$BC_{2.5}$ mean ± SD ($\mu g/m^3$)	$PM_{2.5}$ mean ± SD ($\mu g/m^3$)	line	station/ platform	$BC_{2.5}$ mean ± SD ($\mu g/m^3$)	$PM_{2.5}$ mean ± SD ($\mu g/m^3$)
E	West 4th st Up	15.0 ± 6.0 (5)	100.1 ± 41.0 (3)	NQR	8th st	7.5 ± 5.4 (2)[12.5 ± 8.5]	NA
	14th st	13.7 ± 8.0 (4)	74.1 ± 35.2 (3)		14th st	14.3 ± 2.3 (2)	NA
	23rd st	5.7 ± 1.7 (4)	35.1 ± 8.5 (3)		23rd st	9.0 ± 3.8 (2)	44.9 ± 9.2 (1)
	34th st	6.3 ± 2.7 (4)	40.8 ± 21.7 (3)		28th st	12.1 ± 2.0 (2)	NA
	42nd st	9.0 ± 3.0 (4)	57.8 ± 21.4 (3)		34th st	17.9 ± 5.3 (2)[82.7 ± 28.8]	71.3 ± 33.2 (1)
	50th st	8.3 ± 4.3 (4)	48.1 ± 21.2 (4)		42nd st	23.5 ± 7.7 (2)	NA
	53rd st	14.1 ± 4.5 (2)	69.1 ± 13.7 (2)		49th st	11.3 ± 5.0 (2)	NA
F	West 4th st Low	21.2 ± 6.6 (4)	156.7 ± 47.8 (3)	6	Astor Place	20.5 ± 3.9 (4)	118.0 ± 27.5 (3)
	14th st	22.7 ± 13.2 (3)	200.4 ± 91.6 (3)		14th st	14.8 ± 4.3 (4)	92.0 ± 24.1 (1)
	23rd st	12.1 ± 4.4 (3)	109.8 ± 35.7 (3)		23rd st	14.7 ± 5.0 (4)	98.7 ± 31.5 (1)
	34th st	18.0 ± 3.8 (3)	147.2 ± 40.7 (3)		28th st	15.2 ± 3.2 (3)	101.8 ± 12.8 (1)
	42nd st	13.8 ± 3.6 (3)	116.2 ± 26.5 (3)		33rd st	12.3 ± 5.8 (4)	109.0 ± 30.7 (1)
	47/50th st	9.2 ± 2.6 (3)	64.7 ± 16.5 (3)		42nd st	16.4 ± 2.3 (4)	126.9 ± 15.8 (1)
	57th st	11.7 ± 1.8 (3)	78.2 ± 35.0 (3)		51st st	10.3 ± 4.5 (4)	63.3 ± 35.0 (1)
7	Jackson H (U)	13.6 ± 3.0 (1)	91.3 ± 15.1 (1)				
	Jackson H (A)	1.7 ± 1.3 (1)	14.1 ± 3.4 (1)				
	61st st (A)	3.0 ± 3.0 (1)	9.5 ± 2.6 (1)				
	46th (A)	2.9 ± 2.2 (1)	13.8 ± 4.7 (1)				
	Queens Plz (A)	3.5 ± 2.6 (1)	11.2 ± 3.4 (1)				
	Hunters (U)	9.3 ± 2.4 (1)	69.9 ± 19.4 (1)				
	Vernon B (U)	15.4 ± 6.8 (1)	132.4 ± 13.1 (1)				

[a] **A single measurement at a station was the average of 5−10 min of sampling. In some stations there were multiple measurements. The numbers in parentheses next to the concentrations is the number of times sampling was done**. The mean concentration of the station is the average of these means. Only data from the group sampling runs and individual sampling of the line were used to calculate the mean and SD of each station. Note: Concentrations given in [box] parentheses for 8th st and 34th st (NQR line) are the mean ± SD when a diesel maintenance train passed. They were considerably higher than the mean levels recorded during other sampling days. (A) Aboveground stations. (U) Underground stations.

same subway stations and comparing them with BC levels; (3) comparing BC and $PM_{2.5}$ exposure levels in the underground subways with above ground road exposure levels; and (4) studying the spatial and temporal variations in BC and $PM_{2.5}$ in the subway system.

■ MATERIALS AND METHODS

This research was an exposure assessment study in which concentrations of BC ($BC_{2.5}$ μm size fraction) and $PM_{2.5}$ were simultaneously measured using personal air samplers, during the period of January 2013 to March 2014, in selected subway stations along 5 subway lines in NYC. This personal monitoring was performed to sample airborne concentrations that workers and commuters may experience during work or daily commutes in the NYC subway system.

Monitoring Methods. BC and $PM_{2.5}$ concentrations were measured using both real time personal air sampling instruments and standard filter-based methods. The equipment were carried in a backpack, and switched on before each sampling run.

BC concentrations were measured in real time using a Micro-Aetholameter (Magee Scientific/Aeth Laboratories, San Francisco, CA) and $PM_{2.5}$ concentrations were measured using a nephlometric-based real time DataRAM (DataRAM PDR 1500, Thermo Scientific, Franklin, MA). Both real time machines were set to log data at 1 min intervals giving continuous 1 min average readings as the output. A 2.5 μm cut point cyclone was used with the Micro-Aethalometer and PDR 1500 DataRAM for the measurement of 2.5 μm diameter and below size component of BC and PM respectively. All real time reading instruments had been factory calibrated prior to use in the study. The PDR 1500 DataRAMs were autozeroed with filtered air and compared for interinstrument variability prior to each sampling run

Filter-based methods were also used to sample for particulate matter at some stations for comparison with the real time data. A 2.5 μm cut Personal Environmental Monitor (PEM) (SKC, Shoreview, MN) was used to collect particulate matter samples on prebaked 37 mm quartz filters at 4 or 10 L/min. The mass concentration of elemental carbon (EC) was measured from these filters using the Lab OCEC Aerosol Analyzer following the NIOSH (2003) method 5040 (Sunset Instruments Inc., Hillsborough, NC). $PM_{2.5}$ samples were also collected on 37 mm Teflon (Pall, Ann Arbor, MI) filters with a 2.5 μm cut Personal Environmental Monitor. From the Teflon filters, $PM_{2.5}$ mass concentrations were measured using standard gravimetric analysis in the NYU Sterling Forest laboratory temperature- and humidity-controlled weighing room.

Sampling Protocol. A total of 35 subway platforms in 30 subway stations located along 4 subway lines in Manhattan and 1 subway line in Queens were selected for monitoring of BC and $PM_{2.5}$ levels. Individual as well as group sampling were carried out at selected subway stations and lines. For individual sampling, concentrations at selected single stations and stations along selected lines were monitored by one person at different times. A group sampling run was also carried out in three different subway lines by three individuals measuring concentrations simultaneously at each parallel street crossing. This was done to allow subway line comparisons that minimized variations in concentrations due to time and other spatial factors.

The West fourth Street subway station located in Downtown Manhattan was the primary station used for real time measurements of BC and $PM_{2.5}$. Concentrations were measured on both levels of the station. Real time BC and $PM_{2.5}$ concentrations were measured starting while walking above ground for approximately 5 min, followed by monitoring on the upper level and then the lower level of the West fourth Street station for 5−10 min each. The time of entering the station, the time spent at the upper level, and the time spent at the lower level were recorded.

Due to concerns for temporal variation in measurements, in a group study, BC and $PM_{2.5}$ concentrations were systematically recorded at stations along three different subway lines simultaneously (the parallel E, F, and 6 lines). After leaving from the same above ground starting place, three individuals traveled in the uptown direction of the subway and measured concentrations at six stations uptown from the starting point. Sampling was repeated at the same stations in the downtown direction.

Because the Number 7 subway line has stations situated at both aboveground and underground levels in the same line, it was selected for comparison of aboveground vs underground concentrations. The 7 line runs aboveground in Queens with underground stations located more toward Manhattan.

Data Analyses. Data were analyzed using the Minitab Version 16.2.4 statistical software package to test differences in PM and BC concentrations at the individual stations and stations along different subway lines. A Student's *t* test was used to analyze differences in levels while an analysis of variance (ANOVA) was used to analyze results from the group study.

RESULTS

Black Carbon Concentrations. *Real Time Measurements of $BC_{2.5}$.* Mean $BC_{2.5}$ (with a 2.5 μm cut size) concentrations ranged from 5−23 $\mu g/m^3$ (each individual reading being the mean of 5−10 min of sampling) under normal conditions at the stations sampled during the study period. However, 1 min average peaks as high as 111 $\mu g/m^3$ were recorded when a diesel powered maintenance train passed. The underground stations that had the lowest three mean $BC_{2.5}$ concentrations were 23rd st (E line), 34th st (E line), and 8th st (NQR line) with means ± SDs of 5.7 ± 1.7, 6.3 ± 2.7, and 7.5 ± 5.4 $\mu g/m^3$, respectively. The highest three mean concentrations were at 14th st (F line), West 4th st lower level (F line), and Astor Place (6 line) with concentrations of 22.7 ± 13.2, 21.2 ± 6.6, and 20.9 ± 3.9 $\mu g/m^3$, respectively.

BC concentrations of all stations sampled during the study period are given in Table 1. The averaging time of each reading was 5−10 min, depending on train arrivals.

Multi-Subway Line Group Sampling Study—Concentrations of $BC_{2.5}$ at Stations along Three Parallel Subway Lines and Comparison with Ambient Levels. The mean ± SD $BC_{2.5}$ concentrations of stations on the F, E, and 6 subway lines (average of means of all times sampled at the stations) were 16.8 ± 9.0, 10.2 ± 5.8, and 15.5 ± 4.3 $\mu g/m^3$, respectively. The mean concentrations at stations on the F and 6 subway lines were not significantly different from each other. Mean concentrations at each station along the three sampled lines are given in Table 2.

The outdoor roadside ambient mean ± SD $BC_{2.5}$ concentration measured just prior to the group sampling study was 2.3 ± 1.2 $\mu g/m^3$. Thus, the $BC_{2.5}$ concentrations at the stations along the F, E, and 6 underground subway lines were several times higher than the roadside ambient $BC_{2.5}$ concentrations (Figure 1).

Table 2. $BC_{2.5}$ Concentrations of Stations Located along Three Parallel Lines Sampled at the Same Time[a]

	mean $BC_{2.5}$ concentrations ($\mu g/m^3$)		
street level	F subway line	E subway line	6 subway line
W4th st/Astor	24.2[b]	17.7	15.1
14th st	28.4[b]	13.3	12.6
23rd st	14.3	6.4[b]	17.0
33rd/34th st	17.8[b]	8.2[b]	14.6[b]
42nd st	14.9	9.7[b]	17.4
50th/51st st	9.6[b]	4.4[b]	12.9[b]

[a]Each value reported is the average of two mean measurements where each measurement was a mean of 5−10 min of sampling. The first measurement was taken in the uptown direction, and the second was when the student reached the same station again in the downtown direction. [b]The station's concentration is significantly different from the concentrations of the other two stations located at the same cross street.

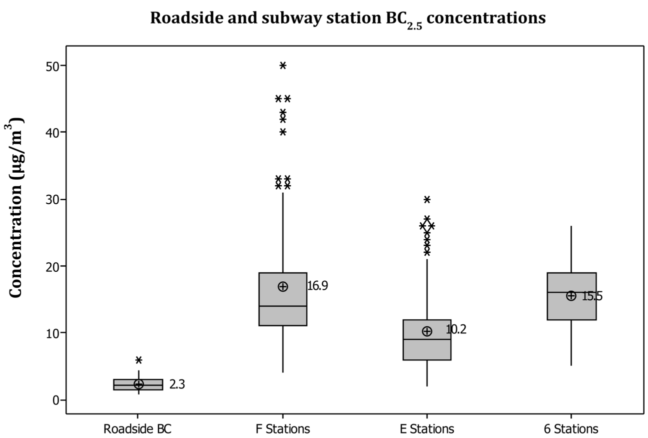

Figure 1. $BC_{2.5}$ concentrations at roadside and in the stations along the three parallel subway lines. The box shows the interquartile range, the line in the box shows the median, and the circle with number shows the mean. The whiskers represent the upper 25% and lower 25% (excluding outliers), while the * symbol represents outliers.

Variation in ConceNtration with Time—Special Observation. The time series graph (Figure 2) shows the variations in $BC_{2.5}$ concentrations at stations during an individual sampling run along the NQR subway line.

Concentrations on the roadside (outside the subway) were between 1−3 $\mu g/m^3$, but these increased rapidly inside the 8th st subway station. Although concentrations at the next two subway stations stayed below 20 $\mu g/m^3$ (1 min averages), the levels rapidly reached a peak of 111 $\mu g/m^3$ at the 34th st station. This peak occurred when a diesel-powered locomotive passed through the station. Concentrations at the next two stations fell to levels observed prior to the passing of the diesel-powered train.

Variations in $BC_{2.5}$ Concentrations at Different Levels of a Selected Station. The mean $BC_{2.5}$ concentrations on the platforms of the upper and lower level of the West 4th st subway station (6 paired samples; each level 8−10 min) were 14.0 ± 5.4 and 20.9 ± 3.8 $\mu g/m^3$, respectively, and were

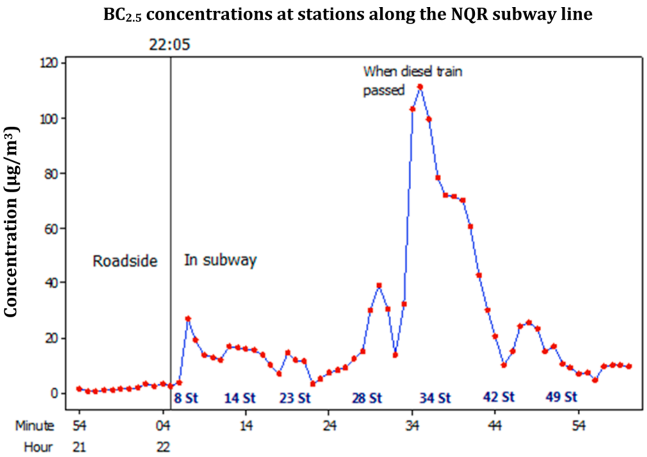

Figure 2. Graph showing change in 1 min average concentration of $BC_{2.5}$ when sampled starting from outside the subway system and then at six stations along the NQR subway line.

significantly different ($p < 0.05$; Figure S1, Supporting Information).

Filter Based Measurements of Elemental (EC) and Organic (OC) Carbon. Filter-based EC concentrations collected simultaneously with real time Aethalometer measurements for $BC_{2.5}$ were 11.5 and 12.5 $\mu g/m^3$ at the Astor Place subway station and 10.2 $\mu g/m^3$ at selected stations on the 6 subway line. For comparison, the mean real time-based $BC_{2.5}$ concentrations simultaneously measured were 18.3, 22.9, and 12.5 $\mu g/m^3$, respectively. The respective OC concentrations were 73.4, 80.3, and 75.6 $\mu g/m^3$ (Table 3).

Table 3. $BC_{2.5}$ vs Filter-Based Measurements of EC and OC Conducted during the Study Period (n = 3)

station/line	time of day	sampling time	mean $BC_{2.5}$ ($\mu g/m^3$)	EC ($\mu g/m^3$)	OC ($\mu g/m^3$)
Astor Place	late night	1 h	18.3	11.5	73.4
Astor Place	evening rush	25 min	22.9	12.5	80.3
6 line	after evening rush	2 h	12.5	10.2	75.6

$PM_{2.5}$ Concentrations. *Real Time Measurements of $PM_{2.5}$.* Similar to the $BC_{2.5}$ results, $PM_{2.5}$ concentrations were found to vary both spatially and temporally. Mean $PM_{2.5}$ concentrations in underground subway stations ranged from 35−200 $\mu g/m^3$ under routine conditions in the subway stations. Above ground stations had $PM_{2.5}$ values as low as 9.5 $\mu g/m^3$. Below ground stations had generally much higher concentrations. Indeed, the three underground stations that had the lowest mean $PM_{2.5}$ concentrations were 23rd st (E line), 34th st (E line), and 23rd st (NQR line) with means ± SDs of 35.1 ± 8.5, 40.8 ± 21.7, and 44.9 ± 9.2 $\mu g/m^3$, respectively. Note that two of these three stations also had the lowest $BC_{2.5}$ concentrations. The stations that had the highest mean concentrations were 14th st (F line), West 4th st (F line), and 34th st (F line), with means ± SDs of 200.4 ± 91.6, 156.7 ± 47.8, and 147 ± 40.7 $\mu g/m^3$, respectively. Similarly, two of the three stations had the highest $BC_{2.5}$ concentrations. The $PM_{2.5}$ concentrations of all stations sampled during the study period are provided in Table 1. The averaging time of each reading was 5−10 min, depending on train arrivals.

Multi-Subway Line Group Sampling Study—Simultaneous Sampling of the Concentrations of $PM_{2.5}$ at Stations along Parallel Subway Lines, with Comparisons to Ambient Levels. The $PM_{2.5}$ mean ± SD concentrations for stations on the F, E, and 6 subway lines were very elevated: 139.3 ± 63.1, 64.8 ± 37.5 and 106.9 ± 31.3 $\mu g/m^3$, respectively. The concentrations of $PM_{2.5}$ recorded at each station are given in Table 4.

Table 4. $PM_{2.5}$ Concentrations of Stations Sampled at the Same Time along Three Parallel Lines during the Group Study[a]

	mean $PM_{2.5}$ concentrations ($\mu g/m^3$)		
street level	F subway line	E subway line	6 subway line
W4th st/Astor	177.2[b]	129.3	101.1
14th st	224.5[b]	88.6	74.9
23rd st	126.1	38.4[b]	113.6
33rd/34th st	149.7[b]	53.0[b]	111.4[b]
42nd st	115.1	68.4[b]	134.4
50th/51st st	74.7	40.0[b]	83.0

[a]Each value reported is the average of two mean measurements where each measurement was a mean of 5−10 min of sampling. The first measurement was taken in the uptown direction, and the second was when the student reached the same station again in the downtown direction. [b]This station's concentration is significantly different from the concentrations of the other two stations located at the same cross street.

The roadside ambient $PM_{2.5}$ concentration measured above-ground during the group sampling study was 9.8 ± 4.8 $\mu g/m^3$ and much lower than the levels in the subway stations (Figure 3).

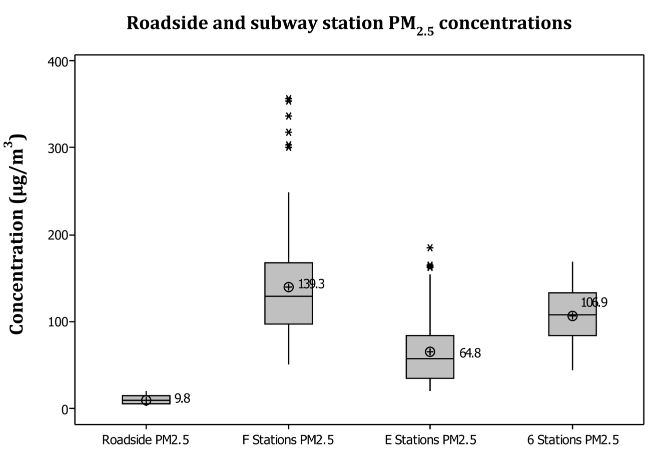

Figure 3. $PM_{2.5}$ concentrations at the roadside and in stations along the three parallel subway lines sampled during the group sampling run. The box shows the interquartile range, the line in the box shows the median, and the number in the box shows the mean. The whiskers represent the upper 25% and lower 25% (excluding outliers), while the * symbol represents outliers.

Filter Based (Gravimetric) Measurements of $PM_{2.5}$. In addition to the real time PDR 1500 DataRAM measurements for $PM_{2.5}$, filter-based $PM_{2.5}$ concentration at Astor Place on two occasions was 232 and 448 $\mu g/m^3$, respectively. For comparison, the mean real time-based $PM_{2.5}$ concentrations were 114 and, 150 $\mu g/m^3$, respectively.

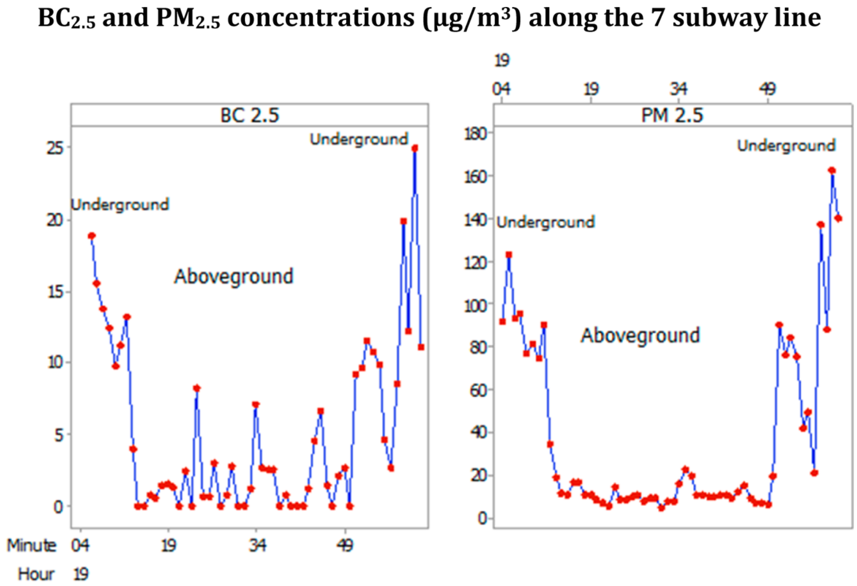

Figure 4. Time series graph showing the spatial change in $BC_{2.5}$ and $PM_{2.5}$ at stations while traveling from an underground station to aboveground stations and then back to underground stations.

Trace element analysis for one Astor Place filter showed that Fe, Mn, and Cr levels were high (consistent with previous studies) measuring 84 $\mu g/m^3$, 693 ng/m^3, and 386 ng/m^3, respectively.

$BC_{2.5}$ and $PM_{2.5}$ Concentrations at Underground and Aboveground Stations along One Subway Line. Figure 4 shows the variation in $BC_{2.5}$ and $PM_{2.5}$ concentrations at stations along the Number 7 subway line, which has both underground and aboveground stations on the same subway line. The mean $BC_{2.5}$ concentration of the underground subway stations was 14.0 ± 4.4 $\mu g/m^3$, while the mean concentration of the aboveground stations was 2.8 ± 2.3 $\mu g/m^3$ (each station's mean measurement being a 5−10 min average). Similarly, the mean $PM_{2.5}$ concentration at the underground subway stations was much higher (93.3 ± 30.5 $\mu g/m^3$) than at the aboveground stations (12.2 ± 4.0 $\mu g/m^3$).

DISCUSSION

$PM_{2.5}$ mass and BC/EC concentration levels have been studied in subway stations in different parts of the world in cities such as London, Stockholm, Helsinki, and Amsterdam. However, this study is the first time that BC levels have been measured at subway stations in New York City.

Of the various particles generated during fossil fuel combustion, particularly in diesel-generated exhaust, exposure to black carbon (BC), sometimes referred to as soot or black smoke, is known to be associated with a range of adverse respiratory health effects and, therefore, has been studied with increased interest in recent years.[14−16] In some studies, the dark component of particulate matter known as black carbon may also be reported as elemental carbon (EC), which is highly correlated but has a different method(s) of detection. In New York City, it has been found that diesel-generated elemental carbon soot was the factor most closely associated with pollution-related asthma exacerbation in children living near roadways and is strongly associated with personal measures of EC.[14] A review of studies showing short-term effects of BC[15] showed that BC can have a greater effect on health compared with $PM_{2.5}$ and PM_{10}.

Although this study was primarily focused on measuring airborne particle concentrations on subway station platforms, BC and $PM_{2.5}$ levels were also measured inside the train car during a single commute and found to be approximately 1/4 to 1/3 the station concentrations along the same line. Further analyses of in-car measurements were not done in the study, although air conditioning was likely responsible for the lower levels.

BC concentrations of the subway stations ranged as low as 5 $\mu g/m^3$ although most stations' BC concentrations were in the range of 10−20 $\mu g/m^3$. It is important to note here that NYC subway passenger trains are powered by electricity and, thus, it is somewhat unexpected to find relatively high levels of BC in the subway system, compared to ambient levels. Subsequent investigations revealed that diesel-powered trains are used for maintenance and operate during the night, which is one likely cause for the buildup of BC levels in the subway system air.

In the group sampling experiment along three parallel subway lines, the $BC_{2.5}$ concentrations in the underground subway stations were several times higher than the ambient roadside concentration. This is consistent with other studies that have looked at BC in subway stations and outside the subway system. A recent study[17] reported a mean of 9 $\mu g/m^3$ for underground subway stations in Amsterdam and Rotterdam, which was five times higher than aboveground levels. In the present study, the $BC_{2.5}$ concentrations in the stations sampled along the selected F, E, and 6 subway lines were seven, four, and six times higher than the ambient roadside $BC_{2.5}$ concentrations, respectively. Interestingly, the NYC underground F, E, and 6 subway station $BC_{2.5}$ means of 16.9, 10.2, and 15.3 $\mu g/m^3$ were higher than previously reported values for subways in Amsterdam and Helsinki.[4,17] This suggests that NYC's subway stations are more polluted in terms of $BC_{2.5}$ levels than other subway systems studied to-date.

As discussed above, concentrations of BC in NYC subway stations measured in this study can be considered high compared to roadside levels and that of previous studies. Therefore, it is an important factor to consider in terms of potential health effects. Most research on BC soot has looked into the effects of diesel exhaust, while measuring BC levels as a component.[15,16] A pooled analysis[15] of the available studies have, however, shown that a 1 $\mu g/m^3$ increase in EC is associated with a 1.45% increase in all cause mortality and a 1.77% increase cardiovascular mortality.[18−21] In a study that looked at acute respiratory health among Bronx schoolchildren with asthma, adverse health effects were found to be strongly associated with personal measures of EC exposure, suggesting the diesel soot fraction of $PM_{2.5}$ derived from high volume roadways was most responsible for the pollution-related asthma exacerbations.[14] The study found that same day elevated risk of wheeze (1.45), shortness of breath (1.41), and total symptoms (1.30) were associated with an increase of personal EC exposure. It is important to note than in all of the above studies, the measured BC/EC levels were between 1 and 5 $\mu g/m^3$. Therefore, the much higher mean concentrations found in NYC subway stations in the present study could be considered as a health risk to individuals exposed to such concentrations, especially in the long term. However, the BC particles measured in the subway system are re-entrained by the rapidly passing trains, and not always freshly emitted, and the potential for BC soot particles found in the subways to cause adverse health impacts may also depend on whether the diesel particles are fresh or "aged". Fresh diesel exhaust has been shown to produce toxicity in various organs and cells,[22,23] but studies on aged particles, such as were measured in this study, are limited. Some studies have shown that both fresh and aged diesel exhaust particles have high oxidant generation capacity and toxicity.[24] Thus, the human health implications of these subway exposures to apparently re-entrained aged diesel particles may or may not be the same as diesel particle exposures in the ambient environment.

BC levels in the sampled NYC subway stations showed high spatial variation depending on the station, depth of the station, and line sampled. Measurements from the West 4th st station showed that the $BC_{2.5}$ concentrations in the upper level (A, C, and E train stop) were significantly lower than in the lower level (B, D, F, and M train stop) by approximately 40%. Significant variations in $BC_{2.5}$ were seen among stations located along each line, possibly due to the depth of the station, efficiency of ventilation, and number of trains passing through the station. It was observed that the stations that generally had lower $BC_{2.5}$ concentrations, such as the 8th st NYU station, were closer to the road level and appeared to have better ventilation. The stations at lower levels, such as the West 4th F train stop and 14th st F stop, recorded much higher $BC_{2.5}$ levels.

$BC_{2.5}$ concentrations also varied greatly between aboveground and underground stations sampled along the 7 train line. Concentrations were several times higher in the underground stations compared with aboveground (Figure 4). The underground station closest to an aboveground station had a lower $BC_{2.5}$ concentration than an underground station located further away from the aboveground station. Thus, ventilation may play an important role in the concentration of $BC_{2.5}$ in underground subway stations.

The variation in $BC_{2.5}$ levels was also dependent on possible sources within the subway system. During sampling along the NQR subway line, the concentration of BC rapidly increased to more than 100 $\mu g/m^3$ (Figure 2) when a diesel-powered maintenance train passed through the station. This is evidence that the diesel-powered maintenance trains running at nights could be a significant contributor to elevated $BC_{2.5}$ levels within subway stations as well as throughout the subway system. These peak exposures may be important, in terms of health impacts, for commuters and particularly for subway workers who work at night and are part of the maintenance crew, since they may be exposed to higher $BC_{2.5}$ levels during a greater portion of their work shift.

In addition to real time measurements of $BC_{2.5}$ in subway stations, filter-based measurements of $EC_{2.5}$ were obtained using quartz filters. Although the real time Aethalometer and the filter sampling occurred during the same time interval on only a limited number of samples (n = 3), the comparison of the two methods showed that the real time mean $BC_{2.5}$ measurements were approximately 60−80% higher than the filter-based mean EC measurement at the Astor Place station and 20% higher along the 6 line. Possible causes for this difference in BC and EC concentrations could be the presence of fine particles that are "dark", differences in measuring methods, and light absorption by metals. However, a 2.5 μm cut cyclone was used with the Aethalometer to minimize possible confounding of real time measurements from larger particles that are "dark/black".

The difference in BC and EC measurements can be somewhat expected since the basis used for the measurements in each method are different. Aethalometers measure in real time utilizing light scattering and absorbance, while the measurement of EC by the NIOSH method uses thermal methods. As reviewed in a study,[15] BC and EC measurements do not always agree and calibration between the two methods is needed for each site/environment to have a better understanding of the relationship of the two components and methods. Regardless, EC measurements were also between 10−12.5 $\mu g/m^3$ in the stations and lines measured, thereby confirming that concentrations of the diesel soot component in the subway stations is several times higher than roadside levels. A study conducted in the Berlin subway, where diesel engines are used, reported mean EC levels of 10.9 and 6.9 $\mu g/m^3$ in summer and winter, respectively.[25]

Real-time measurement of $PM_{2.5}$ in NYC subway stations ranged from 35−200 $\mu g/m^3$, which, as with the $BC_{2.5}$ measurements, was several times higher than the ambient roadside mean concentration of 9.5 $\mu g/m^3$. Similar results have been shown in other studies that have examined $PM_{2.5}$ concentrations in subway systems. In NYC's subways, an earlier study[11] reported a mean $PM_{2.5}$ concentration of 62 $\mu g/m^3$. Studies done on NYC subway workers showed various effects on selected biomarkers in workers, in particular, higher concentrations of chromium in plasma and DNA cross-links, although the chromium levels were below occupational standards.[13] In studies in London, Stockholm, and Helsinki, mean $PM_{2.5}$ concentrations in the subway were 247.2 and 157.3 $\mu g/m^3$ in London during two seasons, 260 $\mu g/m^3$ in Stockholm, and 60 $\mu g/m^3$ in Helsinki, levels which were 3−8, 5−10, and 4−5 times higher than ambient levels measured in busy urban areas in their respective studies.[4,5,26] Therefore, the present study provides further evidence that $PM_{2.5}$ levels, and thus their sources, in underground subway systems are several times higher than busy urban roadside levels. Ambient roadside measurements and subway station measurements were done during the same sampling run to minimize errors and variations due to time/day and seasons. $PM_{2.5}$ levels showed a similar pattern to BC in the aboveground vs underground sampling, which was measured simultaneously to BC measurements (Figure 4). Although $PM_{2.5}$ levels were several times higher than BC levels in this study, they were highly correlated which suggests that both BC and $PM_{2.5}$ may contribute to adverse health effects in commuters and subway workers.

Concentrations of $PM_{2.5}$ at a single subway station were also obtained twice for gravimetric analysis. The gravimetric $PM_{2.5}$ concentrations at the Astor Place station were 232 and 448 $\mu g/m^3$, indicating that the actual $PM_{2.5}$ concentrations were 2 to 3-fold higher than those assessed with the real time monitor (for the subway environment under the same conditions). This variability was likely due to the fact that the real time PDR 1500 instruments had been factory calibrated to standard dust, whereas the PM composition of the NYC subway has a higher proportion of metal particles such as Fe, Mn, and Cr, as shown by previous studies. It is also important to note that the PDR 1500 units were used with humidity correction, which may have also contributed to the difference.

Because subway commuters and workers spend the majority of their day outside of the subway system, it is important to consider the contribution of underground subway exposures to a total daily exposure. We can estimate that, the high levels of $PM_{2.5}$ in the subways, for example, can contribute to an estimated 30% higher daily $PM_{2.5}$ exposure for subway commuters. This calculation assumes an ambient $PM_{2.5}$ concentration of 10 $\mu g/m^3$ and that a commuter waits for a total of 30 min, round trip, in subway stations along the F subway line (observed to have the highest pollution concentrations) at an exposure concentration of 150 $\mu g/m^3$ $PM_{2.5}$ in the subway. Importantly, this augmented particle burden increases from 240 to 1200 $\mu g/m^3 \cdot h$, assuming an 8 h underground work shift in the subway system. In this context, acute and chronic health effects of BC and $PM_{2.5}$ may be more relevant for workers and vendors who spend a significantly greater amount of time underground in subways.

While our data demonstrate significant spatial variation in PM and BC concentrations (e.g., upper vs lower stations; F line vs other lines), sampling at some stations were limited and greater uncertainty may be present in such situations.

The study had some limitations, partly due to subway security concerns that were pertinent during the time of sampling. The equipment that could be carried in the subways and the durations they could be operated were limited, as passengers who may not understand the procedure would see it as a cause of concern. This required sampling at only certain stations in selected lines and limited the sampling time in the subway stations. Filter-based sampling required at least 1 h of sample collection at each station, which was not possible given the security concerns at that time.

There were also limitations with the group sampling experiment in maintaining the same time interval between stations at the same cross streets, due to train arrival times and delays; although the times were approximately within the same 5−10 min time period.

In conclusion, this is the first to demonstrate elevated $BC_{2.5}$ concentrations in NYC's subway stations, showing diesel exhaust could be present in the subway system. The $PM_{2.5}$ and $BC_{2.5}$ levels in the subway stations were found to be several times higher compared to roadside ambient levels and aboveground subway station levels. $PM_{2.5}$ and $BC_{2.5}$ concentrations showed considerable variability among stations, lines, level of station, and location of stations. Seasonal variations were not seen at the single station sampled several times during both summer and winter (data not shown). The study also shows that $BC_{2.5}$ levels increase rapidly when a diesel maintenance train is in operation locally, thereby being a potentially important contributor to elevated $BC_{2.5}$ levels in subway stations. Overall, the $PM_{2.5}$ and $BC_{2.5}$ concentrations in NYC subway stations were higher than previously reported levels in subway systems in Europe and, importantly, at $PM_{2.5}$ levels shown to be associated with adverse health effects. These levels could therefore have significant health impacts on commuters but would likely be of the greatest health import to subway workers, who spend much longer times on subway station platforms and diesel-powered maintenance trains. Diesel engines can have particulate matter traps applied to their exhaust to reduce emissions, providing one potential exposure mitigation measure. Therefore, further air pollution exposure and health effects studies are warranted for underground subway lines and stations, focusing on identifying the contributors to higher levels of $PM_{2.5}$ and $BC_{2.5}$ in the subways of NYC, assessment of the potential health effects of ongoing exposure to passengers and workers, and a determination of potential mitigation measures available (such as improved fresh air ventilation, subway air filtration, or diesel train emission controls).

■ ASSOCIATED CONTENT

Supporting Information

Figure (S1) showing mean $BC_{2.5}$ concentrations of the upper and lower levels of the West 4th st subway station. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

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