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Investigation of a river-tunnel effect on $PM_{2.5}$ concentrations in New York City subway stations

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ABSTRACT

It is well-documented that subway stations exhibit high fine particulate matter ($PM_{2.5}$) concentrations. Little is known about the potential of river-tunnels to increase $PM_{2.5}$ concentrations in subways. We hypothesized a "river-tunnel" effect exists: Stations adjacent to poorly ventilated tunnels that travel beneath rivers exhibit higher $PM_{2.5}$ concentrations than more distant stations. Accordingly, the $PM_{2.5}$ concentrations were monitored at stations adjacent to and two- and three-stations distant from the river-tunnel. Multivariate linear regression analysis was conducted to disentangle how proximity to a river-tunnel and other factors (e.g., depth) influence concentrations. Stations adjacent to a river-tunnel had 80–130% higher $PM_{2.5}$ concentrations than more distant stations. Moreover, distance from a river-tunnel was the strongest $PM_{2.5}$-influencing factor This distance effect was not observed at underground stations adjacent to a river-bridge. The "river-tunnel" effect explains some of the inter-station variability in subway $PM_{2.5}$ concentrations. These results support the need for improving ventilation systems in subways.

1. Introduction

Underground subways provide rapid, inexpensive transit for millions of people globally, but have been found to expose workers and riders to high levels of fine particulate matter ($PM_{2.5}$). In New York City (NYC) alone, over 4 million people ride the subway system daily and while transit systems, such as NYC's Metropolitan Transit Authority (MTA), have reduced aboveground vehicle traffic and ambient air pollution (Lu et al., 2018), subways pose considerable air quality problems for transit workers and riders. Most significantly, subway air contains high levels of particulate matter of 2.5 μm or smaller ($PM_{2.5}$). These $PM_{2.5}$ levels were observed to be elevated severalfold over ambient levels in over 30 subway stations in NYC (Vilcassim et al., 2014). Similarly, Chillrud and colleagues documented the importance of the metal exposures in NYC subways, finding that the subway air concentrations of Fe, Mn, and Cr were more than 100 times ambient NYC levels (Chillrud et al., 2004, Chillrud et al., 2005). Because of the increased respiratory and cardiovascular morbidity and mortality associated with exposure to ambient $PM_{2.5}$ (Xu et al., 2020, Li et al., 2018, Wang et al., 2019, Requia et al., 2018, Thurston et al., 2016), a key health burden question for commuters and transit workers is whether subway air is safe to breathe.

Our most recent research indicates this problem is widespread in other U.S. subway systems. At rush hour, subway station $PM_{2.5}$ in Boston, Washington, DC, and Philadelphia were 33–, 28-, 9-fold higher than ambient $PM_{2.5}$, respectively, although lower than in NYC subways (Luglio et al., 2021). Elevated $PM_{2.5}$ air pollution in U.S. subway stations has been corroborated by numerous studies

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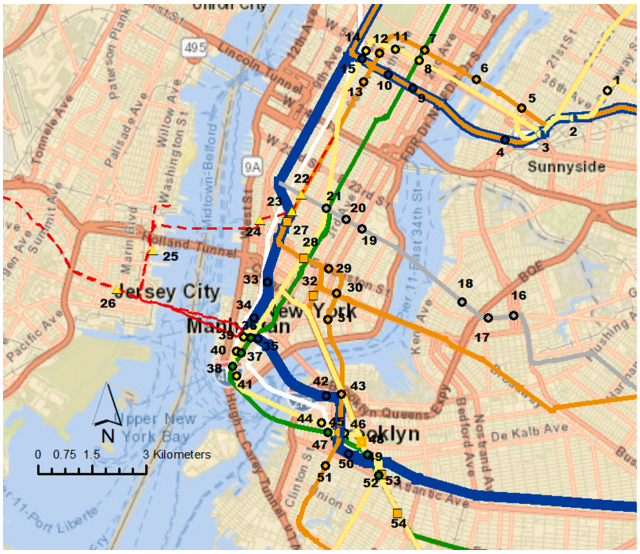

1	Steinway Street (R)	28	Broadway-Lafayette (B)
2	36th Street (E,R)	29	2nd Avenue (F)
3	Queens Plaza (E,R)	30	Delancey Street-Essex Street (F)
4	Court Square-23rd Street (E)	31	East Broadway (F)
5	21st Street-Queensbridge (F)	32	Grand Street (B)
6	Roosevelt Island (F)	33	Canal Street (A,C)
7	Lexington Avenue-63rd Street (F)	34	Chambers Street (A,C)
8	Lexington Avenue/59th Street (R)	35	Fulton Street (A,C)
9	Lexington Avenue/53rd Street (E)	36	Fulton Street (4,5)
10	5th Avenue/53rd Street (E)	37	Wall Street (4,5)
11	5th Avenue/59th Street (R)	38	Bowling Green (4,5)
12	57th Street (F)	39	Cortlandt Street (R)
13	47-50 Streets-Rockefeller Center (F)	40	Rector Street (R)
14	57th Street/7th Avenue (R)	41	Whitehall Street (R)
15	7th Avenue (E)	42	High Street (A,C)
16	Graham Avenue (L)	43	York Street (F)
17	Lorimer Avenue (L)	44	Court Street (R)
18	Bedford Avenue (L)	45	Jay Street-MetroTech (A,C,F)
19	1st Avenue (L)	46	Jay Street-MetroTech (R)
20	3rd Avenue (L)	47	Borough Hall (4,5)
21	14th Street-Union Square (L)	48	Dekalb Avenue (B,R)
22	14th Street (33rd Street)	49	Nevins Street (4,5)
23	9th Street (33rd Street)	50	Hoyt-Schermerhorn Streets (A,C)
24	Christopher Street (33rd Street)	51	Bergen Street (F)
25	Newport (33rd Street)	52	Atlantic Avenue-Barclays Center (4,5)
26	Grove Street (33rd Street)	53	Atlantic Avenue-Barclays Center (B)
27	West 4th Street-Washington Square (B)	54	7th Avenue (B)

Fig. 1. Map of sampled stations. The location of the stations are located with circles, squares or triangles upon lines both in the respective color of the designated line (i.e. green for 4,5, yellow for R, gray for L, blue for A,C and E, and orange for the F and B). Orange squares are used for the B to differentiate it from the nearby F. PATH stations are indicated by yellow triangles on a red dotted line. Numbers adjacent to each marker correspond to the station on the list to the right. The map was created on ArcMap. The MTA lines were generated using publicly available data created by Frank Donelly through the Baruch Geospatial portal based on MTA data and published to CCE_NYC AGOL by Glen Johnson, CUNY School of Public Health. The PATH lines were generated using publicly available data provided by Glenn D. Newman PLS, PP, director of GIS-Transportation at NJ transit and processed by the NJ Office of information Technology (NJCIT), Office of Geographic Information Systems (OGIS). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

throughout North America (Kam et al., 2011, Van Ryswyk et al., 2017, Figueroa-Lara et al., 2019) and the world (Martins et al., 2016, Xu and Hao, 2017, Smith et al., 2020), although the levels are lower than reported for NYC subways (Luglio et al., 2021). Importantly, underground subway aerosols are rich in carbon and metals – particularly iron – but the health impact burden of these metal and carbon rich $PM_{2.5}$ mixtures on subway commuters and workers is not known.

The source(s) and the reasons for the elevated levels of subway $PM_{2.5}$ have been previously investigated. It is likely that suspension of particles, produced by the abrasion of brakes and wheels and rails and electric power conduits, is the source of these iron-rich particles (Lee et al., 2018, Minguillón et al., 2018, Park et al., 2012). Other factors, such as ventilation (Moreno et al., 2017, Moreno et al., 2014), depth below the surface (Figueroa-Lara et al., 2019), train frequency (Tu and Olofsson, 2021), and frequency of cleaning (Johansson and Johansson, 2003) contribute to varying concentrations of airborne particles reported in underground subway and rail systems. In combination, these factors result in the poor air quality encountered by commuters and workers in underground transit systems. Previously, we observed that the highest $PM_{2.5}$ levels in the NYC/NJ PATH rail system occurred in the stations close to the tunnel under the Hudson River (Luglio et al., 2021). Based upon this observation, we hypothesized that $PM_{2.5}$ generated in the poorly ventilated tunnels under the waterways surrounding Manhattan is a significant contributor to airborne $PM_{2.5}$ concentrations encountered on subway platforms. As trains pass through these tunnels, they can generate, resuspend, and push airborne PM into neighboring stations. The objective of this study was to test this hypothesis, which would add to the body of knowledge on why PM concentrations vary between subway stations. Our results may be applicable to other cities with tunnels that travel beneath waterways such as London and Hong Kong. In this study, we expanded our exposure assessment to measuring $PM_{2.5}$ concentrations in the 3 stations closest to both sides of all the river tunnels used by the subway/rail lines in NYC.

2. Methods

2.1. Sampling sites

This study investigated the relative $PM_{2.5}$ concentrations at NYC/NJ's MTA and PATH stations adjacent to subway tunnels that travel beneath the 2 rivers on the East and West sides of Manhattan. More specifically, underground stations in close proximity to seven MTA subway tunnels that travel beneath the East River in NYC were selected for investigation. These tunnels service eleven subways lines (e.g. A, C, E, F, M, 4, 5, R, N, W, and L) that connect the boroughs of Manhattan, Brooklyn, and Queens. In addition, a Hudson River tunnel, which services the 33rd Street-Journal Square line of the PATH rail system between Manhattan and NJ was included. For a comparison, measurements were also conducted at underground stations on a line which crosses the East River by a bridge (i.e. B).

To compare $PM_{2.5}$ concentrations at underground subway stations at different distances from the tunnels, real-time concentrations were measured on the platform of the three consecutive underground stations closest to the river, on both sides of the tunnel, for a total of six stations per tunnel or bridge. These stations are labeled in this manuscript as M3, M2, and M1 for Manhattan stations located three, two, and one stops from the river-tunnel, respectively. Likewise, the stations in Brooklyn, Queens and Jersey City are labeled BQ1, BQ2, and BQ3 in increasing number of stations from the river. A map of all stations is presented in Fig. 1. In addition, all stations are listed in sequential order in the supplementary material (Table A1). All real-time measurements of $PM_{2.5}$ were collected from 0900 h to 1300 h during weekdays in February and March 2022.

2.2. Real-Time measurements

Real-time $PM_{2.5}$ concentrations were measured using nephelometric-based personal DataRAMs (pDR 1500; Thermo Fisher Scientific, Franklin, MA). These instruments were outfitted with 2.5-μm cut-point inlet cyclones, logged concentrations at one-second averaging intervals, and zeroed with HEPA-filtered air before each run. Real-time data from each pDR were adjusted with correction coefficients derived from the calibration curve obtained from gravimetric $PM_{2.5}$ measurements (see below).

The sampling scheme is detailed in the supplementary section (Figure A1). To summarize, as a means to minimize temporal variability while measuring the targeted spatial differences, three investigators sampled at each of three consecutive stations (e.g. M3, M2, M1) at the same time. Real-time $PM_{2.5}$ concentrations were collected on subway platforms for a minimum of 5 min before all three individuals boarded a train and moved on to the next stop, until all stations were sampled at least twice. The sampling instruments were placed at chest height (approximately 1.4 m) at the center of each sampling platform. To measure the $PM_{2.5}$ concentration inside a tunnel itself, an Airbeam 2 (Habitat Map, Brooklyn, NY) was attached to the outside of a train car as it traveled from station M3 to BQ3 through the river-tunnel. The Airbeam 2 concentrations were corrected by comparing it to a calibrated pDR-1500.

2.3. Gravimetric and elemental measurements

$PM_{2.5}$ was collected for 30 to 45 min at each of the stations on the 4,5 lines (Table A1) on 37-mm low-trace element Teflon™ (Pall Inc., Ann Arbor, MI) filters with a 2.5-μm cut-point inlet Personal Environmental Monitor (PEM; SKC, Inc., Shoreview, MN), and a calibrated Leland Legacy Pump (SKC, Inc.) at 10 L/min.

Before and after sampling, the filters were conditioned in a temperature- and humidity-regulated weighing chamber (MTL, Minneapolis, MN) at $21 \pm 1^{\circ}$ C and 35 ± 5 % RH for at least 24 h. After conditioning, the post- and pre-sampling filters were weighed using a microbalance (Model MT5, 1 μg readability; Mettler-Toledo, Columbus, OH). The $PM_{2.5}$ mass concentrations were derived through standard gravimetric analysis. Laboratory blank samples were used to correct for daily variation in the micro-balance analyses.

All six filters were analyzed by X-ray fluorescence (XRF) (Epsilon 5 ED-XRF, PAN Analytical B.V., Netherlands) for elemental concentration analysis. Elements included in these analyses include the following although detection limits for many elements were not achieved: Na, Mg, Al, Si, P, S, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, W, Ir, Pt, Au, Hg, Tl, Pb, Bi, and U.

2.4. Calibration, regression, and statistical analysis

For calibration, all pDR-1500 s were co-located with a $PM_{2.5}$ filter sampling system for gravimetric analysis in the six different stations most proximal to each tunnel. A linear curve was developed comparing the average pDR-1500 concentrations and the gravimetrically-determined concentration for each of the six stations. The y-intercept of the curve was set as 0. Subsequently, the coefficient of the independent value was used as the correction factor for pDR-1500 values. Correction of these pDR-1500 values were done on an individual instrument basis.

The $PM_{2.5}$ concentrations were averaged for each platform across the time period that each investigator was present on the platform. Each of these instances counted as a measurement for that platform (i.e., n = 2 for M3 and BQ3, and 3 for all others). All of these samples were averaged together for each platform independently for each line (n = 59) for presentation in this manuscript. The A,C and F-downtown lines, E and R-uptown lines, and B and F-downtown lines share the same platforms at Jay Street-MetroTech, 36th Street, and Dekalb Avenues, respectively. The data for these readings are considered as separate samples as they are temporally concurrent within a single line but distinct from all others. In addition, the distance (i.e., in meters following the subway line) to the river from these platforms differs depending on the line considered. Some samples are excluded from the regression model as noted below.

To account for potential confounding factors, a multivariate regression analysis was performed with the $PM_{2.5}$ concentrations at all “river-tunnel” stations as the dependent variable. The distance from the river, station age, station depth/number of steps, and number of tracks were included as independent variables. Spearman-rank correlation tests for the relationship between each of the factors and $PM_{2.5}$ concentration were also performed. In addition, a correlation matrix was constructed showing the relationships of each independent variable to each other (Table A3). Highly correlated variables (r greater than 0.7) were excluded from the regression model.

All multivariate regression analyses were conducted with R (version, R version 3.6.1) (R Core Team, 2019) using the agricolae (version 1.3–1) (de Mendiburu and Yaseen, 2019) package. The $PM_{2.5}$ concentration was natural log transformed for each underground station to attain a normal distribution, and was included as the dependent variable. All independent variables are as listed: absolute number of stations from river (i.e. 1, 2, 3), distance from the river in kilometers, age of station in years, number of steps from surface to platform sampled, number of tracks, number of platforms, type of platform (i.e. island (1), side (2), both (3)), and number of trains per minute passing through the station. The distance from the river was measured on ArcMap; the coordinates of the stations were overlaid onto a map of the New York Metropolitan area with the subway tunnels with publicly available data (i.e., NYC Open Data

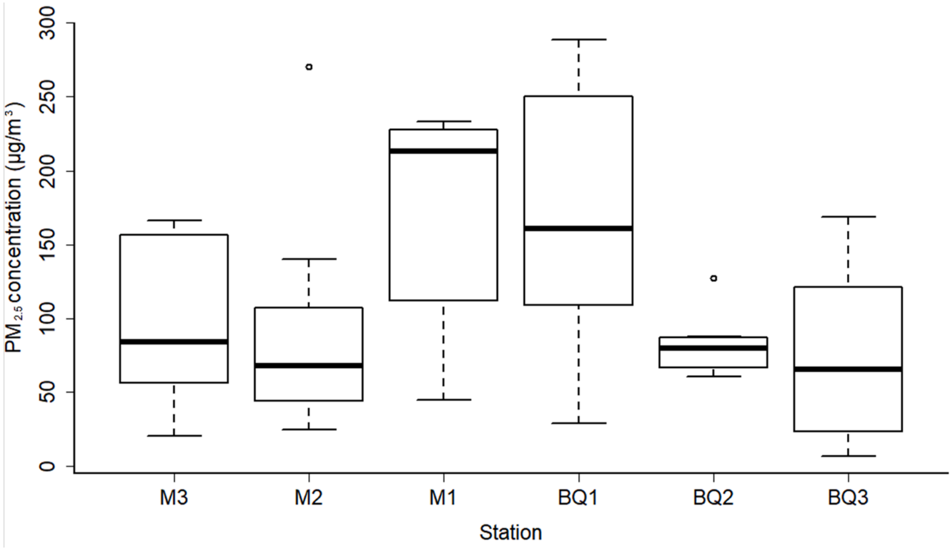

Fig. 2. Average $PM_{2.5}$ concentrations according to location of station. M = Manhattan subway stations and BQ = Brooklyn/Queens subway stations. The number following M or BQ indicates the relative location of the station relative to the tunnel with '1′ being the closest station. Data from the B-bridge line and the F-uptown line are excluded from this chart. The sample number for each of locations is 6.

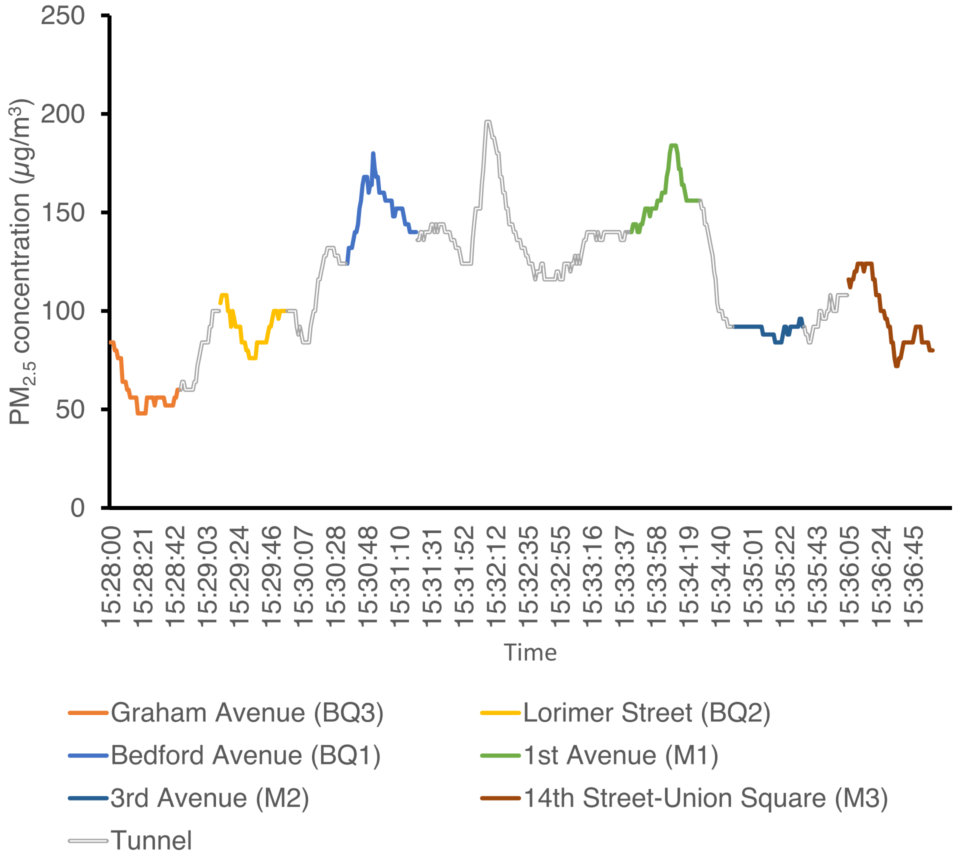

Fig. 3. Time series of $PM_{2.5}$ concentration outside of a train during ride from Graham Avenue (BQ3) to 14th Street-Union Square (M3) on the L-line. The river-tunnel is indicated as the tunnel between Bedford Avenue (BQ1) and 1st Avenue (M1). $PM_{2.5}$ concentration steadily rises as the train approaches the BQ1 and M1 stations from either side. The concentration remains high in the river-tunnel. M = Manhattan subway stations and BQ = Brooklyn/Queens subway stations.

Table 1
Spearman-Rank correlation coefficients and p-values for relationships between station characteristic and $PM_{2.5}$ concentration. The # of steps is a proxy for station depth underground.

Characteristic	r	p-value
Location of station	0.403	0.003
Distance from river-tunnel (meters)	−0.443	0.001
Age (years)	0.174	0.221
# of tracks	−0.225	0.112
# of platforms	−0.289	0.0400
# of steps	0.216	0.127
Train frequency (# of trains/minute)	−0.0512	0.720

for the coordinates; ArcMap Online maps for the MTA and PATH tunnel lines) and the distance to the river was measured by tracing the tunnels using the measure distance tool. The number of steps was selected as a proxy for the depth of a station since the depth data were available for only a few stations. The typical step height in the stations (i.e., MTA or PATH) is 18 cm. The type of platform present in a station is coded as: 1 for island, 2 for side, and 3 for both. The number of trains per minute, or frequency, was determined by counting the number of trains passing through a station in a fifteen-minute interval for all stations in a single line. This specified time period was between 0900 and 1200 h. All the data for each of these factors are included in Table A2. Data for the stations solely on the "bridge" line (n = 6) are excluded from the 'tunnel' analysis. Roosevelt Island (n = 1) is also excluded from the analysis because it does not have a proper position relative to a river tunnel. Journal Square (n = 1) is also excluded because it is not an underground station. Accordingly, the total number of samples included in the model is 51. All Spearman-rank correlation tests were conducted with the same variables in the same codification.

Analysis of variance (ANOVA) was performed to compare the $PM_{2.5}$ concentrations of stations at positions 1, 2, and 3, regardless of location in Manhattan, Brooklyn, Queens or Jersey City. A post-hoc Tukey test was performed to show the pairwise significant differences between groups.

All statistical analyses were conducted in R (R version 3.6.1) (R Core Team, 2019) with the agricolae package (version 1.3–1) (de Mendiburu and Yaseen, 2019). The stations only located on the "bridge" line were excluded from the ANOVA and regression analysis.

3. Results and discussion

3.1. Evaluation of $PM_{2.5}$ concentrations

The mean $PM_{2.5}$ concentrations were the highest in stations adjacent to each river-tunnel connecting Manhattan to Queens, Brooklyn, or NJ (Fig. 2). The stations closest to the river-tunnel (i.e., M1 and BQ1 in Fig. 2) had 80 to 130 % higher $PM_{2.5}$ concentrations than in the stations 2 or 3 stops away from the river-tunnel. A further distance from the river past the 2nd stop, however, did not appear to result in lower $PM_{2.5}$ concentrations. Statistical tests confirmed that stations at position 1 (i.e., M1 or BQ1) was significantly different than at positions 2 and 3, whereas 2 and 3 were not different from each other (Table A4). In some cases, however, the stations at position M3 or BQ3 had poorer air quality than at positions M2 or BQ2 (Table A5). Nevertheless, the hypothesis that the stations closest to the river-tunnels would have higher $PM_{2.5}$ concentrations was substantiated by this study. A similar finding was observed in the unique Roosevelt Island Station (F-uptown Line) which, because it is situated in the middle of the East River, has trains that enter from river-tunnels in both the Manhattan- and Queens-bound directions (Table A5).

To more closely examine the river-tunnel as a source of $PM_{2.5}$, the $PM_{2.5}$ concentration in a tunnel was directly measured using a calibrated low-cost PM sensor (Airbeam) attached to the outside of a train-car as it passed from station BQ3 to M3 on the L-line (Fig. 3). The highest $PM_{2.5}$ concentrations were measured while entering the BQ1 and M1 stations. The river-tunnel had slightly lower $PM_{2.5}$ concentrations than in the two adjacent stations, suggesting that the source of airborne $PM_{2.5}$ in the tunnel-adjacent stations included PM from the tunnel as well as station-specific sources such as human activity and outdoor PM.

To further assess the specific role of the river-tunnel as a $PM_{2.5}$ source, the tunnel sampling procedure was mirrored on a subway line (B) which crosses the East River via a bridge. In this scenario, subway trains would only push ambient air into the river-adjacent underground stations. As these stations were not subjected to the piston effect of a train passing through an underground tunnel, these bridge-associated stations were not expected to have elevated $PM_{2.5}$ concentrations. The $PM_{2.5}$ concentrations at the bridge-associated M1 and BQ1 underground stations were 125.7 +/- 48.6 and 99.7 +/- 41.7 $\mu g/m^3$, respectively, which were lower than the concentrations at M2 and M3 (i.e., the opposite of the effect seen in the river-tunnel scenario; Table A5).

All-in-all, these results are indicative of a "river-tunnel effect" contributing to the $PM_{2.5}$ concentrations in the underground subway stations adjacent to the river-tunnel. Most of the NYC subway system ventilates by the piston effect, which requires a direct passageway from the tunnels to the surface. This is impossible for river-tunnels which are underwater. Instead they have large towers on either side of the river in an attempt to compensate for the lack of tunnel adjacent grates. There may also be operable fans at the ends of the river-tunnel, which may aid in air exchange. The lack of access to the surface, however, remains an issue. Because of low ventilation in the tunnels, we speculate that the $PM_{2.5}$ generated in the river-tunnels has little to no exchange with ambient air and thus airborne and settled particles may accumulate over time. Thus, as trains pass through the long river-tunnels, they push highly concentrated $PM_{2.5}$-laden air forward into the subway stations at either end of the tunnel.

Table 2
Multivariate regression results. The effect of each factor is indicated in the left-hand columns on the natural log of the $PM_{2.5}$ concentrations is displayed.

	Ln($PM_{2.5}$ concentration (μg/m^3))						
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Train frequency (# of trains/ min)							0.0014
# of steps						0.00083	0.00083
Age (years)					0.0020	0.0023	0.0022
# of tracks				0.28*	0.27	0.27	0.27
# of platforms			−0.35*	−0.75**	−0.74**	−0.73*	−0.73*
Type of platform (side platforms, “2”)		−0.33	−0.17	0.43*	0.20	0.22	0.22
Type of platform (both island and side, “3″)		0.60	1.14**	1.86**	1.79**	1.78**	1.78**
Distance from river (km)	**−0.36*******	**−0.32****	**−0.26***	**−0.35****	**−0.34****	**−0.34****	**−0.34****
Constant	5.17***	5.18***	5.57***	5.51***	5.35***	5.24***	5.24***
Observations	51	51	51	51	51	51	51
R^2	0.193	0.282	0.329	0.367	0.357	0.343	0.328
Residual Std. Error	0.655 (df = 49)	0.618 (df = 47)	0.597 (df = 46)	0.580 (df = 45)	0.585 (df = 44)	0.591 (df = 43)	0.598 (df = 42)
F Statistic	12.9*** (df = 1; 49)	7.56** (df = 2; 48)	7.12*** (df = 4; 46)	6.79** (df = 5; 45)	5.63*** (df = 6; 44)	4.73*** (df = 7; 43)	4.04** (df = 8; 42)

There are seven models constructed as indicated by the numbers on top, reducing in complexity from 7 to 1, as the factors with the highest p-values are subsequently removed. The distance from the river-tunnel of the station is the only constant. The β coefficients for each factor are listed for each model alongside indications of their significance with * in the top-half of the table. Below each model are model characteristics, such as its R^2 and F-statistic values. The significance of the F-statistic is indicated with *. df = degrees of freedom. Observations refer to the number of samples included in each model. * (p-value) < 0.05; ** < 0.01; *** < 0.001.

3.2. *Influence of station characteristics on $PM_{2.5}$ variability*

There appeared to be considerable variability in $PM_{2.5}$ concentrations among stations across the different positions in the targeted subway lines (Table A5). Therefore, other factors, such as station depth, age of station, or train frequency, were expected to be influential contributors to subway station $PM_{2.5}$ levels. Depth, in particular, could be a major factor because as stations get closer to the river-tunnel, they are expected to increase in depth to accommodate passage into the sub-seabed tunnels. In fact, there appears to be a weak correlation between station depth and distance to a river (Table A3). Yet, based upon the station depth in this study (i.e., counting the number of steps from street level to each platform), there was no significant correlation between depth and $PM_{2.5}$ (Table 1). The Bowling Green station, for example, is adjacent to the river and has some of the highest concentrations (233.0 +/- 86.7 μg/m^3) observed in this study, but appears to be the shallowest of the sampled stations on the line (Table A2 and A4). In addition, train frequency was expected to be an influential factor with increases in $PM_{2.5}$ concentrations via increasing frequency of particle resuspension and generation and the piston effect of trains. An example of this is the 36th Street Station on the R-uptown and E Lines which had higher train frequencies and $PM_{2.5}$ concentrations than at (the river-tunnel-adjacent) Queens Plaza station despite being shallower and further from the river (Table A2-A3). Overall, however, there was no significant correlation between train frequency (i.e., # of trains/minute) and $PM_{2.5}$ concentration ($r = -0.051$, p-value = 0.720; Table 1). The variability of many other factors may have occluded any observable relationship of $PM_{2.5}$ and train frequency.

To assess the contribution of multiple station characteristics, such as depth, a multivariate regression analysis was performed (Table 2). In this analysis, subway station distance from the river-tunnel had the most statistically significant association with $PM_{2.5}$ concentrations when considering all lines together (Table 2). The type and number of platforms were the next most influential factors. The best fit model additionally included the number of tracks ($r^2 = 0.367$) (Table 2). Other factors, however, not accounted for here, may be involved in determining air pollution levels in underground subway stations.

Previous studies have investigated the effect of various station characteristics on $PM_{2.5}$ concentration with varying results. Figueroa-Lara et al., (2019), Vilcassim et al. (2014), and Ma et al., (2014) previously found that deeper subway transfer lines exhibited higher $PM_{2.5}$ concentrations for the same station. The results presented here show the same directionality of correlation, albeit weakly and non-significantly (Tables 1 & 2). In this study, $PM_{2.5}$ concentrations were positively correlated with station age. This matches well with previous findings in Shanghai and Barcelona (Zhao et al., 2017, Querol et al., 2012), although this age-effect was found to be not a factor in other systems (Cha et al., 2019). The number of platforms at a station can serve as a proxy for station size, which was shown here to be negatively correlated with $PM_{2.5}$ concentrations, which was one of the more influential regression factors (Tables 1 & 2). Larger volumes of air-space likely dilute the mass concentration of suspended PM entering a station. Few studies, however, have investigated the size of a station’s effect on PM levels. Interestingly, the type of platform played a major role in explaining the PM level variability. $PM_{2.5}$ concentrations were the highest in stations with both island and side platform(s). These stations represent a complex situation, in which these stations are larger but have more tracks and high train passing frequencies. To tease-out the mechanistic influence of this factor requires more work.

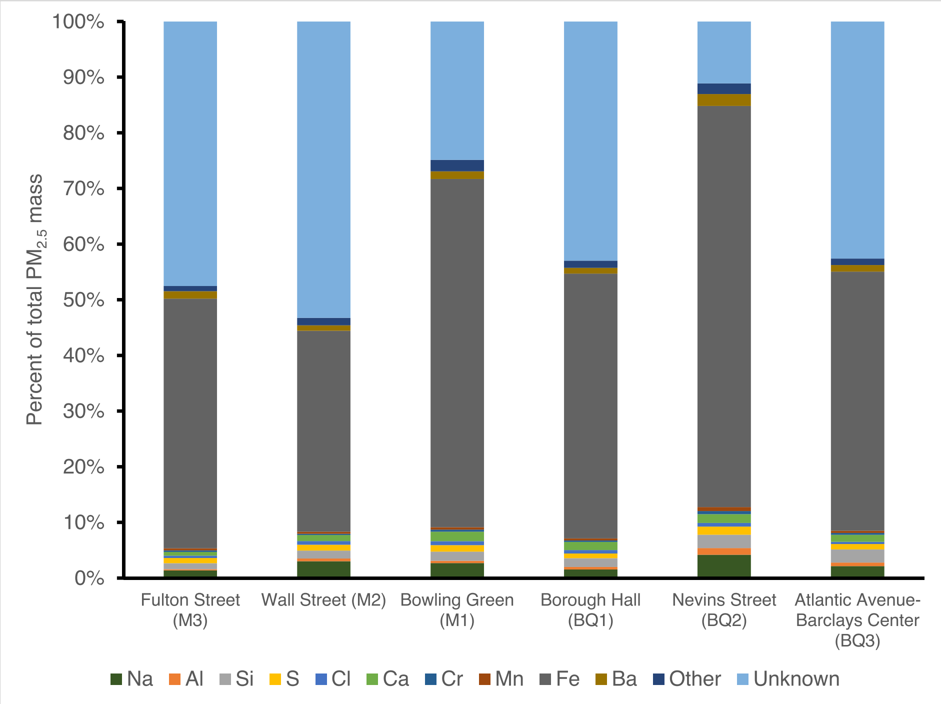

Fig. 4. $PM_{2.5}$ composition for the six sampled stations on the 4,5 line. Elements in the "other" category include: Mg, K, Ti, Ni, Cu, Zn, As, Se, Br, Rb, Sr, Y, Cd, Sn, Ce, Pr, Eu, Er, Lu, Ir, Au, Tl, and Pb. M = Manhattan subway stations and BQ = Brooklyn/Queens subway stations.

3.3. Compositional analysis

Compositional analysis was also performed on the six river-tunnel stations sampled on the 4/5 subway line. As expected, based on previous findings (Lu et al., 2015, Lee et al., 2018, Minguillón et al., 2018, Smith et al., 2020, Luglio et al., 2021), iron was the dominant element, accounting for 36 to 72 % of total $PM_{2.5}$ mass, although the relative concentration did vary among the stations (Fig. 4). Other elements such as silicon, chromium, copper, sulfur and barium were present but comprised<3 % of the total mass. Thus, overall, fresh generation and resuspension of the friction products of the wheels, rails, and electrical conduction elements are the likely source of airborne $PM_{2.5}$ in these subway tunnels. The unknown component(s) for the PM at some of these stations, however, is relatively large. This can be attributed in part to the limitations of the analytical techniques, but also to the fact that a limited number of elements were analyzed. For example, we did not analyze for carbon and oxygen, and carbon may have contributed a significant mass to the $PM_{2.5}$ as was seen in previous work (Luglio et al., 2021). Similarly, the large iron content of subway $PM_{2.5}$ was present as rust (unpublished observations) and thus oxygen may also have been an important contributor.

3.4. Potential solutions

In order to reduce river-tunnel effects on $PM_{2.5}$ concentrations at station platforms, innovative solutions are needed to reduce particle sources and improve ventilation to protect commuters and transit workers. Platform screen doors (PSD) are being implemented around the world, and have been shown to effectively reduce concentrations in subway stations (Kim et al., 2012, Zhang et al., 2019, Han et al., 2015). Yet, this suggestion must be met with caution as it may trap subway PM at the tracks and tunnels, increasing concentrations in those areas (Son et al., 2013). Accordingly, in-train PM levels have been demonstrated to have increased, as train cars draw air from these tunnels (Son et al., 2014). Implementation of PSD should be coupled with improved filtration of in-train air to maintain lower PM concentrations. Providing active ventilation to stations, in general and especially at river-tunnel adjacent stations, is an additional mitigation strategy (Moreno et al., 2017, Tu and Olofsson, 2021). Reducing the PM levels in the tunnels could have, presumably, the most powerful, positive impact on subway station air quality.

4. Conclusions

It has been well-documented that PM concentrations on underground subway platforms are much higher than in aboveground settings. Yet, the reasons why these concentrations are so high and why they vary among stations, subway lines, and transit systems is less clear. The results from this study have revealed that stations adjacent to river-tunnels have generally greater $PM_{2.5}$ concentrations than in more distant stations. This metric of a station's distance to a river-tunnel proved to be the most influential when considering all factors. As so, we have ascribed there to be an impactful river-tunnel effect on $PM_{2.5}$ concentrations in a subway system. Efforts to reduce PM concentrations on subway platforms should focus on reducing the PM concentrations in the tunnels themselves or the ability of the particles to travel between the tunnels and the stations. One limitation in this study was our inability to collect direct information about the depth and dimensions of each station, which would have provided more accurate data for our models. Another limitation was the inability to track whether and relative proportion of particles had traveled from the tunnels and ambient air into the stations directly. This information could substantially support this river-tunnel hypothesis and could be done in future studies with tracer molecules. This river-tunnel effect is likely not unique to NYC, but to our knowledge, it has yet to be studied in other cities and would warrant investigation.

Glossary

PM – Particulate matter, solid and liquid particles in the air.
$PM_{2.5}$ – Particulate matter whose particles have an aerodynamic diameter of 2.5 μm or less.

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Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2022.103579.

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