

**Note to readers with disabilities:** *EHP* strives to ensure that all journal content is accessible to all readers. However, some figures and Supplemental Material published in *EHP* articles may not conform to [508 standards](#) due to the complexity of the information being presented. If you need assistance accessing journal content, please contact [ehp508@niehs.nih.gov](mailto:ehp508@niehs.nih.gov). Our staff will work with you to assess and meet your accessibility needs within 3 working days.

### **Supplemental Material**

#### **PM<sub>2.5</sub> Concentration and Composition in Subway Systems in the Northeastern United States**

David G. Luglio, Maria Katsigeorgis, Jade Hess, Rebecca Kim, John Adragna, Amna Raja, Colin Gordon, Jonathan Fine, George Thurston, Terry Gordon, and M.J. Ruzmyn Vilcassim

#### **Table of Contents**

**Table S1.** Real-time (light-scattering) measured PM<sub>2.5</sub> and BC<sub>2.5</sub> concentrations presented by location (i.e., underground and aboveground stations, on-train, and aboveground ambient) for each transit system and line. All data, except in Philadelphia (February and August 2015), was collected from June to September 2019. Underground data were collected for 5 to 10-minutes at underground stations with single or multiple platforms (the latter were counted as multiple locations), whereas aboveground data correspond to aboveground station platforms. Ambient location samples were collected aboveground outside station entrances. On-train samples represent the concentration measured inside a train-car during the ride between stations (for inter-station rides greater than 3 minutes) and averaged for each run. RH, PM<sub>2.5</sub> and BC<sub>2.5</sub> was collected simultaneously. Real-time PM<sub>2.5</sub> concentrations were adjusted for RH and corrected with gravimetric data.

**Table S2.** Individual station characteristics and real-time PM<sub>2.5</sub> and BC<sub>2.5</sub> concentrations in individual stations according to subway line and urban transit system. PM<sub>2.5</sub>, BC<sub>2.5</sub>, and RH were simultaneously collected on each subway platform for a period between 5 and 10 minutes. PM<sub>2.5</sub> concentrations for underground stations were adjusted for RH and corrected based upon gravimetric data. Average weekday entries refers to the number of turnstile entries for each subway station as reported by the transit agency. Stations are listed in the order of location along each subway line.

**Table S3.** Gravimetric PM<sub>2.5</sub> and simultaneously collected real-time PM<sub>2.5</sub> concentrations. All real-time PM<sub>2.5</sub> concentrations are adjusted for RH (but not yet corrected with the gravimetric data). These stations represent those with the highest measured real-time PM<sub>2.5</sub> concentrations for each subway system. The simultaneously collected data were used to derive a correction factor for real-time PM<sub>2.5</sub> data as reported elsewhere.

**Table S4.** Real-time PM<sub>2.5</sub> concentrations at the different sampling locations (i.e., underground and aboveground platforms, on-train, and ambient) according to subway line and rush hour period. Morning and evening rush-hour corresponds to 6:00 to 10:00 AM and 3:00 to 7:00 PM, respectively. PATH-NYC/NJ and Philadelphia samples were excluded from overall counts since they were only collected during one of the two rush-hours. Underground locations refer to platforms on underground stations. Aboveground locations refer to platforms on aboveground stations. Ambient location samples were collected outside station entrances. On-train samples represent the concentration measured in the train-car during the ride between each station (provided the inter-station ride was greater than 3 minute) and averaged for each run. All concentrations are adjusted for RH and corrected with gravimetric data.

**Table S5.** Trace element airborne concentrations for stations with high PM<sub>2.5</sub> concentrations on 3 urban transit systems. Each sample was collected onto a Teflon filter at 10 L/min for 45 to 60 minutes and analyzed by ED-XRF.

**Table S6.** Normalized trace element concentrations ( $\mu\text{g}$  element/mg PM<sub>2.5</sub>) for stations with high PM<sub>2.5</sub> concentrations on 3 urban transit systems. Each sample was collected onto a Teflon filter at 10 L/min for 45 to 60 minutes. Elemental analysis was conducted using ED-XRF.

**Figure S1.** Regression analysis between the simultaneously collected gravimetric and real-time (light-scattering) measurements of PM<sub>2.5</sub>. The line represents the power curve that best fit the gravimetric and real-time PM<sub>2.5</sub> data. This comparison includes the filter data collected in Washington (n=3), New York City/Jersey City (n=6), Boston (n=6) and Philadelphia (n=7). The regression analysis was performed in R and the power curve with the highest R<sup>2</sup> was selected. One Washington data-point was excluded as an outlier after being identified as having a Cook's distance greater than 4/total sample number.

**Figure S2.** Real-time PM<sub>2.5</sub> concentrations of underground stations according to urban transit line. The vertical lines separate the urban centers. The X's represent the mean PM<sub>2.5</sub> concentration for each subway line. The top and bottom edge and middle line of each box represent the first quartile (Q1), third quartile (Q3) and median, respectively. The error bars represent the minimum and maximum points with values  $\geq Q1 - 1.5 * (Q3 - Q1)$  and  $\leq Q3 + 1.5 * (Q3 - Q1)$ , respectively. Points outside this range are considered outliers, represented as circles. n= 10, 18, 52, 45, 24, 36, 28, 8, 20, 6, 12, and 4, respectively from left to right. WTC = World Trade Center.

**Figure S3.** Comparison of PM<sub>2.5</sub> and BC<sub>2.5</sub> concentrations at underground stations by linear regression, overall combined and separated by urban transit system. All PM<sub>2.5</sub> data were adjusted for RH and corrected with gravimetric data. The line represents the linear equation that best fits the data; Pearson correlation coefficient value is displayed on the upper right of each figure. a) A total of 219 data-points, all samples at underground stations for which BC<sub>2.5</sub> data exists from this study, are included; b) Boston (n=78); c) PATH-NYC/NJ (n=20); d) MTA-NYC (n=12); e) LIRR (n=4); f) Philadelphia (n=21); and g) Washington (n=84).

**Figure S4.** Average percent contribution of elemental constituents to total mass of PM<sub>2.5</sub> collected on filters in underground stations in 3 urban transit systems. Each system is represented by two stations with the highest measured PM<sub>2.5</sub> concentrations. PM<sub>2.5</sub> was collected onto Teflon and quartz filters simultaneously at 10 L/min over a period of 45 to 60 minutes. Trace element analysis was conducted by XRF of the Teflon filters and carbon analysis was performed on the quartz filters using the NIOSH's 5040 method (NIOSH, 2003). a) Average percent contributions in Boston's Government Center (n=1) and Broadway (n=2) stations. More mass was explained than was present on the PM<sub>2.5</sub> filters and therefore the extra mass is indicated by the negative 'Unexplained' wedge. b) Average percent contributions in PATH-NYC/NJ's Christopher Street (n=4) and Newport (n=2) stations. c) Average percent contributions in Washington, DC's Van Ness (n=2) and Capitol South (n=2) stations.

Table S1 – Real-time (light-scattering) measured PM<sub>2.5</sub> and BC<sub>2.5</sub> concentrations presented by location (i.e., underground and aboveground stations, on-train, and aboveground ambient) for each transit system and line. All data, except in Philadelphia (February and August 2015), was collected from June to September 2019. Underground data were collected for 5 to 10-minutes at underground stations with single or multiple platforms (the latter were counted as multiple locations), whereas aboveground data correspond to aboveground station platforms. Ambient location samples were collected aboveground outside station entrances. On-train samples represent the concentration measured inside a train-car during the ride between stations (for inter-station rides greater than 3 minutes) and averaged for each run. RH, PM<sub>2.5</sub> and BC<sub>2.5</sub> was collected simultaneously. Real-time PM<sub>2.5</sub> concentrations were adjusted for RH and corrected with gravimetric data.

System and Line	Number of locations	Number of samples	PM <sub>2.5</sub> (µg/m <sup>3</sup> )				BC <sub>2.5</sub> (µg/m <sup>3</sup> )					RH (%)
			Mean ± SD	Median	Min	Max	Number of samples	Mean ± SD	Median	Min	Max	Mean ± SD
<b>Boston</b>												
Orange												
Underground	6	24	297 ± 110	281	136	514	24	23.3 ± 5.6	13.6	2.0	23.0	51.8 ± 13.3
Aboveground	1	4	16.1 ± 8.8	13.8	806	28.7	4	2.6 ± 1.7	2.1	1.3	5.1	47.4 ± 16.2
On-train	1	4	126 ± 40.6	128	76	174	4	4.4 ± 1.8	4.6	1.9	6.3	47.6 ± 14.0
Ambient	1	3	10.7 ± 3.2	10.9	7.47	13.82	3	1.0 ± 1.1	1.1	0	2.1	59.5 ± 12.3
Green												
Underground	7	28	286 ± 84.8	285	95.9	502	28	13.2 ± 18.1	10.3	2.1	103	47.9 ± 7.7
Aboveground	1	4	13.3 ± 4.9	13.8	7.2	18.4	4	2.2 ± 0.7	2.1	1.5	3.2	39.1 ± 7.2
On-train	1	3	175 ± 57.4	182	114	228	3	4.2 ± 0.7	2.5	3.6	5.0	42.4 ± 3.5
Ambient	1	1	7.2				1	0.3				45.4
Blue												
Underground	2	8	472 ± 118	472	309	637	8	20.4 ± 6.3	20.8	12.6	32.4	52.1 ± 11.0
Aboveground	ND											
On-train	ND											
Ambient	ND											
Red												
Underground	9	36	348 ± 164	359	48	630	18	5.4 ± 4.2	10.4	1.04	15.6	49.6 ± 10.0
Aboveground	1	4	13.3 ± 4.2	13.5	8.12	18.2	2	1.1 ± 1.3	2.1	0.2	2.0	42.1 ± 7.3

On-train	1	5	230 ± 30.6	222	200	267	5	2.3 ± 2.7	4.08	0	6.45	46.5 ± 8.3
Ambient	1	1	10.6				1	0.900				40.9
<b>PATH-NYC/NJ</b>												
Journal Square-33 <sup>rd</sup> St												
Underground	5	20	836 ± 231	764	590	1499	20	28.5 ± 10.2	25.3	17.1	50.8	61.1 ± 7.6
Aboveground	ND											
On-train	1	4	539 ± 281	418	365	958	4	13.9 ± 3.3	14.7	9.2	16.9	58.7 ± 6.9
Ambient	2	2	25.3 ± 7.1	25.3	20.3	30.4	2	2.2 ± 1.9	2.2	0.9	3.5	43.7 ± 0.5
Newark-World Trade Center												
Underground	3	6	614 ± 181	557	392	888	ND					51.1 ± 6.9
Aboveground	ND											
On-train	1	2	267 ± 66.9	267	219	314	ND					47.2 ± 5.3
Ambient	1	1	11.81				ND					42.1
<b>MTA-NYC (F line)</b>												
Underground	3	12	547 ± 207	509	263	959	12	22.4 ± 7.5	23.7	10.9	33.7	59.8 ± 3.5
Aboveground	ND											
On-train	1	4	343 ± 147	279	250	563	4	19.2 ± 22.5	8.82	6.23	52.8	50.9 ± 3.1
Ambient	2	4	24.1 ± 5.9	22.1	19.5	32.6	4	1.8 ± 0.7	1.8	0.9	2.6	56.2 ± 6.8
<b>LIRR (Babylon line)</b>												
Underground	1	4	91.2 ± 38.9	103	36.7	123	4	6.4 ± 3.8	7.8	0.7	9.2	53.8 ± 13.1
Aboveground	1	3	13.8 ± 9.6	10.2	6.5	24.6	3	2.3 ± 1.5	2.1	0.9	3.9	53.6 ± 7.2
On-train	1	6	11.6 ± 5.1	10.7	7.3	18.6	6	1.1 ± 1.0	0.7	0.3	2.9	47.9 ± 5.7
Ambient	ND											
<b>Philadelphia</b>												
Broad Street												
Underground	8	10	118 ± 44.1	110	69	205	3	4.7 ± 3.3	3.4	2.3	8.5	48.3 ± 1.9

Aboveground	ND											
On-train	ND											
Ambient	1	1	6.6				1	1.6				54.5
<b>Market-Frankford</b>												
Underground	6	18	109 ± 49.2	93.3	49.7	227	18	7.5 ± 5.3	6.3	0.9	19.0	38.2 ± 3.7
Aboveground	ND											
On-train	1	3	55.7 ± 2.2	56.0	53.4	57.8	3	2.0 ± 1.1	1.4	1.3	3.3	37.0 ± 3.6
Ambient	6	6	13.6 ± 4.4	15.6	5.3	17.1	6	2.4 ± 0.8	2.5	1.1	3.3	52.7 ± 24.8
<b>Washington, DC</b>												
<b>Red</b>												
Underground	9	36	328 ± 139	291	122	683	36	5.7 ± 2.9	5.5	1.6	16.0	55.4 ± 10.7
Aboveground	2	8	14.4 ± 8.8	12.7	5.0	24.4	8	2.3 ± 0.9	2.3	0.9	3.4	58.0 ± 14.4
On-train	1	4	189 ± 38.2	186	146	239	4	2.6 ± 0.9	2.9	1.3	3.4	45.4 ± 8.1
Ambient	1	3	12.0 ± 7.8	9.1	6.13	20.8	3	1.2 ± 0.8	1.6	0.3	1.6	58.4 ± 9.6
<b>Orange</b>												
Underground	12	48	350 ± 152	317	91.7	720	48	5.3 ± 2.6	4.9	1.3	11.5	50.0 ± 4.2
Aboveground	1	4	15.7 ± 4.6	15.6	10.3	21.2	4	1.1 ± 0.7	1.3	0.1	1.9	59.7 ± 7.2
On-train	1	3	183 ± 33.8	198	144	206	3	1.7 ± 0.7	2.2	0.9	2.2	46.1 ± 8.6
Ambient	ND											

ND – not done

Table S2 – Individual station characteristics and real-time PM<sub>2.5</sub> and BC<sub>2.5</sub> concentrations in individual stations according to subway line and urban transit system. PM<sub>2.5</sub>, BC<sub>2.5</sub>, and RH were simultaneously collected on each subway platform for a period between 5 and 10 minutes. PM<sub>2.5</sub> concentrations for underground stations were adjusted for RH and corrected based upon gravimetric data. Average weekday entries refers to the number of turnstile entries for each subway station as reported by the transit agency. Stations are listed in the order of location along each subway line.

System, Line, and Station	Year station opened	Avg. weekday entries <sup>a</sup>	Type of station	Dates of sample collection	Relative Humidity (%)	PM <sub>2.5</sub> (µg/m <sup>3</sup> )			BC <sub>2.5</sub> (µg/m <sup>3</sup> )		
					Mean ± SD	N	Mean ± SD	Min–Max	N	Mean ± SD	Min–Max
<b>Boston<sup>b</sup></b>											
Orange Line											
Community College		4,159	Above	July 2019	47.4 ± 16.2	4	16.1 ± 8.8	8.1 – 28.7	4	2.6 ± 1.7	1.3 – 5.1
North Station--Lower level	1975	16,273	Under	July 2019	52.1 ± 13.9	4	327 ± 124	170 – 441	4	16.5 ± 0.8	15.8 – 17.5
Haymarket--Orange Line level	1908	10,597	Under	July 2019	51.2 ± 16.7	4	313 ± 137	205 – 514	4	12.6 ± 7.1	7.2 – 22.9
State Street--Orange Line level	1908	12,928	Under	July 2019	54.6 ± 16.4	4	339 ± 70.9	287 – 440	4	15.2 ± 6.4	6.8 – 21.0
Downtown Crossing--Orange Line level	1908	24,074	Under	July 2019	51.5 ± 14.6	4	267 ± 79.6	184 – 373	4	12.3 ± 4.9	5.1 – 16.3
Chinatown	1908	5,747	Under	July 2019	50.0 ± 13.7	4	233 ± 84.5	136 – 340	4	8.2 ± 4.9	2.0 – 12.6
Tufts Medical Center	1987	5,976	Under	July 2019	51.4 ± 14.1	4	305 ± 171	157 – 511	4	15.0 ± 6.6	9.6 – 23.0
Green Line											
Science Park/West End		873	Above	July 2019	39.1 ± 7.2	4	13.3 ± 4.9	7.2 – 18.4	4	2.2 ± 0.7	1.5 – 3.2
North Station--Upper level	2004	16,273	Under	July 2019	45.5 ± 6.3	4	302 ± 50.3	147 – 369	4	12.0 ± 1.9	9.6 – 14.2
Haymarket - Green Line level	1898	10,597	Under	July 2019	41.5 ± 4.3	4	216 ± 94.9	95.9 – 327	4	8.0 ± 4.4	2.1 – 12.3
Government Center - Green Line level	1898	7,677	Under	July 2019	48.3 ± 4.9	4	339 ± 89.2	226 – 443	4	12.3 ± 1.2	10.5 – 13.1
Park Street--Green Line level	1897	16,571	Under	July 2019	48.2 ± 4.7	4	349 ± 115	252 – 502	4	11.8 ± 5.8	4.4 – 17.8
Boylston	1897	5,265	Under	July 2019	47.7 ± 3.6	4	309 ± 30.4	278 – 349	4	9.7 ± 6.3	2.2 – 17.5
Arlington	1921	6,813	Under	July 2019	48.6 ± 5.1	4	291 ± 33.8	265 – 339	4	8.5 ± 2.1	5.5 – 10.4

Copley	1914	12,244	Under	July 2019	55.3 ± 16.1	4	194 ± 42.3	153 – 247	4	29.9 ± 48.9	4.5 – 103
<b>Blue Line</b>											
Government Center - Blue Line level	1898	7,677	Under	July 2019	49.9 ± 4.2	4	507 ± 93.5	381 – 604	4	22.8 ± 6.7	17.4 – 32.4
State Street--Blue Line level	1904	12,928	Under	July 2019	54.3 ± 15.9	4	437 ± 144	309 – 638	4	18.0 ± 5.7	12.6 – 23.0
<b>Red Line</b>											
JFK/Umass		8,012	Above	July 2019	42.1 ± 7.3	4	13.3 ± 4.2	8.1 – 18.2	2	1.1 ± 1.3	0.2 – 2.0
Andrew	1918	5,721	Under	July 2019	44.1 ± 7.2	4	277 ± 47.5	214 – 325	2	2.5 ± 2.1	1.1 – 4.0
Broadway	1918	6,020	Under	July 2019	48.1 ± 6.7	4	599 ± 38.2	545 – 631	2	9.8 ± 8.1	4.1 – 15.6
South Station	1916	24,639	Under	July 2019	50.3 ± 8.2	4	350 ± 43.0	293 – 390	2	5.6 ± 0.02	5.61 – 5.64
Downtown Crossing - Red Line level	1915	24,704	Under	July 2019	51.7 ± 9.5	4	473 ± 70.6	423 – 574	2	4.9 ± 1.4	3.9 – 5.8
Park Street--Red Line level	1912	16,571	Under	July 2019	52.0 ± 9.9	4	455 ± 109	351 – 604	2	4.2 ± 2.7	2.3 – 6.2
Charles/MGH	1932	10,515	Under	July 2019	43.5 ± 11.7	4	58.1 ± 6.9	48.3 – 64.4	2	1.3 ± 0.3	1.0 – 1.5
Kendall/MIT	1912	17,018	Under	July 2019	19.1 ± 12.1	4	288 ± 111	170 – 398	2	6.0 ± 5.4	2.2 – 9.9
Central	1912	15,405	Under	July 2019	50.8 ± 13.0	4	240 ± 64.9	182 – 302	2	4.7 ± 1.6	3.5 – 5.9
Harvard	1983	18,528	Under	July 2019	56.7 ± 13.6	4	389 ± 121	213 – 475	2	10.0 ± 6.8	5.2 – 14.7
<b>PATH-NYC/NJ'</b>											
Journal Square – 33 <sup>rd</sup> St											
Newport	1909	19,351	Under	July & August 2019	69.5 ± 3.2	4	835 ± 144	687 – 979	4	288 ± 4.7	24.7 – 35.3
Christopher Street	1908	5,199	Under	July & August 2019	65.3 ± 5.0	4	1208 ± 195	1095 – 1499	4	45.8 ± 4.3	41.3 – 50.8
9th Street	1908	5,067	Under	July & August 2019	60.6 ± 5.9	4	819 ± 96.7	755 – 977	4	27.7 ± 3.6	24.7 – 32.9

14th Street	1908	9,121	Under	July & August 2019	56.5 ± 6.0	4	674 ± 76.0	590 – 773	4	20.9 ± 3.0	17.1 – 24.0
23rd Street	1908	9,682	Under	July & August 2019	53.7 ± 6.0	4	644 ± 29.5	616 – 685	4	19.2 ± 0.7	18.5 – 20.0
Newark – World Trade Center											
Exchange Place	1910	18,262	Under	August 2019	48.0 ± 0.6	2	510 ± 166	392 – 627	ND		
Grove Street	1910	22,191	Under	August 2019	58.4 ± 1.5	2	779 ± 155	669 – 888	ND		
World Trade Center	1971	64,048	Under	August 2019	46.9 ± 8.5	2	473 ± 19.7	459 – 486	ND		
<b>MTA-NYC<sup>d</sup></b>											
2nd Avenue	1936	16,703	Under	July & August 2019	59.6 ± 4.3	4	685 ± 220	479 – 959	4	22.9 ± 8.2	10.9 – 28.2
West 4th Street - Lower level	1940	41,938	Under	July & August 2019	60.0 ± 3.1	4	543 ± 179	367 – 727	4	26.6 ± 7.0	18.7 – 33.7
14th Street (F/M Line)	1940	46,363	Under	July & August 2019	59.9 ± 4.1	4	414 ± 166	263 – 646	4	17.8 ± 6.1	12.2 – 25.8
<b>LIRR (Babylon Line)<sup>e</sup></b>											
Seaford		NF	Above	August 2019	53.6 ± 7.2	3	13.8 ± 9.6	6.5 – 24.6	3	2.3 ± 1.5	0.9 – 3.9
Penn Station		NF	Under	August 2019	53.8 ± 13.1	4	91.2 ± 38.9	36.7 – 123	4	6.4 ± 3.8	0.7 – 9.2
<b>Philadelphia<sup>f</sup></b>											
Broad Street Line											
Girard	1928	3,592	Under	August 2015	47.8	1	120		1	8.52	
Fairmont	1928	1,776	Under	August 2015	49.6	1	101		ND		
Spring Garden	1928	5,513	Under	August 2015	49.9	1	155		ND		
Race-Vine	1928	2,573	Under	August 2015	46.3 ± 3.7	2	112 ± 60.7	69.2 – 155	1	2.26	

City Hall	1928	2,313	Under	August 2015	49.68 ± 1.8	2	137 ± 96.0	69.1 – 204.8	1	3.44	
Walnut-Locust	1930	6,804	Under	August 2015	48.6	1	79.0		ND		
Lombard South	1930	2,586	Under	August 2015	47.8	1	95.6		ND		
Ellsworth-Federal	1938	3,004	Under	August 2015	48.0	1	127		ND		
Market-Frankford Line											
2nd Street	1908	3,431	Under	February 2015	43.7 ± 0.5	3	114 ± 68.9	49.7 – 187	3	9.0 ± 6.5	1.9 – 14.5
5th Street	1908	3,482	Under	February 2015	43.6 ± 1.4	3	74.7 ± 9.2	67.8 – 85.1	3	4.5 ± 1.8	2.5 – 6.0
13th Street	1908	7,107	Under	August 2015	39.3	1	71.3		1	1.13	
15th Street	1907	30,031	Under	February & August 2015	34.8	4	113 ± 51.6	55.8 – 169.3	4	6.7 ± 6.5	0.9 – 14.7
30th Street	1955	6,729	Under	February & August 2015	34.6	4	137 ± 60.5	99.8 – 227	4	11.1 ± 6.1	6.2 – 19.0
34th Street	1955	6,175	Under	February 2015	37.9 ± 1.8	3	109 ± 46.1	78.8 – 162.3	3	7.5 ± 3.6	4.4 – 11.5
Washington <sup>9</sup>											
Red Line											
Rhode Island Avenue		5,078	Above	June 2019	56.8 ± 15.6	4	13.5 ± 9.5	4.99 – 24.4	4	2.1 ± 1.1	0.9 – 3.4
NoMa		10,350	Above	June 2019	59.3 ± 15.3	4	15.2 ± 9.5	7.03 – 24.2	4	2.6 ± 0.8	1.8 – 3.3
Union Station	1976	27,950	Under	June 2019	61.0 ± 14.3	4	176 ± 40.0	122 – 208	4	9.3 – 5.4	3.6 – 16.0
Judiciary Square	1976	7,230	Under	June 2019	50.5 ± 8.9	4	308 ± 111	195 – 462	4	4.3 ± 0.9	3.4 – 5.2
Gallery Place, Upper level	1976	22,770	Under	June 2019	49.5 ± 8.2	4	337 ± 58.2	271 – 411	4	5.2 ± 2.2	2.0 – 7.3
Metro Center, Upper level	1976	24,790	Under	June 2019	48.3 ± 7.8	4	226 ± 44.3	193 – 288	4	3.2 ± 1.1	1.6 – 4.2
Farragut North	1976	22,750	Under	June 2019	62.5 ± 11.1	4	339 ± 118	202 – 455	4	5.3 ± 2.4	3.2 – 7.6

Dupont Circle	1977	16,710	Under	June 2019	65.0 ± 11.6	4	370 ± 232	137 – 683	4	5.1 ± 1.2	4.1 – 6.7
Woodley Park	1981	6,056	Under	June 2019	51.7 ± 8.4	4	347 ± 126	172 – 445	4	4.3 ± 1.8	2.2 – 5.9
Cleveland Park	1981	3,818	Under	June 2019	56.1 ± 10.1	4	389 ± 120	213 – 482	4	5.8 ± 2.4	2.4 – 7.9
Van Ness	1981	5,585	Under	June 2019	54.4 ± 9.9	4	465 ± 176	210 – 599	4	8.7 ± 1.2	7.6 – 10.4
Orange Line											
Minnesota Avenue		2,251	Above	June 2019	59.7 ± 7.2	4	15.7 ± 4.6	10.3 – 21.2	4	1.1 ± 0.7	0.1 – 1.9
Stadium-Armory	1977	2,398	Under	June 2019	54.5 ± 6.1	4	323 ± 148	163 – 492	4	5.6 ± 4.0	1.7 -- 1.2
Potomac Avenue	1977	3,503	Under	June 2019	52.8 ± 4.4	4	471 ± 126	311 – 607	4	7.5 ± 3.2	4.0 – 11.5
Eastern Market	1977	5,638	Under	June 2019	50.4 ± 3.6	4	462 ± 64.3	391 – 527	4	7.5 ± 3.1	4.0 – 10.3
Capitol South	1977	7,132	Under	June 2019	49.9 ± 3.0	4	540 ± 183	319 – 720	4	5.6 ± 3.5	1.3 – 8.8
Federal Center Southwest	1977	5,791	Under	June 2019	50.5 ± 3.2	4	388 ± 213	91.7 – 581	4	6.2 ± 2.7	3.8 – 9.4
L'Enfant Plaza, Lower level	1977	20,270	Under	June 2019	47.8 ± 2.2	4	380 ± 102	272 – 477	4	6.1 ± 2.1	3.3 – 8.23
Smithsonian	1977	9,119	Under	June 2019	51.5 ± 3.8	4	240 ± 133	109 – 406	4	3.6 ± 1.8	1.6 – 5.5
Federal Triangle	1977	7,150	Under	June 2019	49.7 ± 1.7	4	300 ± 171	161 – 534	4	4.5 ± 2.2	1.8 – 6.5
Metro Center, Lower level	1977	24,790	Under	June 2019	47.8 ± 1.9	4	243 ± 55.3	194 -- 316	4	3.5 ± 1.4	1.9 – 5.2
McPherson Square	1977	14,090	Under	June 2019	44.1 ± 3.3	4	294 ± 57.0	244 – 375	4	3.6 ± 1.4	2.5 – 5.8
Farragut West	1977	19,950	Under	June 2019	47.9 ± 3.3	4	270 ± 110	171 – 436	4	4.0 ± 1.5	1.8 – 5.1
Foggy Bottom	1977	18,800	Under	June 2019	52.9 ± 5.2	4	292 ± 166	182 – 537	4	4.4 ± 1.7	2.5 – 6.4

<sup>a</sup>All ridership data are from 2019 (Washington, PATH-NYC, MTA-NYC, and Boston) and 2017 (Philadelphia).

<sup>b</sup>Ridership data retrieved from: <https://mbta-massdot.opendata.arcgis.com/datasets/average-weekday-gated-entries-fy19/data>. A map of the transit system may be found at <https://www.mbta.com/schedules>

°Ridership data retrieved from: <https://www.panynj.gov/path/en/about/stats.html>. A map of the transit system may be found at <https://www.panynj.gov/path/en/schedules-maps.html>.

°Ridership data retrieved from: <https://new.mta.info/agency/new-york-city-transit/subway-bus-ridership-2019>. A map of the transit system may be found at <https://new.mta.info/maps>.

°Ridership data retrieved from: <http://septaopendata-septa.opendata.arcgis.com/datasets/septa-broad-street-line-stations> and <http://septaopendata-septa.opendata.arcgis.com/datasets/septa-market-frankford-line-stations>. A map of the transit system may be found at <http://www.septa.org/maps/system/index.html>.

°Ridership data retrieved from: <https://www.wmata.com/initiatives/ridership-portal/Rail-Data-Portal.cfm>. A map of the transit system may be found at <https://www.wmata.com/schedules/maps/index.cfm>.

ND – not done

NF – not found

Table S3 – Gravimetric PM<sub>2.5</sub> and simultaneously collected real-time PM<sub>2.5</sub> concentrations. All real-time PM<sub>2.5</sub> concentrations are adjusted for RH (but not yet corrected with the gravimetric data). These stations represent those with the highest measured real-time PM<sub>2.5</sub> concentrations for each subway system. The simultaneously collected data were used to derive a correction factor for real-time PM<sub>2.5</sub> data as reported elsewhere.

System, Line, and Station	Date of sample collection	AM or PM	Real-time PM <sub>2.5</sub>		Gravimetric PM <sub>2.5</sub>	
			N	Concentration or mean ± SD (µg/m <sup>3</sup> )	N	Concentration or mean ± SD (µg/m <sup>3</sup> )
<b>Boston</b>						
Overall			6	106 ± 21.6	6	450 ± 138
Red Line						
Broadway, sample 1	July 2019	AM	1	85.3	1	415
Broadway, sample 2	July 2019	AM	1	136	1	413
Broadway mean			2	111 ± 36.0	2	414 ± 1.8
Blue Line						
Government Center, sample 1	July 2019	AM	1	95.7	1	244
Government Center, sample 2	September 2020	PM	1	90.4	1	630
Government Center mean			2	93.0 ± 3.8	2	437 ± 273
Orange Line						
Tufts Medical Center, sample 2	September 2020	PM	1	100	1	419
Tufts Medical Center, sample 2	September 2020	PM	1	131	1	579
Tufts Medical Center mean			2	115 ± 21.5	2	499 ± 113
<b>PATH-NYC/NJ</b>						
Overall			6	444 ± 188	6	1020 ± 557
Newport station, sample 1	July 2019	AM	1	271	1	590
Newport station, sample 1	July 2019	PM	1	336	1	516
Newport station, mean			2	303 ± 45.9	2	553 ± 52.3
Christopher station, sample 1	July 2019	AM	1	418	1	1780
Christopher station, sample 2	July 2019	PM	1	292	1	824
Christopher station, sample 3	August 2019	AM	1	635	1	742
Christopher station, sample 4	August 2019	AM	1	716	1	1669
Christopher station, mean			4	515 ± 195	4	1254 ± 546
<b>Philadelphia</b>						
Overall						
Broad Street Line						
Race/Vine	August 2015	PM	1	20.1	1	68.3
City Hall	August 2015	PM	1	20.0	1	51.7
Entire-line <sup>a</sup>	August 2015	PM	1	41.4	1	131
Market-Frankford Line						
13 <sup>th</sup> Street	August 2015	PM	1	20.9	1	67.7
15 <sup>th</sup> Street	August 2015	PM	1	27.1	1	93.4

30 <sup>th</sup> Street	August 2015	PM	1	31.1	1	96.8
Entire-line <sup>a</sup>	August 2015	PM	1	29.8	1	93.4
<b>Washington</b>						
Overall			4	182 ± 89.2	4	255 ± 114
Red Line						
Van Ness, sample 1	June 2019	AM	1	70.2	1	217
Van Ness, sample 2	June 2019	AM	1	166	1	268
Van Ness mean			2	118 ± 67.9	2	243 ± 36.1
Orange Line						
Capitol South, sample 1	June 2019	AM	1	285	1	403
Capitol South, sample 2	June 2019	AM	1	206	1	130
Capitol mean			2	245 ± 56.1	2	267 ± 193

<sup>a</sup>Simultaneous real-time and gravimetric PM<sub>2.5</sub> sampling was performed both on the train and at the subway station platforms.

Table S4 – Real-time PM<sub>2.5</sub> concentrations at the different sampling locations (i.e., underground and aboveground platforms, on-train, and ambient) according to subway line and rush hour period. Morning and evening rush-hour corresponds to 6:00 to 10:00 AM and 3:00 to 7:00 PM, respectively. PATH-NYC/NJ and Philadelphia samples were excluded from overall counts since they were only collected during one of the two rush-hours. Underground locations refer to platforms on underground stations. Aboveground locations refer to platforms on aboveground stations. Ambient location samples were collected outside station entrances. On-train samples represent the concentration measured in the train-car during the ride between each station (provided the inter-station ride was greater than 3 minute) and averaged for each run. All concentrations are adjusted for RH and corrected with gravimetric data.

System and location	Morning rush-hour			Evening rush-hour		
	Number of locations	Number of samples	Mean PM <sub>2.5</sub> ± SD (µg/m <sup>3</sup> )	Number of locations	Number of samples	Mean PM <sub>2.5</sub> ± SD (µg/m <sup>3</sup> )
Underground stations						
Overall <sup>a</sup>	49	102	356 ± 171	49	94	326 ± 139
Boston	24	52	326 ± 152	24	44	330 ± 117
PATH-NYC/NJ	8	26	779 ± 242	ND		
MTA-NYC	3	6	563 ± 249	3	6	532 ± 179
LIRR	1	2	103 ± 17.9	1	2	79.8 ± 60.9
Philadelphia	ND			14	28	112 ± 46.7
Washington	21	42	377 ± 158	21	42	305 ± 126
Aboveground stations						
Overall <sup>a</sup>	7	13	18.3 ± 6.0	7	14	10.8 ± 5.3
Boston	3	6	16.7 ± 3.2	3	6	11.8 ± 7.2
LIRR	1	1	10.2	1	2	15.6 ± 12.8
Washington	3	6	21.3 ± 3.1	3	6	8.3 ± 3.4
On-train						

Overall	7	15	180 ± 137	7	14	159 ± 95.5
Boston	3	6	187 ± 68.3	3	6	176 ± 56.1
PATH-NYC/NJ	2	6	449 ± 261	ND		
MTA-NYC	2	2	407 ± 221	2	2	279 ± 5.3
LIRR	1	3	10.8 ± 4.9	1	3	12.3 ± 6.3
Philadelphia	ND			1	3	55.7 ± 2.2
Washington	2	4	183 ± 26.8	2	3	191 ± 47.2
Ambient						
Overall <sup>a</sup>	5	7	16.8 ± 8.3	5	5	13.0 ± 8.4
Boston	2	3	11.8 ± 1.8	2	2	7.4 ± 0.2
PATH-NYC/NJ	3	3	20.8 ± 9.3	ND		
MTA-NYC	2	2	26.1 ± 9.3	2	2	22.1 ± 1.8
Philadelphia	ND			7	7	12.6 ± 4.8
Washington	1	2	15.0 ± 8.3	1	1	6.1

ND – not done

<sup>a</sup> PATH-NYC/NJ and Philadelphia samples were excluded from overall counts because they were only collected during 1 of the 2 rush-hours.

Table S5 – Trace element airborne concentrations for stations with high PM<sub>2.5</sub> concentrations on 3 urban transit systems. Each sample was collected onto a Teflon filter at 10 L/min for 45 to 60 minutes and analyzed by ED-XRF.

System, Line, and Station	Number of samples	Mean ± SD (µg/m <sup>3</sup> )								
		Na	Mg	Al	Cr	Mn	Ni	Cu	Zn	Ba
<b>Boston</b>										
Government Center—Blue Line	1 <sup>a</sup>	1.9	2.3	0.8	1.3	2.1	0.1	0.8	0.2	2.0
Broadway	2	1.8 ± 0.5	1.7 ± 0.3	1.8 ± 0.3	1.0 ± 0.1	1.5 ± 0.1	0.2 ± 0.02	1.1 ± 0.1	0.3 ± 0.1	1.5 ± 0.4
<b>PATH-NYC/NJ</b>										
Newport	2	2.4 ± 0.2	0.7 ± 0.04	0.2 ± 0.3	0.4 ± 0.1	1.6 ± 0.4	0.2 ± 0.4	0.9 ± 0.2	0.8 ± 0.2	4.2 ± 0.9
Christopher Street	4	2.8 ± 0.9	1.2 ± 0.4	0.5 ± 1.0	0.7 ± 0.3	3.0 ± 1.0	0.4 ± 0.1	1.5 ± 0.5	1.2 ± 0.4	6.0 ± 1.8
<b>Washington, DC</b>										
Van Ness	2	1.4 ± 0.7	3.4 ± 1.1	0.7 ± 0.2	0.5 ± 0.1	1.5 ± 0.4	0.2 ± 0.1	0.8 ± 0.2	0.4 ± 0.03	0.7 ± 0.1
Capitol South	2	4.1 ± 5.0	1.9 ± 2.0	1.6 ± 1.2	0.4 ± 0.2	1.1 ± 0.6	0.3 ± 0.2	4.6 ± 3.7	3.2 ± 2.7	0.6 ± 0.3

<sup>a</sup>One sample was excluded due to a sampling error.

Table S6 – Normalized trace element concentrations ( $\mu\text{g}$  element/ $\text{mg}$   $\text{PM}_{2.5}$ ) for stations with high  $\text{PM}_{2.5}$  concentrations on 3 urban transit systems. Each sample was collected onto a Teflon filter at 10 L/min for 45 to 60 minutes. Elemental analysis was conducted using ED-XRF.

System, Line, and Station	Number of samples	Mean $\pm$ SD ( $\mu\text{g}/\text{mg}$ )								
		Na	Mg	Al	Cr	Mn	Ni	Cu	Zn	Ba
<b>Boston</b>										
Government Center—Blue Line	1 <sup>a</sup>	7.8	9.3	3.3	5.4	8.4	0.6	3.4	0.9	8.3
Broadway	2	4.3 $\pm$ 1.3	4.1 $\pm$ 0.8	4.6 $\pm$ 0.6	1.5 $\pm$ 0.3	3.7 $\pm$ 0.4	0.4 $\pm$ 0.05	2.7 $\pm$ 0.3	0.7 $\pm$ 0.1	3.6 $\pm$ 1.1
<b>PATH-NYC/NJ</b>										
Newport	2	4.4 $\pm$ 0.1	1.4 $\pm$ 0.1	0.4 $\pm$ 0.6	0.6 $\pm$ 0.2	3.0 $\pm$ 0.9	0.4 $\pm$ 0.1	1.6 $\pm$ 0.5	1.4 $\pm$ 0.5	7.7 $\pm$ 2.4
Christopher Street	4	2.4 $\pm$ 1.6	1.0 $\pm$ 0.5	0.6 $\pm$ 1.3	0.6 $\pm$ 0.4	2.5 $\pm$ 1.7	0.3 $\pm$ 0.2	1.2 $\pm$ 0.5	1.0 $\pm$ 0.7	5.1 $\pm$ 3.5
<b>Washington, DC</b>										
Van Ness	2	6.2 $\pm$ 0.1	14.5 $\pm$ 3.2	3.2 $\pm$ 1.4	2.3 $\pm$ 0.9	6.2 $\pm$ 2.4	0.8 $\pm$ 0.4	3.3 $\pm$ 1.3	1.9 $\pm$ 0.4	2.9 $\pm$ 1.0
Capitol South	2	11.3 $\pm$ 10.8	5.8 $\pm$ 6.6	5.9 $\pm$ 0.3	1.8 $\pm$ 0.4	4.4 $\pm$ 1.0	1.0 $\pm$ 0.1	16.3 $\pm$ 2.2	11.2 $\pm$ 2.0	2.4 $\pm$ 0.6

<sup>a</sup>One sample was excluded due to a sampling error.

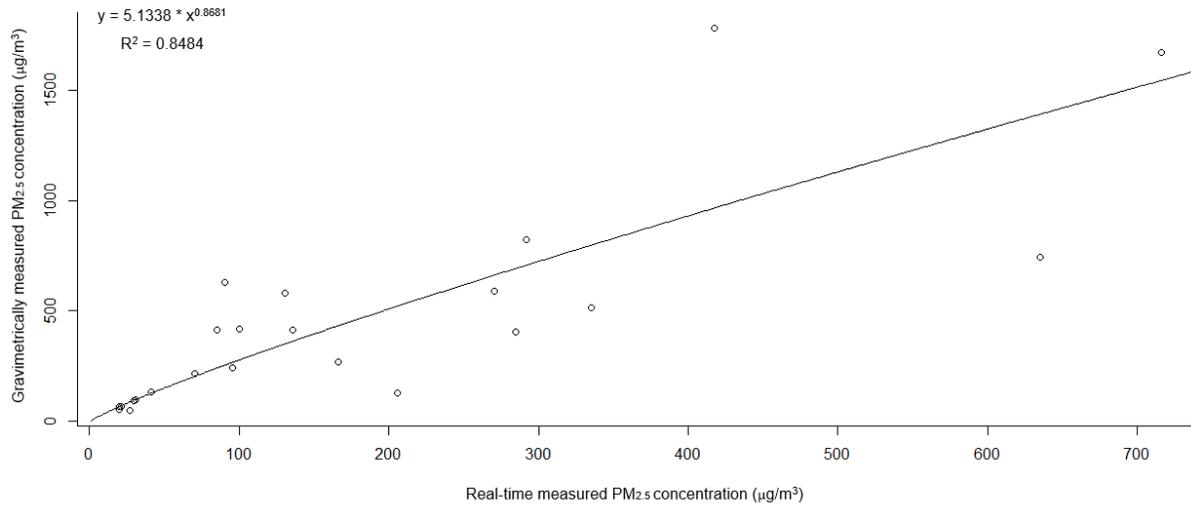


Figure S1 - Regression analysis between the simultaneously collected gravimetric and real-time (light-scattering) measurements of PM<sub>2.5</sub>. The line represents the power curve that best fit the gravimetric and real-time PM<sub>2.5</sub> data. This comparison includes the filter data collected in Washington (n=3), New York City/Jersey City (n=6), Boston (n=6) and Philadelphia (n=7). The regression analysis was performed in R and the power curve with the highest R<sup>2</sup> was selected. One Washington data-point was excluded as an outlier after being identified as having a Cook's distance greater than 4/total sample number.

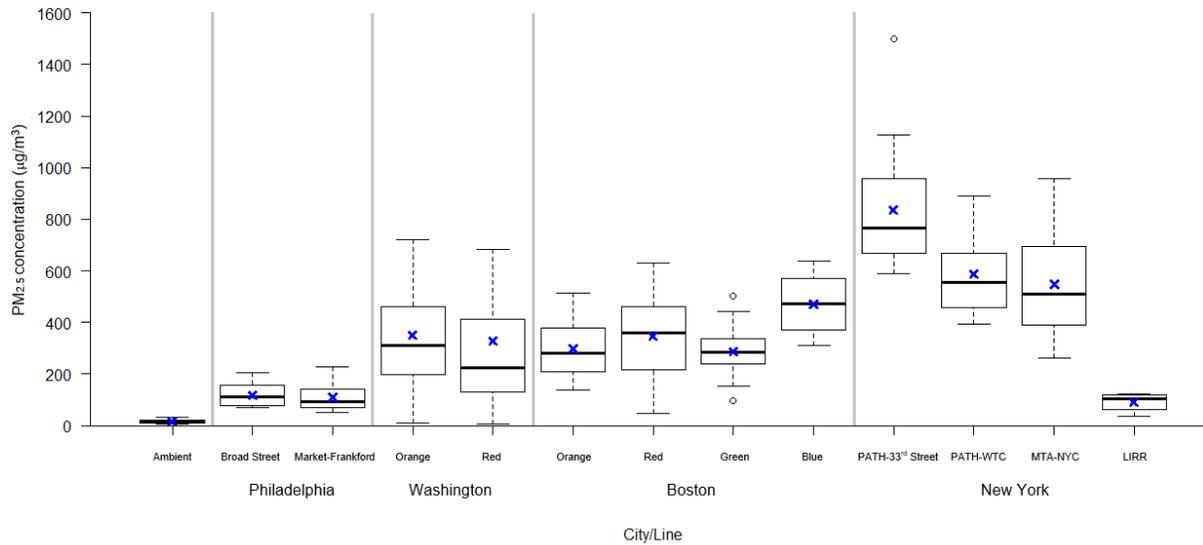


Figure S2 - Real-time  $PM_{2.5}$  concentrations of underground stations according to urban transit line. The vertical lines separate the urban centers. The X's represent the mean  $PM_{2.5}$  concentration for each subway line. The top and bottom edge and middle line of each box represent the first quartile (Q1), third quartile (Q3) and median, respectively. The error bars represent the minimum and maximum points with values  $\geq Q1 - 1.5 * (Q3 - Q1)$  and  $\leq Q3 + 1.5 * (Q3 - Q1)$ , respectively. Points outside this range are considered outliers, represented as circles. n= 10, 18, 52, 45, 24, 36, 28, 8, 20, 6, 12, and 4, respectively from left to right. WTC = World Trade Center.

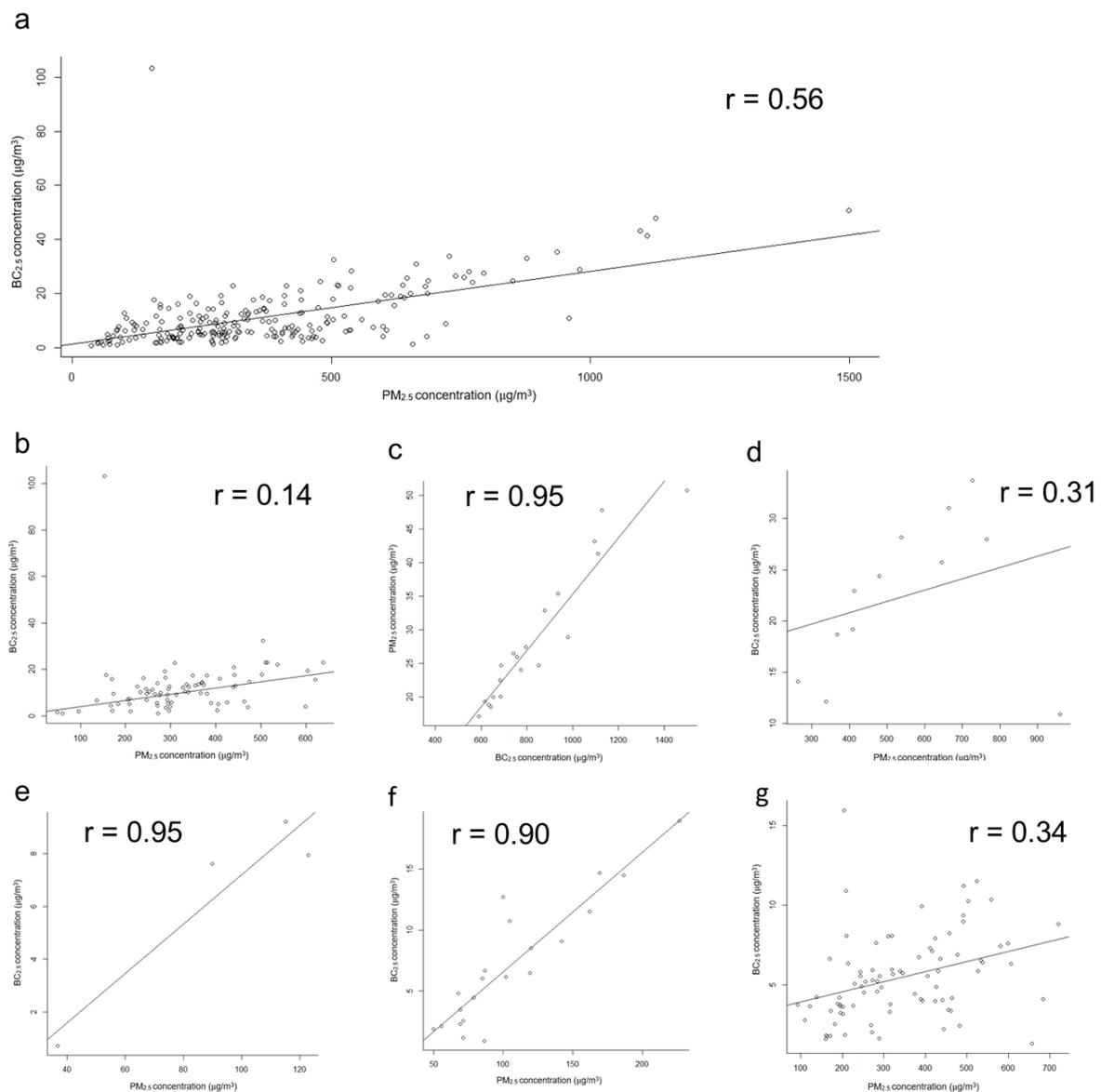


Figure S3 – Comparison of PM<sub>2.5</sub> and BC<sub>2.5</sub> concentrations at underground stations by linear regression, overall combined and separated by urban transit system. All PM<sub>2.5</sub> data were adjusted for RH and corrected with gravimetric data. The line represents the linear equation that best fits the data; Pearson correlation coefficient value is displayed on the upper right of each figure. a) A total of 219 data-points, all samples at underground stations for which BC<sub>2.5</sub> data exists from this study, are included; b) Boston (n=78); c) PATH-NYC/NJ (n=20); d) MTA-NYC (n=12); e) LIRR (n=4); f) Philadelphia (n=21); and g) Washington (n=84).

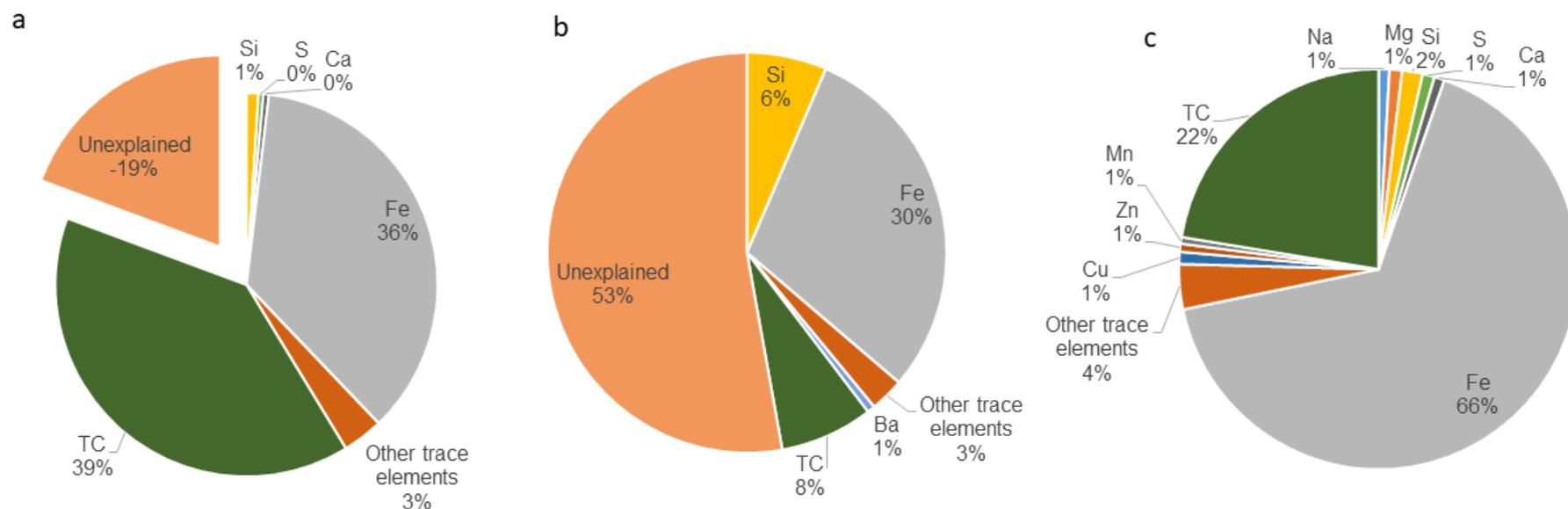


Figure S4 – Average percent contribution of elemental constituents to total mass of  $PM_{2.5}$  collected on filters in underground stations in 3 urban transit systems. Each system is represented by two stations with the highest measured  $PM_{2.5}$  concentrations.  $PM_{2.5}$  was collected onto Teflon and quartz filters simultaneously at 10 L/min over a period of 45 to 60 minutes. Trace element analysis was conducted by XRF of the Teflon filters and carbon analysis was performed on the quartz filters using the NIOSH's 5040 method (NIOSH, 2003). a) Average percent contributions in Boston's Government Center (n=1) and Broadway (n=2) stations. More mass was explained than was present on the  $PM_{2.5}$  filters and therefore the extra mass is indicated by the negative 'Unexplained' wedge. b) Average percent contributions in PATH-NYC/NJ's Christopher Street (n=4) and Newport (n=2) stations. c) Average percent contributions in Washington, DC's Van Ness (n=2) and Capitol South (n=2) stations.