Environmental Science & Technology

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Impacts of Subway System Modifications on Air Quality in Subway Platforms and Trains

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Cite This: https://doi.org/10.1021/acs.est.1c00703

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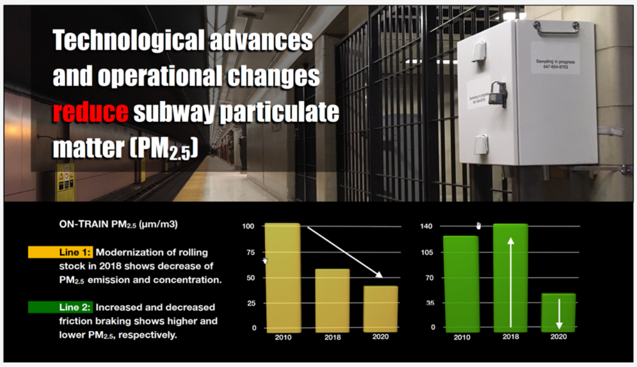

ABSTRACT: Subway $PM_{2.5}$ can be substantially sourced from the operation of the system itself. Improvements in subway air quality may be possible by examining the potential to reduce these emissions. To this end, $PM_{2.5}$ was measured on the trains and station platforms of the Toronto subway system. A comparison with previously published data for this system reveals significant changes in below ground platform $PM_{2.5}$. A reduction of nearly one-third (ratio (95% CI): 0.69 (0.63, 0.75)) in $PM_{2.5}$ from 2011 to 2018 appears to have resulted from a complete modernization of the rolling stock on one subway line. In contrast, below ground platform $PM_{2.5}$ for another line increased by a factor of 1.48 (95% CI; 1.42, 1.56). This increase may be related to an increase in emergency brake applications, the resolution of which coincided with a large decrease in $PM_{2.5}$ concentrations on that line. Finally, platform $PM_{2.5}$ in two newly opened stations attained, within one year of operation, typical concentrations of the neighboring platforms installed in 1963. Combined, these findings suggest that the production of platform $PM_{2.5}$ is localized and hence largely freshly emitted. Further, $PM_{2.5}$ changed across this subway system due to changes in its operation and rolling stock. Thus, similar interventions applied intentionally may prove to be equally effective in reducing $PM_{2.5}$. Moreover, establishing a network of platform $PM_{2.5}$ monitors is recommended to monitor ongoing improvements and identify impacts of future system changes on subway air quality. This would result in a better understanding of the relationship between the operations and air quality of subways.

KEYWORDS: *$PM_{2.5}$, subway, exposure, metro, intervention, braking, vacuuming, trains*

1. INTRODUCTION

Over the past century, commuter railways have become a staple of public transit. As well as being ideal for cross-city mass transit, they decrease private vehicle dependency, which can improve ambient air quality.[1−4] While the below ground (BG) option (subways) is the most expensive to build,[5] it can preserve developed street-level property. Unfortunately, the BG sections of commuter rail systems have significantly higher levels of particulate matter (PM) air pollution.[6−8] Research on the sources, levels, and trends of subway PM has revealed fine particulate matter ($PM_{2.5}$) concentrations to be substantially above ambient levels[7,9−11] and contribute a significant proportion of daily $PM_{2.5}$ for subway commuters.[8,10−13] Further, its large steel- and brake-sourced nature results in daily personal $PM_{2.5}$ exposures that are elementally distinct from those of nonsubway commuters.[6,14−16] These findings have raised health concerns. Currently, research on the health effects of subway air pollution is limited in number and lack consensus.[17] While a well-established causal link exists between outdoor $PM_{2.5}$ exposure and health,[18,19] this evidence cannot be reliably applied to subway $PM_{2.5}$ on account of the physiochemical differences between outdoor and subway $PM_{2.5}$.[6,20−24] Policy initiatives aiming to assess the risk of subway air quality have been conducted in London, U.K.[25] and Toronto, Canada[26] and recommended the development of air quality mitigation strategies to lower subway PM levels in both the short and long-term.

Multiple studies have evaluated approaches to improve subway air quality.[27] While viable strategies have been identified, there is complexity in the circumstances of their efficacy. Subway stations with platform screen doors (PSDs) have been associated with lower PM levels relative to those without.[28−30] However, in-train PM can increase as a result.[30] To meet federal fire protection regulations, mechanical ventilation systems are an essential component of subway tunnels. These systems can

Received: February 17, 2021
Revised: June 22, 2021
Accepted: June 22, 2021

ACS Publications

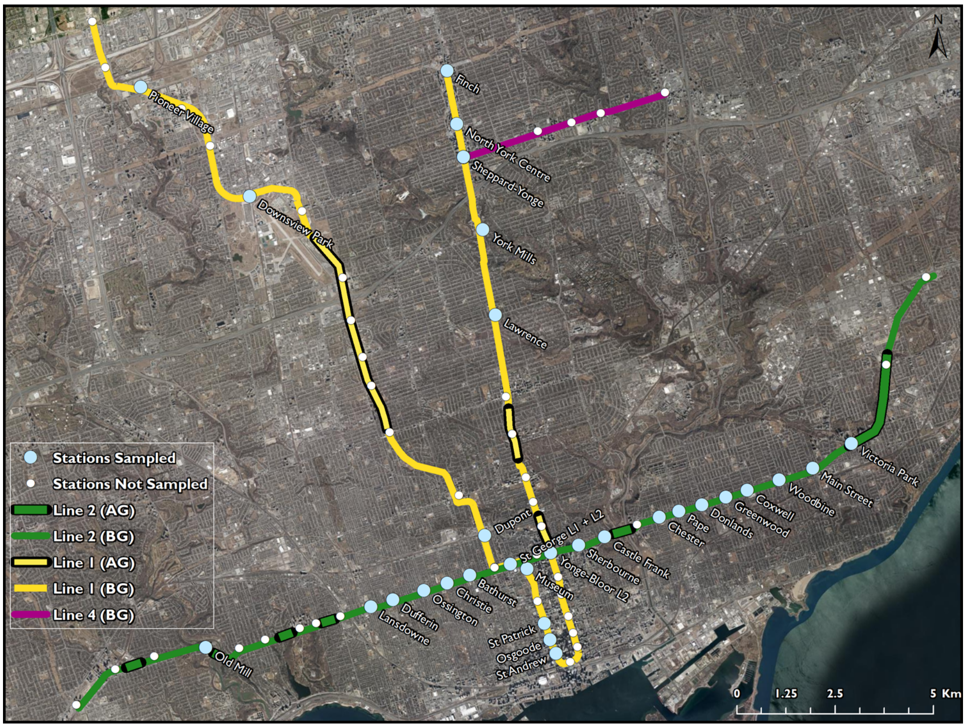

Figure 1. Toronto subway system. Platform $PM_{2.5}$ monitoring of 2017/2018. Data was collected from 3 to 5 platforms at a time on Lines 1 and 2 from December 2017 to August 2018 for the purpose of research question no. 1. On-train monitoring was conducted line wide for several days on Lines 1 and 2 in the fall of 2018 and winter of 2019/2020. These platform and on-train data were compared to that of the previous 2010/2011 study[8] for the purposes of research question no. 2. Research question no. 3 used 2017/2018 platform data from the west side of Line 1.

also provide ventilation during maintenance work such as rail grinding. In the Montreal metro and Barcelona subway systems, constant ventilation is required to maintain a comfortable temperature for passengers. This continual ventilation has been estimated to yield lower platform PM concentrations relative to platforms that rely on natural, piston-driven ventilation.[31] However, the impact of continual ventilation on platform PM mass and number concentrations for several size fractions can differ depending on factors such as fan speed, flow direction (impulsion/expulsion), station design (single-track/double-track/double-track with separating wall), and presence of PSDs.[6,31,32] Cost can be an issue as well. Novel approaches are being explored to increase the efficiency of mechanical ventilation systems to reduce their considerable energy consumption.[33] Strategies involving increasing the rate of particle removal via filtration and magnetism have been explored. Filtration such as train HVAC systems can reduce in-train PM concentrations.[6,34,35] The efficacy of a baffle dust collector was limited to particles > 7.8 μm; however, magnetism is being explored to innovate this novel approach.[36] The efficacy of a hybrid system using an electrostatic precipitator (for low train speeds) and an inertial dust separator (for high train speeds) has also been estimated in simulated trials.[37] Magnetic filtration systems have also been evaluated to reduce the proportion of PM being emitted from a subway tunnel.[38] Magnetic filtration is an ideal approach for subway systems as PM can be highly composed of Fe and Fe oxides.[8,13,23,24,39−42] Air quality interventions that seek to reduce the generation of subway PM at source may also prove useful.

Previous work on the Toronto subway found median platform $PM_{2.5}$ levels to be approximately 140 $\mu g/m^3$ (IQR = 80−184) based on system-wide monitoring conducted in the peak hours (7−10 a.m. and 3−6 p.m.) of 15 summer and winter weekdays.[8] This places the Toronto system in the upper range of platform $PM_{2.5}$ levels in the published literature[10] and suggests the potential for improvement in air quality. Selecting the approach with the best suitability for improving the air quality of a subway station or line may be aided by gaining a better understanding of the age, production, and removal mechanisms of subway $PM_{2.5}$. This study was conducted to address three research questions relating to one main question: what proportion of subway $PM_{2.5}$ is freshly emitted vs. resuspended legacy dust? Addressing this question can inform the design of air quality interventions; should the focus be on increasing the removal or decreasing the emission of subway PM? The first research question focused on assessing an intervention aimed at reducing legacy dust. It estimated the impact of introducing track bed vacuuming operations on platform $PM_{2.5}$ concentrations. The second research question focussed on estimating shifts in platform and in-train $PM_{2.5}$ from 2010/2011 levels.[8] These changes in subway $PM_{2.5}$ were examined for their potential relationship to a complete modernization of rolling stock on one line and a significant increase and subsequent reduction of emergency brake (EB) use on another. Both of these events were interpreted as changes in the rate of subway $PM_{2.5}$ emission. The third research question involved a semiquantitative assessment on the proportion of platform $PM_{2.5}$ that is legacy dust versus freshly emitted. The platform $PM_{2.5}$ levels of two neighboring below ground sections opened in 1963 and 2017 were compared. While the daily input of freshly emitted $PM_{2.5}$ is comparable between these two sections, only the older section has accumulated legacy dust. The results of these three questions were then used to inform a discussion on the potential of interventions that increase PM removal versus decrease PM emission.

https://doi.org/10.1021/acs.est.1c00703
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

2. METHODS

This study focussed on the Yonge-University line (Line 1) and the Bloor-Danforth line (Line 2) of the Toronto subway. These lines constitute the bulk of Toronto's system (69 of 75 stations). Line 1 runs south from the northwest to the city center and then to the northeast; it has 31 BG and seven above grade (AG) stations. BG stations are typically bored (vs cut and cover) and range from 5 to 18 m in depth. These stations were opened from 1954 to 1974 ($n = 23$), 1978 ($n = 7$), 1987 ($n = 1$), and 1996 ($n = 1$). Most recently, a six-station extension was opened at the northwest end of the line in 2017. Line 2 runs east−west with 27 BG and four AG stations opened in 1966−1968 ($n = 28$) and 1978−1980 ($n = 3$). This study measured $PM_{2.5}$ concentrations on several BG platforms on Lines 1 ($n = 13$) and 2 ($n = 18$) from December 2017 to August 2018 (Figure 1). During this nine month period, these 31 platforms were monitored three to five platforms at a time, for periods of days to weeks. Primarily, these data were collected to assess the efficacy of a track bed vacuum car (TBVC, see Section 2.3) that began operations in early 2018. Subsequently, these data were compared with platform $PM_{2.5}$ measured in the summer of 2010 and winter of 2011 to examine changes in the levels of $PM_{2.5}$ in the system. Finally, on-train $PM_{2.5}$ monitoring was conducted on Lines 1 and 2 over ten days in the fall of 2018 and nine days in the winter of 2019/2020. These data were compared with previously published on-train $PM_{2.5}$ concentrations measured in 2010/2011.[8]

2.1. Statistical Analysis. In this study, subway $PM_{2.5}$ was compared between various time periods. Concentrations were compared before and after the use of a track bed vacuum car (Section 2.3), platform $PM_{2.5}$ between 2010/2011 and 2017/2018 (Section 2.4), and on-train $PM_{2.5}$ between 2010/2011 and 2018 and 2019−2020 (Section 2.6). In each case, a randomized block design (RBD) was conducted to test for differences in subway $PM_{2.5}$ with subway stations or rail segments treated as a random effect. In each RBD model, assumptions of normality (Anderson-Darling test) and constant variance (Levene's test) were assessed on the residuals to validate model assumptions. Logarithmic transformations and nonparametric approaches were attempted when either the normality or constant variance assumption was violated. A statistical significance was specified as a p-value of less than 0.05. Analyses were conducted using SAS Enterprise Guide 7.1.

2.2. Subway Platform $PM_{2.5}$ Monitoring. The schedule of the 2017/2018 platform $PM_{2.5}$ monitoring was dependent on the work schedule of the TBVC (research question no. 1). During periods when the TBVC was not scheduled, other BG platforms of Lines 1 and 2 were selected for monitoring. Stations were selected that increased our data's representation of BG platform $PM_{2.5}$ concentrations for Lines 1 and 2 to strengthen the comparison to 2011 data (research question no. 2). Monitoring also included two BG platforms of the six-station 2017 extension to Line 1 as well as its neighboring BG 1966 segment to provide data for our third research question. Monitoring units were positioned at the end of platforms to avoid disturbing the commuting public. The platform end that was closest to the planned vacuuming and a point of entry for the trains was chosen. The platform monitoring setups featured steel cabinets with clear labels, locks, and steel legs. Monitoring units were fixed to platform walls with steel strapping for security (see Figure S1, Supporting Information). Continuous, 5 s $PM_{2.5}$ data were collected using the TSI DustTrak 8530 (TSI, Shoreview, MN). Temperature and relative humidity data were monitored using a Hobo meter (Onset Corp.). Daily visits were made to replace DustTrak 8530 batteries, download data, conduct DustTrak zero checks, and clean DustTrak impaction plates. DustTrak sample flow was calibrated on a weekly basis. DustTraks were collocated with filter samples on a subset of monitoring days. Their data was used for the derivation of a gravimetric calibration factor (see Figure S3, Supporting Information). Gravimetric samples were collected using the Harvard School of Public Health's Cascade Impactor (HSPHCI). By connecting the HSPHCI to a programmable pump, the HSPHCI collected $PM_{2.5}$ at a flow rate of 5 lpm on a 37 mm Teflon filter. The HSPHCI samples ran for 12 h 6 a.m. to 6 p.m. time periods. All DustTraks were factory calibrated before the beginning of the study. Intercomparison sessions were conducted at the end of the study with all units to provide data for an analysis of instrument bias and precision. The elemental composition of the $PM_{2.5}$ samples was analyzed using X-ray fluorescence (XRF).

2.3. Impact of Track Bed Vacuuming on Platform $PM_{2.5}$. In 2017, the Toronto Transit Commission (TTC) commissioned the TBVC. The main purpose of the unit is to remove debris and garbage collecting in track beds. Track-level waste represents a fire hazard that can cause significant service stoppages and delays for subway systems. While vacuuming, the unit traveled at speeds of 2−5 km/h and vacuumed with an airflow rate of 66 000 m^3/h. It had a series of filtration stages in its operation that began with a chain curtain to catch debris and ended with a high-efficiency particulate air (HEPA) filter. Platform monitoring began several weeks before its first use/introduction into the system. This allowed for the collection of baseline data before a scheduled TBVC cleaning event. A cleaning event was designated as the vacuuming of the track bed of the platform or either of the connecting rail segments. Cleaning events were scheduled during nonservice hours (2−6 a.m.), during which several hundred meters of track would be cleaned. Work car fleet managers notified researchers of planned uses of the TBVC several days in advance. Use of the TBVC was confirmed via subscription to the nightly work schedule mailing list. Use of the TBVC was identified as work orders involving work car "RT-89". Daily means reflecting the hourly averages of 6 a.m. to 6 p.m. were used to test for the impact of the TBVC use. Each day of data was assigned a value of "x" days before or after a vacuuming event. The first day of monitoring following a vacuuming event was assigned day 0. RBD analysis (Section 2.1) was used to test for an effect of "vacuuming event".

2.4. Comparison of Platform $PM_{2.5}$ 2011 vs 2017−2018 for Lines 1 and 2. Platform $PM_{2.5}$ concentrations of this study were compared to that of previously published data of 2010/2011.[8] These data represent weekday peak-hour (7−10 a.m. and 3−6 p.m.) monitoring conducted for 15 consecutive weekdays in the summer of 2010 and the winter of 2011 ($n = 30$ days). Since 2010/2011, the rolling stock on Line 1 was completely modernized. Before 2012, both Lines 1 and 2 of the Toronto subway were serviced by an even mix of the older H-series trains and the T1 train. From late 2011 to 2014, the H-series trains on Line 1 were replaced by the introduction of the new T35A08 "Toronto Rocket" (TR). In 2017, the six-station extension of the northwest end of Line 1 was opened and featured automatic train control (ATC). As T1 trains were not compatible with ATC, they were exclusively assigned to Line 2, while Line 1 was completely serviced by the newer TR trains. This provided the opportunity to examine the impact of a complete modernization of rolling stock on a subway line's platform $PM_{2.5}$.

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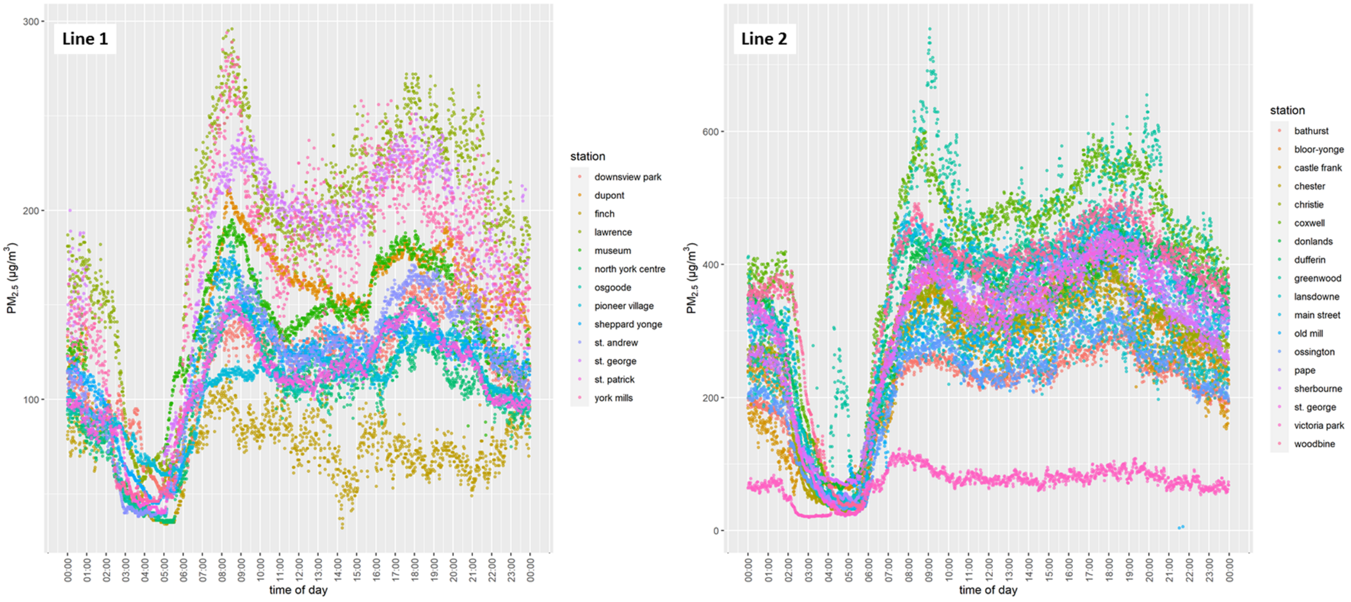

Figure 2. Platform $PM_{2.5}$ integrated over "minute of day" and plotted in time series by station for Lines 1 (n = 13) and 2 (n = 18). The characteristic diurnal pattern of subway $PM_{2.5}$: maximums during peak commute times and minimums during nonservice hours (2−6 a.m.).

To allow for this comparison, several differences in monitoring methodology between the 2010/2011 and 2017/2018 campaigns were addressed. Details on the monitoring methods of the previous study can be found here.[8] Briefly, it involved monitoring the entirety of the platform and in-train environments of Lines 1 and 2 each weekday peak-hour period for 15 consecutive weekdays in the summer of 2010 and winter of 2011. For this comparison, the inclusion of data from each study was restricted to weekday hours of 7−10 a.m. and 3−6 p.m. collected on the platforms of the stations monitored in the 2017/2018 campaign. As well, a small monitoring session was conducted in the subway with two DustTrak 8520s (2010/2011 study) and two DustTrak 8530 (2017/2018) to test for any relative bias between the two DustTrak models used in these studies. Averages for each combination of study year (2010/2011 and 2017/2018), line (Lines 1 and 2), station (n = 31), weekday (Mon−Fri), and peak hour (7 a.m., 8 a.m., 9 a.m., 3 p.m., 4 p.m., and 5 p.m.) were calculated. To test for a difference in weekday peak-hour BG platform $PM_{2.5}$ between lines (Lines 1 and 2) and year (2010/2011 and 2017/2018), a two-way RBD model was conducted.

2.5. Subway Train $PM_{2.5}$ Monitoring. This study included line-wide on-train monitoring sessions in the fall of 2018 (n = 10) and winter of 2019/2020 (n = 9). Each session was conducted on a weekday on either Line 1 or Line 2. Data collection was conducted in line with the methodology used in the previous 2010/2011 study.[8] Briefly, two DustTrak 8520s were carried in backpacks with the tube inlets positioned in the breathing zone. Audio recordings were made to assign data to rail segments. Instrument zero and sample flow calibrations were performed before each monitoring session. Time-stamped digital voice recordings were made when entering and leaving station platforms to assign rail line segment and direction (eastbound, westbound) to $PM_{2.5}$ data. All data were calibrated to gravimetric-adjusted DustTrak 8530 data.

2.6. Comparison of On-Train $PM_{2.5}$ between 2010/2011, Fall 2018, and Winter 2019/2020. To compare on-train $PM_{2.5}$ between these three separate time periods, averages for each combination of study year (2010/2011, Fall 2018, and Winter 2019/2020), line (Lines 1 and 2), direction-specific rail segment, and peak hour were calculated. To test for a difference in weekday peak-hour on-train $PM_{2.5}$, between lines (Lines 1 and 2) and year (2010/2011, Fall 2018, and Winter 2019/2020), a two-way randomized block design (RBD) model with direction-specific rail segments treated as random effects was conducted to estimate the effect of "study period" relative to the 2010/2011 $PM_{2.5}$ data.

2.7. Comparison of Platform $PM_{2.5}$ between Line 1's 2017 and 1963 Segments. The question of the age of subway $PM_{2.5}$ was explored by comparing platform $PM_{2.5}$ concentrations of the older east side of Line 1 to its adjoining 2017 extension to the north (see Figure S2, Supporting Information). The 2017 section was represented by two stations that had been in operation for less than a year at the time of monitoring. The older section was represented by six stations opened in 1963 (n = 5) and 1978 (n = 1). The position that the comparison of the platform $PM_{2.5}$ of these two sections would provide insight on the age of subway-sourced $PM_{2.5}$ was based on several premises. First, since the 2017 section was in operation for less than 1 year and the 5 km "open cut" would prevent the migration of legacy dust from the older section, its $PM_{2.5}$ was presumed to be predominantly "freshly emitted" with little "legacy dust". Second, the older stations to the south would be characterized as both freshly emitted and legacy dust. Finally, their shared rail activity should result in equal contributions of freshly emitted $PM_{2.5}$. Thus, similar levels between these two groups would suggest the platform $PM_{2.5}$ of this line to be dominated by freshly emitted dust, while higher levels in the older section would suggest legacy dust to be a significant source of subway $PM_{2.5}$. The hourly means from 6 a.m. to 8 p.m. for each station were included in this analysis. These data were then compared semiquantitatively by examining boxplots by station.

3. RESULTS AND DISCUSSION

From December 2017 to August 2018, a total of 13 and 18 stations were monitored from Lines 1 and 2 for an average of 14 (min-max: 6−25) and 17 (min-max: 2−39) days, respectively (see Table S1, Supporting Information for descriptive statistics).

Table 1. Difference in $PM_{2.5}$ in Pre- and Postvacuuming Event Days

factor	value	LSGM[a] (μg/m^3)	95% CI	ratio[b]	95% CI	p-value
vacuuming event	pre	289	(218, 384)	1.00	(0.94, 1.05)	0.8805
	post	291	(219, 386)			
day of week	weekday	349	(263, 463)	1.45	(1.38, 1.52)	<0.0001
	weekend	241	(181, 320)			

[a] LSGM—least-squares geometric means based on the RBD model adjusting for weekday/weekend and vacuuming event, with stations treated as random effects. [b] The difference between geometric means is the ratio of geometric means; differences were taken as postvacuuming minus prevacuuming event and weekday minus weekend.

Table 2. Comparison of Peak-Hour Platform $PM_{2.5}$ between Lines 1 and 2 in Years 2011 and 2018

line	year	LSGM[a] (μg/m^3)	95% CI	ratio[b]	95% CI	p-value
1	2010/2011	250	(216, 289)	0.69	(0.63, 0.75)	<0.0001
	2017/2018	172	(149, 199)			
2	2010/2011	252	(222, 286)	1.48	(1.42, 1.56)	<0.0001
	2017/2018	374	(330, 425)			

[a] LSGM—least-squares geometric means based on the RBD model adjusting for line and year, with stations treated as random effects. [b] The difference between geometric means is the ratio of geometric means; differences were taken as 2018 minus 2011 data.

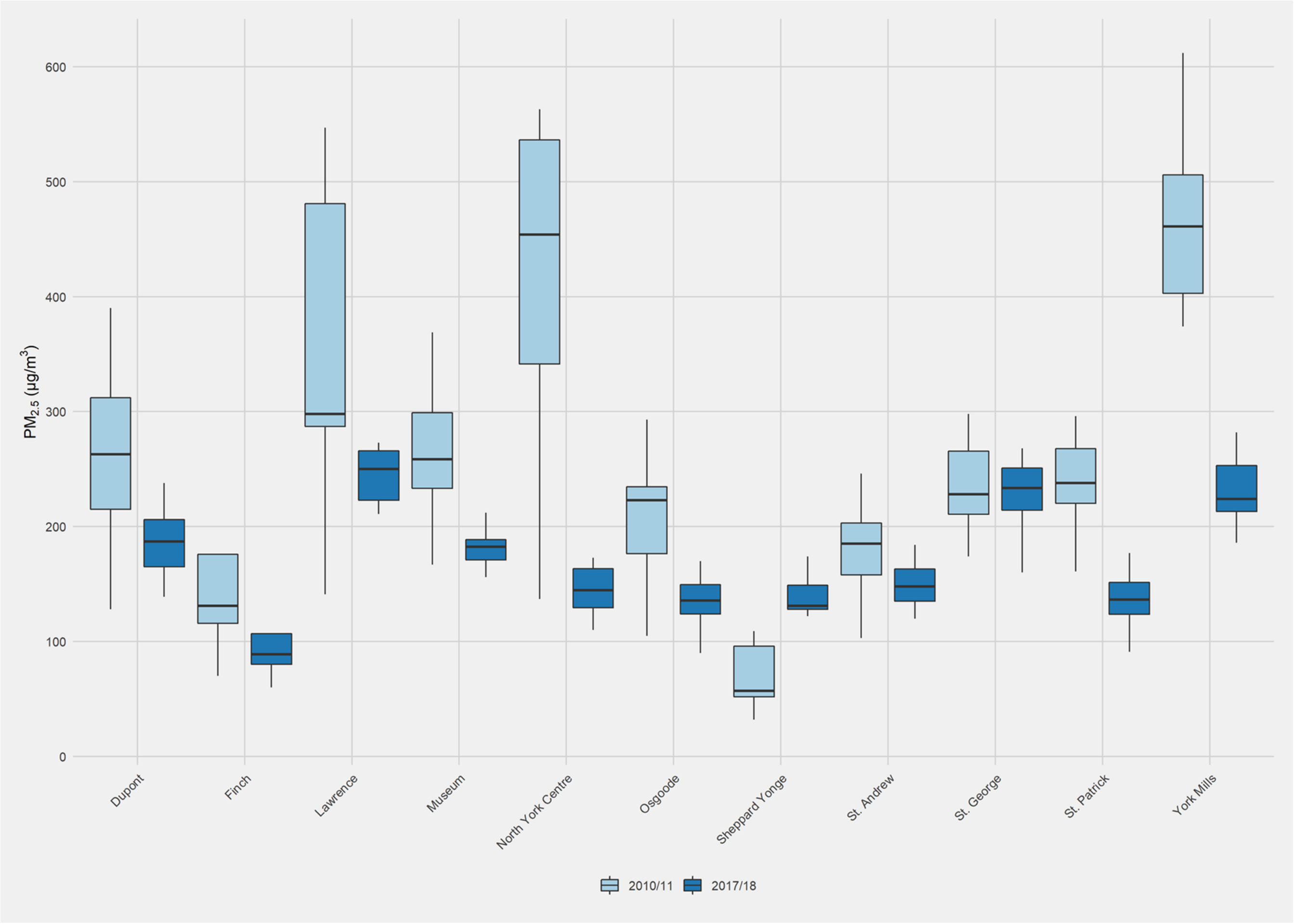

Figure 3. Distribution of hourly means for peak-hour platform $PM_{2.5}$ measured on below grade stations of Line 1 (n = 11) in 2010/2011, and 2017/2018. Box plots present the median as well as the Q1 − 1.5IQR (lower whisker of the box plot), 25th (bottom line of box), 50th (middle line inside the box), 75th (upper line of box), and Q3 + 1.5IQR (upper whisker of the box plot).

Each platform exhibited the diurnal trend of $PM_{2.5}$ typical of subway platforms (see Figure 2).[7,9,11,31,32] On-train data was collected for both Lines 1 and 2 for 10 days in the fall of 2018 and for 9 days in the winter of 2019/2020 (see Table S2, Supporting Information). The comparison of DustTrak 8530 $PM_{2.5}$ to its collocated gravimetric measures in the platform monitoring revealed an underestimation of $PM_{2.5}$ by a factor of 1.59 (see Figure S3, Supporting Information). As well, the DustTrak 8520 (used in on-train monitoring) underpredicted the DustTrak 8530 by ∼5% (see Figure S4, Supporting Information). All

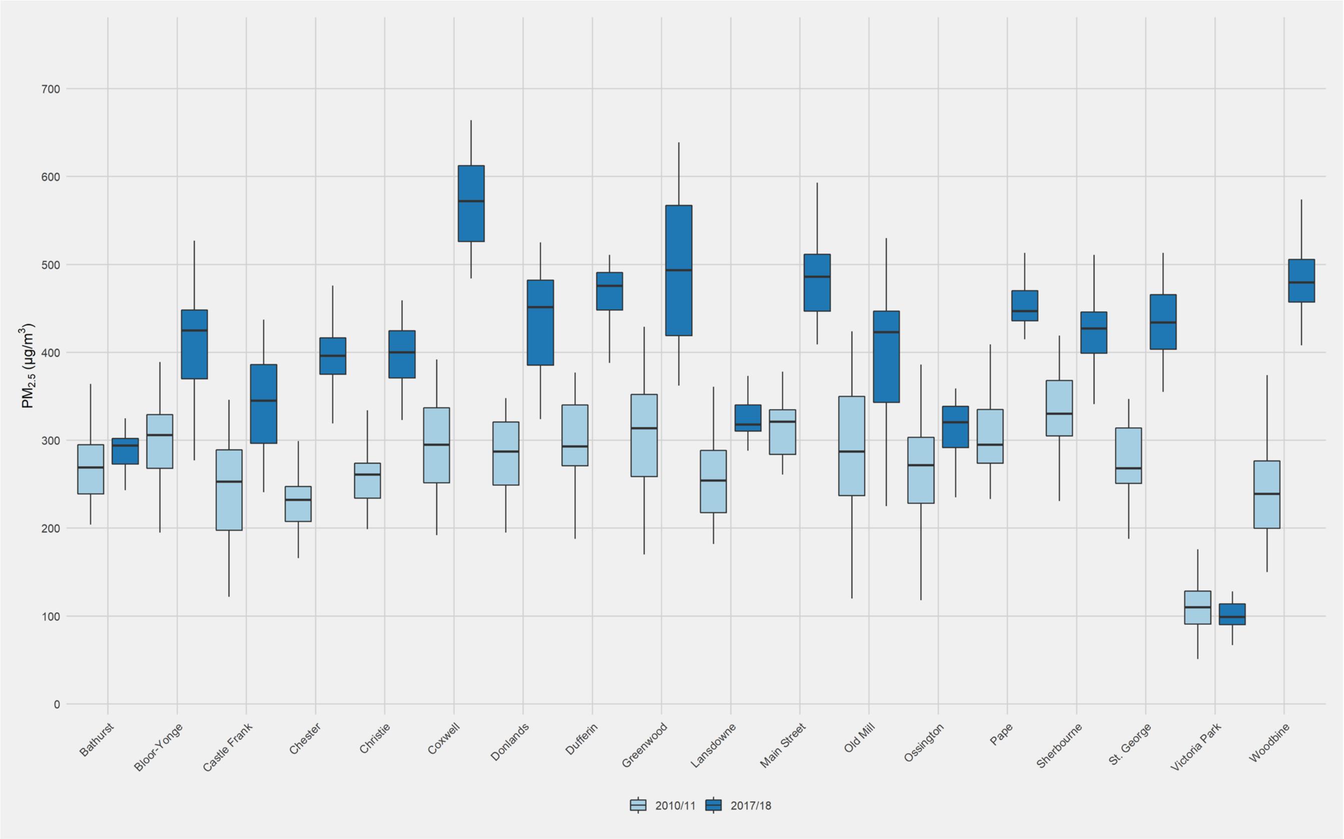

Figure 4. Distribution of hourly means for peak-hour platform $PM_{2.5}$ measured on below ground stations of Line 2 ($n = 18$) in 2010/2011 and 2017/2018. Box plots present the median as well as the Q1 − 1.5IQR (lower whisker of the box plot), 25th (bottom line of box), 50th (middle line inside the box), 75th (upper line of box), and Q3 + 1.5IQR (upper whisker of the box plot).

$PM_{2.5}$ data from the DustTraks presented in this paper have been corrected to match collocated gravimetric measurements. The results of the elemental composition analysis by XRF for the gravimetric $PM_{2.5}$ samples are presented in the Supporting Information in Figure S5 (Line 1) and Figure S6 (Line 2).

3.1. Impact of Track Bed Vacuuming on Platform $PM_{2.5}$. Pre- and postvacuuming data were collected from 10 randomly selected BG subway stations in the Toronto system (see Table S3, Supporting Information). The analysis focused on up to 10 days before and after the vacuuming event with the day of vacuuming counting as day 0. A total of 85 days were included in the analysis (62 postvacuuming and 23 pre vacuuming). Several confounding variables were considered in the RBD analysis that tested for an impact of vacuuming events on platform $PM_{2.5}$ concentrations. Station, ambient temperature, relative humidity, and ambient $PM_{2.5}$ were not found to be confounders. Only the weekend/weekday status of a monitoring day was associated with $PM_{2.5}$ levels and therefore was included in the RBD model. The adjusted or least-squares geometric means (LSGM) of $PM_{2.5}$ levels were considered to be statistically similar, vacuuming events were found to have no effect on $PM_{2.5}$ (ratio (95% CI) = 1.00 (0.94−1.05)) (Table 1).

As the TBVC's principal purpose is to remove debris and reduce track fires, this analysis investigated the potential for an additional benefit: reducing platform $PM_{2.5}$. The null finding suggests that accumulated legacy dust does not represent a significant proportion of daily subway $PM_{2.5}$. While weekly 1−2 h vacuuming sessions covering 1−2 km can meet the needs of debris removal, it does not lower platform $PM_{2.5}$. Increased TBVC cleaning may not be an option as nightly maintenance schedules may not permit an increase in the use of the TBVC. During the administration of the study, scheduled vacuuming events were canceled several times on account of the prioritization of other maintenance activities.

3.2. Comparison of Platform $PM_{2.5}$ for Lines 1 and 2 (2010/2011 vs 2017/2018). Between 2010/2011 and 2017/2018, the adjusted or least square geometric mean weekday peak-hour platform $PM_{2.5}$ concentration of Line 1 decreased from 250 to 172 μg/m³, a decrease of nearly one-third (ratio (95% CI): 0.69 (0.63, 0.75), $p < 0.0001$) (Table 2). In contrast, Line 2 $PM_{2.5}$ concentrations increased by a factor of 1.48 (95% CI; 1.42, 1.56) from 252 to 374 μg/m³. The direction of $PM_{2.5}$ changes (decrease for Line 1, increase for Line 2) were shared with nearly all platforms included in the analysis. There were three exceptions to these trends. Figures 3 and 4 present the by-station variation of the weekday peak-hour platform $PM_{2.5}$ means of both monitoring periods for Lines 1 and 2, respectively. No change was noted for the Warden station of Line 2. This was likely on account of it being an AG station with the lowest concentrations in both 2010/2011 and 2017/2018. For Line 1, the Sheppard West station did not share the downward trend of platform $PM_{2.5}$. In fact, $PM_{2.5}$ concentrations increased. In 2010/2011, this station was named "Downsview" and was the terminus of the northwest end of Line 1. From this station, Line 1 extended south for ∼750 m of BG track, at which point a ∼5 km AG section began. The 2017 extension to Line 1 added a six-station BG line extending to the north from the Sheppard West station. This connection to a significant BG section of the subway likely resulted in these observed increases. Finally, the St. George station was an exception to the Line 1

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decrease. Platform $PM_{2.5}$ of the two monitoring years are relatively equal. This is likely on account of the influence of the higher $PM_{2.5}$ levels of its Line 2 platform, to which it is connected by two open stairwells. Apart from these exceptions, there was uniformity across stations in the direction of these changes in the platform $PM_{2.5}$. As these data represent 11/25 of Line 1, 18/24 BG stations of Line 2, and are located throughout each line, both of these shifts in platform $PM_{2.5}$ were likely line-wide.

The line-wide nature of the ~30% decrease of Line 1's platform $PM_{2.5}$ strongly suggests the contributing factor to be one that is shared throughout the line. In the absence of any changes to ventilation protocols or line-wide station design, the complete modernization of rolling stock stands out as a likely cause. Line 1's transition from an even mix of the H-series (built 1974−1989) and T1 (built 1995−2001) to the TR (built 2009−2015) took place from 2012 to 2017. While these trains are very similar in terms of dimension, weight, speed, and passenger capacity, the TR features less use of its friction brakes. As with most commuter rail rolling stock, the braking systems of these trains feature dynamic braking, which is a combination of electric (regenerative) and pneumatic (friction) brakes. Regenerative braking involves the conversion of kinetic energy into electric potential. Regenerative braking decelerates a train from its full speed (~80 km/h) to speeds of 20−5 km/h. Friction brakes then bring the train to a complete stop. The TR's decreased use of friction brakes may have yielded a reduction in the emission of brake dust and better air quality for Line 1.

Changes in friction brake use were also the likely cause of the 1.48 factor increase of $PM_{2.5}$ on Line 2. Concurrent with Line 1, Line 2 underwent a change in rolling stock from 2012 to 2017. As with Line 1, Line 2 had an even mix of the H-series and T1 trains in 2010/2011. By 2017, Line 2 was serviced exclusively by T1 trains. An analysis comparing the $PM_{2.5}$ emission capabilities of the H-series and T1 trains indicated that this change in rolling stock would not have had an effect on platform $PM_{2.5}$ levels (see Section S2 of the Supporting Information). A combination of poor wheel metallurgy, increased emergency brake (EB) applications, and lower track surface adhesion was the likely cause of this line-wide increase in platform $PM_{2.5}$. Prior to 2016, a significant increase in metal flakes due to poor wheel metallurgy was occurring.[43] To address this, a phasing-in of wheels with improved metallurgy and new brake shoes was initiated.[44] This process was still ongoing during the platform monitoring of 2018. This increase in metal flakes produced by the wheels may account for some of the observed increases in platform $PM_{2.5}$. An increase in the frequency of emergency brake applications may also have contributed to the increase of Line 2 $PM_{2.5}$. In early 2018, the TTC began experiencing a significant increase in the rate of wheel flats on T1 cars (exclusively assigned to Line 2). By October of 2018, 90% of T1 cars had moderate to severe flats.[43] Wheel flats were found to be created during EB of the T1 cars. Under high rail-wheel adhesion conditions, an EB application applies a prescribed maximum braking effort to the wheels through the brake shoes while allowing the wheels to continue rolling. Under low rail-wheel adhesion conditions, an EB application can result in wheel skidding. The high frictional forces during skidding cause the abrasion and ablation of rails and wheels, resulting in a wheel flat.[44] An EB application differs from a service brake (SB) application, which occurs at every station stop. A SB application on a T1 car will not produce wheel lockup as the spin-slide protection system remains engaged. If a series of safety conditions are not met during the operation of the T1 car, the T1 speed control system (SCS) will initiate an EB brake application.[44] The SCS is a critical safety system on T1 cars to supervise drivers in operating the vehicles at prescribed speeds and compliance to signals.[44] Following the full implementation of the SCS onto the T1 fleet, the TTC observed an increase in EB applications (as early as fall of 2016, the TTC had noted nuisance-emergency brake incidents) reaching an average of 280 EB applications per month by June 2018.[44] In the spring of 2019, refinements to the SCS had reduced nuisance EB applications and a campaign among operators to reduce the use of EB whenever possible was in play.[44] By summer 2019, wheel flats (an indication of excessive EB under low adhesion conditions) had been reduced to 7% of the T1 fleet.[44] If indeed the estimated increase of platform $PM_{2.5}$ for Line 2 was related to the high occurrences of EB (and related wheel flat issue), it would lend evidence to the position that subway $PM_{2.5}$ can be highly composed of subway-sourced $PM_{2.5}$. Further, the reduction of nuisance EB applications could result in a significant improvement of Line 2 air quality. This potential is further explored in Section 3.3.

The comparison of platform $PM_{2.5}$ concentrations between two time periods separated by 7 years is not without its complications. Platform $PM_{2.5}$ has been found to vary by several spatial and temporal factors. In our comparison, we compensated for factors of time of day, weekday vs weekend, and air monitoring methodology. The monitoring positions differed between the 2010/2011 data (middle of platform) and 2017/2018 (end of the platform at the point of entry for trains). This is a possible confounder as a platform has been shown to vary by platform position.[32] Moreno et al.[32] monitored laterally at four equidistant points along 10 platforms of Line 2 of the Barcelona subway. In the condition of "without forced tunnel ventilation" (most comparable to the data of this study), variation of PM_3 was noted to vary across the platform position of each station. However, the point of highest PM was not consistent, owing to differences in station design. Therefore, while our change in monitoring position does introduce error into our temporal comparisons, the direction of this error would have varied across the 31 stations in our analyses. Since near complete uniformity in the direction of our observed changes was still evident, the magnitude of this error is smaller than that of the line-wide changes in $PM_{2.5}$ observed. The monitoring periods of the 2010/2011 and 2017/2018 data also differed seasonally. In 2010/2011, each station was monitored evenly in both summer and winter. In 2017/2018, data was collected in both winter and summer as well. However, as the monitoring schedule was dependant on the TBVC, the season of each platform's monitoring differed. While some stations were monitored in both seasons, others have data from only one season. As with the platform monitoring location issue, the direction of this error would have varied between stations.

3.3. Comparison of On-Train $PM_{2.5}$ for Lines 1 and 2 (2018 and 2019/2020 vs 2010/2011).

The decision to include on-train $PM_{2.5}$ concentration data in this study was made *a posteriori*. After observing the significant changes of Lines 1 and 2 platform $PM_{2.5}$ that took place between 2010/2011 and 2017/2018, the on-train monitoring of fall 2018 was included to examine if this divergence had taken place in the on-train environments as well. The on-train monitoring of winter 2019/2020 was included to explore the possibility that the reduction of nuisance EB applications on Line 2 resulted in a decrease in $PM_{2.5}$. A time-series plot of one of these on-train monitoring sessions is presented in the Supporting Information in Figure S7.

Table 3. Comparison of In-Train $PM_{2.5}$ between Lines 1 and 2 in Years 2010/2011, Fall 2018, and Winter 2019/2020[a]

line	year	LSGM[a] (μg/m^3)	95% CI	ratio[b]	95% CI	p-value
1	2010/2011	100	(88, 112)	ref		
	fall 2018	58	(50, 68)	0.58	(0.5, 0.68)	<0.0001
	winter 2019/2020	43	(37, 49)	0.43	(0.38, 0.48)	<0.0001
2	2010/2011	125	(110, 141)	ref		
	fall 2018	141	(109, 182)	1.13	(0.82, 1.56)	0.8797
	winter 2019/2020	52	(44, 62)	0.42	(0.36, 0.5)	<0.0001

[a] LSGM—least-squares geometric means based on the RBD model adjusting for line and year, with stations treated as random effects. [b] The difference between geometric means is the ratio of geometric means; differences were taken with the reference group being 2010/2011 data, within line.

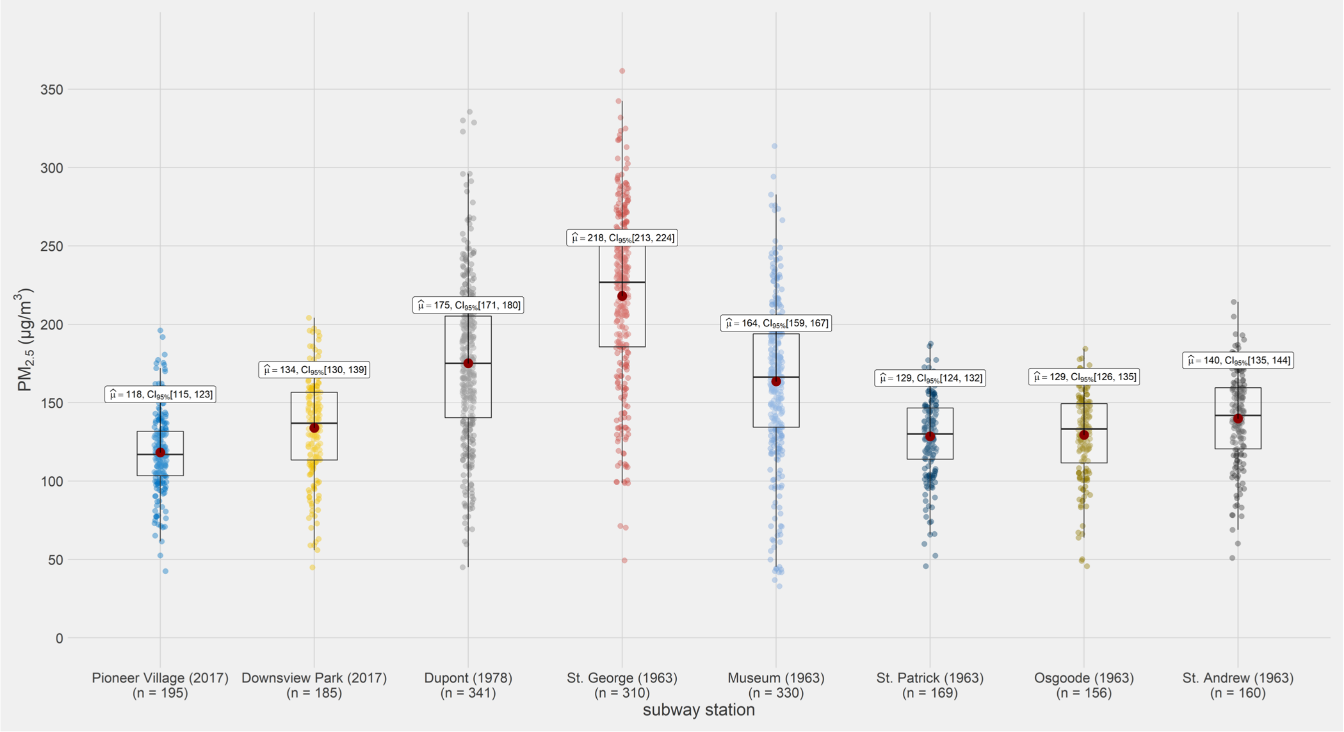

Figure 5. Distribution of hourly $PM_{2.5}$ means for 2017 stations (Pioneer Village and Downsview Park; at left) and older 1978 (Dupont) and 1963 stations. Stations are presented in their geographical order. A ~5 km open cut exists between the Downsview park and Dupont stations. St. George station is a junction between Lines 1 and 2. Box plots present the arithmetic mean (red circle solid) as well as the Q1 − 1.5IQR (lower whisker of the box plot), 25th (bottom line of box), 50th (middle line inside the box), 75th (upper line of box), and Q3 + 1.5IQR (upper whisker of the box plot).

Table 3 presents the LSGM after fitting an RBD model to the log of on-train $PM_{2.5}$ levels. For Line 1, we observe that on-train $PM_{2.5}$ significantly decreased by ~50% by fall 2018 compared to 2010/2011; on-train $PM_{2.5}$ further decreased in winter 2019/2020 compared to fall 2018. This trend reflects what was observed in the platform data: a line-wide reduction of $PM_{2.5}$ between 2011 and 2017. Further, a conservative interpretation of 2019/2020 vs 2010/2011 comparison is that this new baseline was still present in 2019/2020, or even that the on-train air quality had continued to improve. For Line 2, levels of in-train $PM_{2.5}$ increased by 13% between 2010/2011 and fall 2018, although the increase was not considered significant (p = 0.8797). Therefore, the substantial increase seen on Line 2 platforms between 2011 and 2017 (factor of 1.48) was not reflected as strongly in the on-train environment. However, the on-train $PM_{2.5}$ data measured in the winter of 2019/2020 indicate that $PM_{2.5}$ decreased by more than half to 52 μg/m^3 ($p < 0.0001$) relative to the 2010/2011 data. This would suggest that platform levels decreased as well and that the resolution of the nuisance EB application issue improved $PM_{2.5}$ concentrations on Line 2. These results support the hypothesis that factors relating to friction brake use contributed to the significant changes seen in Line 1 (decrease in friction brake use by newer TR trains: decrease in $PM_{2.5}$) and Line 2 (increase in friction brake use: increase in $PM_{2.5}$). This is also supported by data on the proportion of PM composed of barium, a known marker of brake shoes.[23] Gravimetric $PM_{2.5}$ samples analyzed by XRF estimated that Line 1 $PM_{2.5}$ was 1.2% Ba (see Figure S5, Supporting Information) vs 2.9% for Line 2 (see Figure S6, Supporting Information).

3.4. Comparison of Platform $PM_{2.5}$ between Line 1's 2017 and 1963 Stations.

Two of the six BG stations of the 2017 extension were monitored in July and August of 2018. This monitoring occurred within 1 year of their September 2017 opening. To semiquantitatively assess the proportion of platform $PM_{2.5}$ that is resuspended legacy dust versus freshly emitted $PM_{2.5}$, these data were compared to that of the neighboring older stations opened in 1963 ($n = 5$) and 1978 ($n = 1$) (see Figure S2, Supporting Information). The hourly means of platform $PM_{2.5}$ for each station are presented in the boxplots of Figure 5, with the platforms arranged north to south from left to right. First, the two newer 2017 stations had platform $PM_{2.5}$ concentrations comparable with the most southerly St. Patrick, Osgoode, and St. Andrew stations. This would suggest that, within 1 year of operation, a BG station can attain a baseline of $PM_{2.5}$ equivalent to BG stations of the same line despite being of significantly greater age. This also suggests that the majority of platform $PM_{2.5}$ is less than 1 year in age. Therefore, significant changes to the rate of the emission of subway-sourced $PM_{2.5}$ would take a short period of time to alter daily concentrations of platform $PM_{2.5}$. This seems to be the case when comparing the 2018 and 2019/2020 in-train data from Line 2, where the resolution of the wheel flat issue appears to have yielded a sharp decrease in platform $PM_{2.5}$ for that line.

The platform $PM_{2.5}$ concentrations of the Dupont, St. George, and Museum stations are higher than the other stations in this sample. This may be related to St. George being a link between Lines 1 and 2. As previously discussed in Section 3.2, the Line 1 St. George platform is positioned directly above its Line 2 platform and is connected by two open stairwells. The platform $PM_{2.5}$ for both the Lines 1 and 2 platforms can be found in Figures 3 and 4, respectively. The influence of Line 2's higher $PM_{2.5}$ concentrations on that of St. George's Line 1 platform is suggested by the fact that St. George is the only below ground platform where levels did not decrease relative to 2010/2011. If indeed this mixing is occurring, then it is plausible that the significantly higher $PM_{2.5}$ of Line 2 is increasing the platform $PM_{2.5}$ levels of the Dupont and Museum stations as well. The Museum station is immediately adjacent to St. George, while Dupont is two stations down the line. While the influence of the low $PM_{2.5}$ concentrations of an AG section of a subway can be observed for sections of a BG line that include several stations, in this case, the high $PM_{2.5}$ of St. George Line 2 (~400 $\mu g/m^3$) is affecting not only its Line 1 platform, but the neighboring stations as well. If the influence of Line 2's higher $PM_{2.5}$ is raising the platform $PM_{2.5}$ of the St. George, Museum, and Dupont stations of Line 1, the evidence of the two 2017 stations attaining a baseline level of $PM_{2.5}$ equal to that of its neighboring 50 year old stations is strengthened (Figure 5).

3.5. Subway $PM_{2.5}$: Freshly Emitted or Legacy Dust?

The absence of any apparent acute reduction in platform $PM_{2.5}$ by track bed vacuuming suggests that it is either ineffective at capturing legacy dust or that legacy dust is a minor proportion of subway $PM_{2.5}$. Our other results suggest the latter. The comparable platform $PM_{2.5}$ concentrations of two newly opened stations and their neighboring >50 year old stations suggest the majority of subway PM to be freshly emitted (<1 year in age). This study also provided two examples of the impact of reducing the rate of subway-sourced $PM_{2.5}$. By comparing platform $PM_{2.5}$ between data collected in 2010/2011 and 2017/2018 and on-train $PM_{2.5}$ between data collected in 2010−2011, fall 2018, and winter 2019/2020, line-wide shifts in subway $PM_{2.5}$ on Lines 1 and 2 were observed. The line-wide nature of these shifts and historical information on rolling stock modernization (Line 1) and emergency brake use (Line 2) strongly suggest that these operational changes relate to the rate of subway-sourced $PM_{2.5}$ emission. On Line 1, the complete changeover to new rolling stock may have contributed to the reduction of $PM_{2.5}$ to nearly two-thirds of its 2010/2011 level. The Line 2 increase in platform $PM_{2.5}$ by 1.48 between 2010/2011 and 2017/2018 was likely related to an increase in the frequency of emergency brake applications. After the resolution of this issue, on-train $PM_{2.5}$ for Line 2 was noted to be significantly lower. Each of these examples demonstrates the potential of subway operation activities, namely braking, to affect subway $PM_{2.5}$.

This study demonstrates how decisions on the operation of a subway can greatly affect the $PM_{2.5}$ exposure of its patrons. Specifically, relatively rapid changes in air quality can result. Thus, air quality should be considered in decisions regarding subway system operation and rolling stock management. Moreover, it is important to be immediately aware of improvements or reductions in air quality to facilitate the identification of its causes. Establishing real-time, system-wide platform PM monitoring networks could increase a transit authority's awareness of the relationship between system management and subway air quality. Not only could this be an integral part of subway air quality management, it could also alert system managers of issues and yield savings in limiting the degradation of wheels and rails and extending the life of brake shoes. Responsible stewardship over the maintenance of this monitoring network and use of the data would be paramount. Future air quality interventions would benefit from this baseline data. Such a knowledge base would enable transit authorities to establish what standards of subway air quality are achievable.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c00703.

> Sampling setup, descriptive statistics for platform and on-train monitoring, gravimetric calibration of $PM_{2.5}$ data, and $PM_{2.5}$ elemental composition (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was funded by the Government of Canada's Addressing Air Pollution Horizontal Initiative and supported by Health Canada, the University of Toronto, The National Research Council of Canada, and the Toronto Transit Commission. The authors would like to acknowledge the contributions of Stephanie Fortin, Virgil Umali, Sarah Maleska, Laurent Frion, Kathleen Eng, Katarina Kunarac, Tim Shin, Ronald Garson, and Lisa McDonald-Bourg as well as the reviewers for their insightful comments.

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