*Aerosol and Air Quality Research*, 19: 2746–2756, 2019

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2019.05.0263

# Characteristics of $PM_{10}$ Levels Monitored for More than a Decade in Subway Stations in South Korea

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## ABSTRACT

This study aimed to evaluate the variation in $PM_{10}$ concentration and identify the factors influencing it in Korean subways during the past decade. The $PM_{10}$ measured internally by subway companies according to legal requirements was categorized by the subway's characteristics, which were statistically examined using a mixed effects model to identify the relevant parameters. The average levels monitored near or on the platforms and in the waiting rooms ranged from 53.9 to 92.4 µg $m^{-3}$, remaining below the Indoor Air Quality Control Act regulatory standard of 150 µg $m^{-3}$. However, the levels monitored on the platforms far exceeded the average yearly atmospheric environmental standard (50 µg $m^{-3}$). Based on both univariate and multiple analyses, several subway characteristics, including the presence of a platform screen door (PSD), were found to significantly correlate with the concentration, although slight differences in the significant factors were detected between the cities. Particularly, the absence of transfer lines and the presence of a PSD reduced the platform concentration, except at Busan and during specific years.

***Keywords:*** Subway; $PM_{10}$; Platform screen door (PSD); Indoor air quality.

## INTRODUCTION

Subway systems are the most used public transportation service in South Korea. Subway lines have been expanding continuously since their inception in 1974. Physically, the underground portion of the subway system is a semi-confined environment that may accumulate either internally generated contaminants or those from the outside environment. Proper mechanical ventilation is vital to this situation; otherwise, contaminants may accumulate to a severely harmful level (Nieuwenhuijsen *et al.*, 2007). The level of efficiency of the ventilation system varies among subways and according to their year of construction. In general, it has been reported that subway users are likely to be exposed to higher levels of particulate matter (PM) than the outdoor concentration (Kamani *et al.*, 2014; Ramos *et al.*, 2015).

In South Korea, the Indoor Air Quality Control Act (IAQ Act) was first established in 1996 as the Underground Living Space Air Quality Control Act (KMOE, 1996). In 1998, under the IAQ Act, the 24-hour average indoor air quality standard (IAQ standard) for $PM_{10}$ (defined as particulate matter with an aerodynamic diameter equal to or less than 10 µm) was first set as 250 µg $m^{-3}$. It was revised to 200 µg $m^{-3}$ in 2000 and finally to 150 µg $m^{-3}$ in 2002 (KMOE, 1998). Since 2005, only $PM_{10}$ in subway stations has been required to be monitored once per year and reported to the Korean Ministry

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of Environment (KMOE) mandatorily (KMOE, 2004).

No comprehensive studies have been conducted to assess variation in hazardous pollutants, including $PM_{10}$, that may likely be associated with commuters' health. The annual variations in $PM_{10}$ have never been reported. This study aimed to assess the variation in $PM_{10}$ over the past decade in South Korea and identify subway characteristics influencing the $PM_{10}$ level.

## METHODS

### *General Information about Subway Systems in South Korea*

A subway transportation system has been fully established in five metropolitan cities in South Korea, including in Seoul. General information on subway systems is shown in Table 1. This information includes the first and last year of construction, the number of lines, and the number of stations covered. A total of 34 lines are currently operating nationwide. About 14 million commuters use the subway every day nationwide. The number of people who use the subway daily are compared among the cities as of the end of 2017 along with the increase by year.

### *Data Collection*

According to the IAQ Act, all subway corporations in South Korea are required to monitor five pollutants, including $PM_{10}$, once per year, and to report the measurements of these to KMOE; a history of recorded measurements is also kept. All $PM_{10}$ measurements recorded in 13 subway corporations that operate in 7 large cities across Korea (Table 1) were collected and analyzed based on this study strategy. We asked each subway company to report their monitored $PM_{10}$ measurements from 2005 through 2017 according to both year and location; a total number of 12,174 $PM_{10}$ measurement data were collected from 2005 to 2017. Among them, 570 measurement data with missing values of concentration were excluded. In addition, we excluded 356 measurement data from subway cabins, driving rooms, and tunnels. In total, 11,248 measurement data taken from platforms, waiting rooms, or transfer passageways were considered to be valid and were consequently selected for our analysis.

The $PM_{10}$ sampling and analytical methods that subway companies have to use are standard, as designated by the Korean National Institute of Environmental Research (NIER) (NIER, 2017). According to the primary standard method, $PM_{10}$ samples are collected using nitrocellulose membrane filters with an air sampling pump operated from 1 to 30 L $min^{-1}$ and should be analyzed using a gravimetric method. All samples were monitored at specific locations within the subways, including on station platforms, in concourses, or in transfer passageways for longer than 6 hours. Although $PM_{10}$ can be monitored by a secondary standard method using a beta attenuation monitor, over 90% of samples were measured by the primary standard method. In addition, outdoor $PM_{10}$ levels monitored in each city during the same year were also collected and compared with levels in the subways.

### *Data Analysis*

A total number of $PM_{10}$ measurement data in various subway environments (n = 11,248) were categorized according to the following variables used as an independent analysis unit.

- The year measured was categorized into one of four groups: 2005–2008, 2009–2011, 2012–2014, or 2015–2017
- The area measured: platform, waiting rooms, or transfer passageways
- The presence of a transfer line: yes or no
- The number of transfer lines: none, 2, or > 2
- The presence of a platform screen door (PSD): yes or no (screen doors were established to isolate the platform from the railway and ensure the safety of passengers, and the year of establishment varies among the subway stations)
- The season measured: spring (March–May), summer (June–August), autumn (September–November), or winter (December–February)

**Table 1.** General information on the subway system in major metropolitan cities.

| City | Number of lines | Opening year of lines | | Number of subway station by location[a] | | Number of daily passengers in 2017[b] |
|---|---|---|---|---|---|---|
| | | First | Most recent | Underground | Above ground | |
| Seoul | 10 | 1974 | 2017 | 295 | 26 | 7,793,756 |
| Incheon | 2 | 1999 | 2016 | 48 | 8 | 429,334 |
| Metropolitan area surrounding Seoul (excluding Seoul & Incheon) | 14 | 1978 | 2018 | 91 | 245 | 3,702,575 |
| Daejeon | 1 | 2006 | 2007 | 22 | 0 | 108,772 |
| Daegu | 3 | 1997 | 2016 | 61 | 30 | 447,532 |
| Busan | 6 | 1985 | 2017 | 90 | 59 | 1,004,091 |
| Gwangju | 1 | 2004 | 2008 | 18 | 2 | 51,258 |
| Total | 37 (34)[c] | | | 625 | 370 | 13,537,318 |

[a] Transfer stations were counted in duplication.

[b] The number of daily passengers was calculated from the overall number of transported persons. In terms of the metropolitan area surrounding Seoul, data from 12 lines could be counted.

[c] Three lines (Nos. 1, 3, and 4) in Seoul are operated to the metropolitan area surrounding Seoul (duplicated). The line number is the same, but the operating section is different.

- The age of the station: < 5 years, 5–10 years, or > 10 years

We statistically examined both the environmental and subway characteristics significantly influencing the $PM_{10}$ level. All $PM_{10}$ measurements monitored were summarized using the following descriptive statistics: arithmetic mean (AM) and standard deviation (SD) with 95% confidence interval (CI); geometric mean (GM) and geometric standard deviation (GSD) with 95% CI; range; and quartiles. Box plots were used to show the distribution of measurements by subway characteristics, such as region and location monitored. Since $PM_{10}$ was monitored in each subway station every year and the measurements were thus correlated, both univariate and multiple linear mixed models were implemented to ascertain through a likelihood ratio test whether experimental factors such as region, location, and subway characteristics have a significant influence on the level of mean $PM_{10}$ while taking into account the correlation. All the statistical analyses were conducted using R software (version 3.5.1; R Foundation for Statistical Computing, Vienna, Austria).

## RESULTS

The $PM_{10}$ levels monitored in subway platforms, waiting rooms, and transfer passageways are compared by year (Fig. 1), city (Table 2), and subway and environmental characteristics (Table 3). Average $PM_{10}$ values are found to decrease slightly with year, which was consistently detected in all stations and regions. Average $PM_{10}$ levels monitored near subway platforms or waiting rooms ranged from 53.9 to 92.4 µg $m^{-3}$, and all levels were below 150 µg $m^{-3}$, the IAQ standard regulated by the IAQ Act. There have been 14 stations (9 in Seoul in 2007, 2 in Seoul in 2008, and 3 in Daegu in 2011) exceeding 150 µg $m^{-3}$. These are located above the dashed line in the box plot (Fig. 1).

When comparing the $PM_{10}$ levels on the platform by city, Seoul (AM = 91.9 µg $m^{-3}$, max = 170.2 µg $m^{-3}$) and Daegu (AM = 92.4 µg $m^{-3}$, max = 153.1 µg $m^{-3}$) were the highest, and Busan (AM = 56.6 µg $m^{-3}$, max = 128.6 µg $m^{-3}$) was the lowest (Table 2). Based on both univariate analysis and mixed effects multiple analysis, several subway characteristics, including the presence of PSDs, were found to be significantly associated with $PM_{10}$ level (Tables 3 and 4), even though there is a little difference in significant factors among cities. We indicated the univariate and multiple analysis results from Seoul at Table 4 and results from other regions can be found in Tables S1–S5 of the supplement. In terms of Seoul and the surrounding metropolitan area, the $PM_{10}$ concentration around the subway platform and in the waiting rooms was significantly high for Subway Line 1 when monitored from 2005 to 2007 when there was no PSD. In particular, the presence of PSDs was found to contribute to a significant reduction in $PM_{10}$ levels on the platform (Fig. 2), with the exception of in Busan (Fig. 2(e)) and in certain cities for specific years (2015–2016 in Gwangju). The $PM_{10}$ levels in the subway were found to be significantly higher than those monitored outdoors, regardless of city or year (Fig. 3).

## DISCUSSION

We analyzed variation in $PM_{10}$ concentrations over more than a decade in subways in Korea and found several characteristics influencing $PM_{10}$ level. The yearly average of $PM_{10}$ has fallen to 65.9 µg $m^{-3}$ in 2017 from a peak of

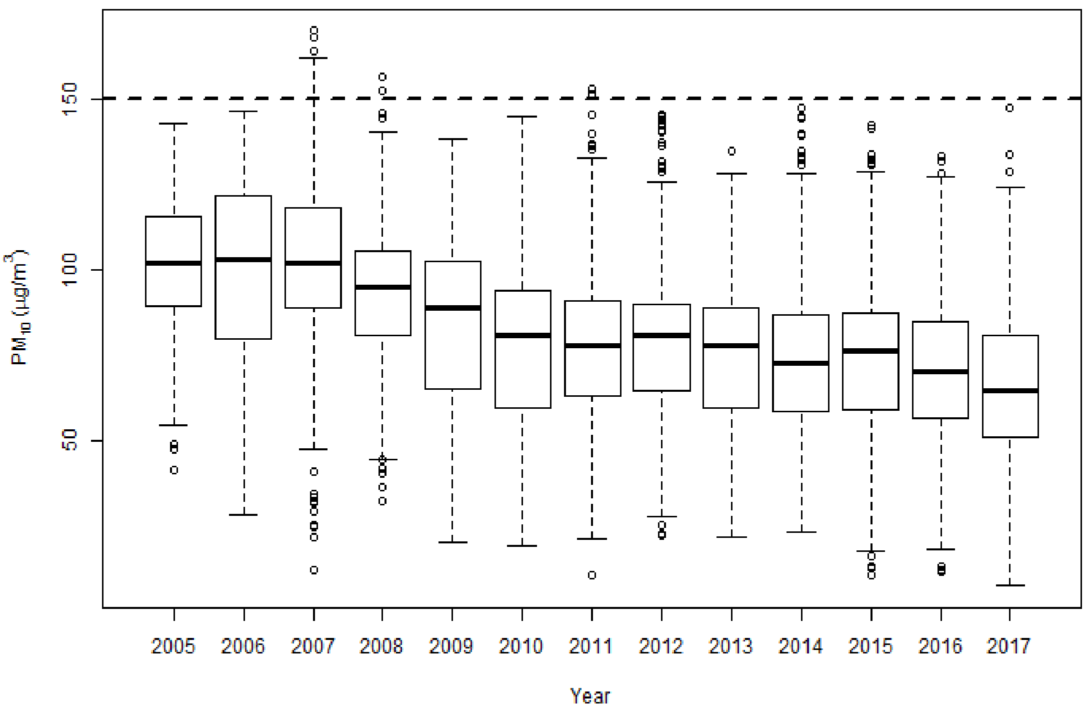


**Fig. 1.** Distribution of $PM_{10}$ levels by year. A total of 14 stations (9 in Seoul in 2007, 2 in Seoul in 2008, and 3 in Daegu in 2011) exceeded the indoor air quality standard of 150 µg $m^{-3}$ indicated by the dashed line.

**Table 2.** $PM_{10}$ levels ($\mu g\ m^{-3}$) measured over the study period in each city.

| City | Sampling location | Number of measurements | AM | SD | GM | GSD | Min | Max | Q1 | Q2 | Q3 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Seoul | Platform | 1,758 | 91.9 | 17.9 | 90.1 | 1.23 | 22.2 | 170.2 | 82.3 | 92.0 | 100.5 |
| | Waiting rooms | 1,985 | 80.2 | 14.5 | 78.8 | 1.22 | 20.6 | 140.8 | 72.2 | 81.4 | 88.7 |
| | Passages for transfer | 2,076 | 90.6 | 19.4 | 88.3 | 1.27 | 10.6 | 146.8 | 78.9 | 90.0 | 102.7 |
| Incheon | Platform | 363 | 85.4 | 27.6 | 80.6 | 1.43 | 11.4 | 147.8 | 63.9 | 82.5 | 107.5 |
| | Waiting rooms | 466 | 68.0 | 23.8 | 63.4 | 1.49 | 7.3 | 143.2 | 52.6 | 65.4 | 84.4 |
| | Passages for transfer | 17 | 60.9 | 14.8 | 58.9 | 1.32 | 32.4 | 85.2 | 56.8 | 60.8 | 73.1 |
| Daejeon | Platform | 244 | 64.3 | 18.76 | 61.6 | 1.36 | 19.5 | 133.7 | 54.3 | 62.9 | 73.4 |
| | Waiting rooms | 268 | 53.9 | 17.15 | 51.3 | 1.39 | 11.9 | 123.5 | 42.6 | 52.0 | 62.7 |
| Daegu | Platform | 693 | 92.4 | 25.6 | 88.3 | 1.38 | 12.4 | 153.1 | 74.9 | 93.3 | 110.2 |
| | Waiting rooms | 822 | 71.5 | 24.0 | 67.2 | 1.44 | 13.1 | 153.0 | 54.3 | 70.1 | 86.7 |
| | Passages for transfer | 2 | 60.4 | 12.5 | 59.8 | 1.23 | 51.6 | 69.2 | 56.0 | 60.4 | 64.8 |
| Busan | Platform | 1,184 | 56.6 | 15.0 | 54.7 | 1.30 | 20.7 | 128.6 | 46.5 | 54.8 | 64.3 |
| | Waiting rooms | 915 | 56.7 | 15.4 | 54.6 | 1.32 | 10.3 | 112.7 | 46.0 | 54.6 | 65.1 |
| Gwangju | Platform | 218 | 69.0 | 16.7 | 67.0 | 1.27 | 33.1 | 135.0 | 59.0 | 67.8 | 78.0 |
| | Waiting rooms | 236 | 64.0 | 13.9 | 62.5 | 1.26 | 30.1 | 111.8 | 55.0 | 64.3 | 72.3 |
| | Passages for transfer | 1 | 61.8 | N/A | 61.8 | N/A | 61.8 | 61.8 | 61.8 | 61.8 | 61.8 |
| Total | | 11,248 | 77.8 | 23.37 | 74.0 | 1.39 | 7.3 | 170.2 | 60.3 | 78.4 | 92.8 |

*Abbreviations:* AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; Min, minimum; Max, maximum; Q1, the first quartile; Q2, the second quartile; Q3, the third quartile; N/A, not available.

**Table 3.** Univariate analysis examining relationships between $PM_{10}$ level and subway characteristics.

| Variable[a] | | No. of measurements | AM | SD | GM | GSD | Min | Max | *p*-value[b] |
|---|---|---|---|---|---|---|---|---|---|
| Presence of platform screen door | Yes | 6,989 | 74.0 | 19.8 | 71.0 | 1.35 | 7.3 | 147.8 | < 0.001 |
| | No | 3,993 | 84.6 | 27.3 | 79.7 | 1.44 | 10.3 | 170.2 | |
| | NI | 266 | | | | | | | |
| Depth, m[c] | [0,13.3] | 2,771 | 81.6 | 23.0 | 78.1 | 1.36 | 18.9 | 161.5 | < 0.001 |
| | [13.3,17.2] | 2,728 | 75.6 | 22.9 | 71.9 | 1.39 | 12.6 | 170.2 | |
| | [17.2,21.3] | 2,748 | 77.6 | 23.3 | 73.8 | 1.39 | 7.3 | 162.3 | |
| | [21.3,64.2] | 2,725 | 76.5 | 23.8 | 72.5 | 1.41 | 11.4 | 149.3 | |
| | NI | 276 | | | | | | | |
| Location | Platform | 4,460 | 79.5 | 25.1 | 75.2 | 1.41 | 11.4 | 170.2 | < 0.001 |
| | Waiting rooms | 4,692 | 70.6 | 20.4 | 67.3 | 1.38 | 7.3 | 153 | |
| | Passages for transfer | 2,096 | 90.4 | 19.6 | 88.0 | 1.27 | 10.55 | 146.8 | |
| Number of lines at transfer station | No transfer | 8,547 | 76.0 | 23.9 | 72.0 | 1.41 | 7.3 | 170.2 | < 0.001 |
| | 2 | 2,228 | 82.6 | 21.5 | 79.5 | 1.34 | 12.6 | 159.6 | |
| | 3 | 382 | 87.9 | 16.5 | 86.3 | 1.22 | 35.6 | 142.7 | |
| | 4 | 91 | 84.6 | 13.9 | 83.4 | 1.19 | 51.2 | 128.3 | |
| Season | Spring | 2,600 | 66.4 | 22.4 | 62.7 | 1.41 | 7.3 | 153.1 | < 0.001 |
| | Summer | 4,117 | 78.3 | 21.0 | 75.3 | 1.34 | 11.9 | 153 | |
| | Autumn | 1,955 | 71.1 | 21.8 | 67.6 | 1.39 | 11.4 | 143.3 | |
| | Winter | 78 | 73.7 | 30.9 | 65.9 | 1.68 | 10.6 | 134.2 | |
| | NI | 2,458 | | | | | | | |
| Year of measurement | 2005–2008 | 1,756 | 98.7 | 23.01 | 95.6 | 1.31 | 11.9 | 170.2 | < 0.001 |
| | 2009–2011 | 2,517 | 79.1 | 23.21 | 75.2 | 1.40 | 10.3 | 153.1 | |
| | 2012–2014 | 2,819 | 75.5 | 19.71 | 72.7 | 1.33 | 21.7 | 147.5 | |
| | 2015–2017 | 4,156 | 69.7 | 20.27 | 66.5 | 1.38 | 7.3 | 147.8 | |
| Total | | 11,248 | | | | | | | |

*Abbreviations:* AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; Min, minimum; Max, maximum; NI, no information.

[a] The number of $PM_{10}$ measurements for each season, the presence of a screen door, and the depth were not the same due to some missed measurements. [b] Each *p*-value was from the likelihood ratio test with a mixed effects model. [c] Depth was categorized into quartiles.

**Table 4.** Subway characteristics influencing the level of $PM_{10}$ in Seoul and the surrounding metropolitan area.

| Variable[a] | | Univariate analysis[b] | | | | Multiple analysis[b] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Estimate | Lower 95% CI | Upper 95% CI | *p*-value | Estimate | Lower 95% CI | Upper 95% CI | *p*-value |
| Route | Line 2 | –9.15 | –12.65 | –5.63 | < 0.001 | –9.01 | –12.40 | –5.63 | < 0.001 |
| | Line 3 | –10.78 | –14.33 | –7.23 | | –10.67 | –14.11 | –7.24 | |
| | Line 4 | –8.41 | –12.16 | –4.64 | | –8.41 | –12.04 | –4.79 | |
| | Line 5 | –18.44 | –21.80 | –15.07 | | –19.71 | –22.99 | –16.43 | |
| | Line 6 | –15.04 | –18.49 | –11.60 | | –16.72 | –20.08 | –13.36 | |
| | Line 7 | –16.45 | –19.83 | –13.05 | | –16.91 | –20.22 | –13.60 | |
| | Line 8 | –17.69 | –21.52 | –13.84 | | –18.60 | –22.32 | –14.88 | |
| | Line 9 | –24.72 | –28.51 | –20.94 | | –21.88 | –25.63 | –18.15 | |
| | Airport railroad | –34.46 | –42.70 | –26.22 | | –36.47 | –44.33 | –28.59 | |
| | Sinbundang line | –25.97 | –30.27 | –21.65 | | –27.57 | –31.82 | –23.31 | |
| Year | 2009–2011 | –30.90 | –33.45 | –28.34 | < 0.001 | –25.88 | –30.83 | –20.95 | < 0.001 |
| | 2012–2014 | –21.70 | –23.72 | –19.67 | | –18.12 | –22.82 | –13.46 | |
| | 2015–2017 | –24.70 | –26.86 | –22.54 | | –19.64 | –24.43 | –14.91 | |
| Season | Winter | –52.68 | –60.03 | –45.32 | < 0.001 | –47.64 | –54.12 | –41.04 | < 0.001 |
| | Spring | –4.02 | –5.46 | –2.58 | | –3.30 | –4.57 | –2.02 | |
| | Summer | –1.91 | –3.07 | –0.73 | | –3.17 | –4.23 | –2.10 | |
| Others | Transfer station | 2.35 | 1.00 | 3.71 | 0.002 | 1.81 | 0.69 | 2.92 | 0.007 |
| | Platform screen door | –22.16 | –24.02 | –20.30 | < 0.001 | –4.90 | –9.21 | –0.55 | 0.055 |

[a] Reference group: route (Line 1), year (from 2005 to 2008), season (autumn), transfer station (non-transfer station), platform screen door (no screen door).
[b] A total of 2,256 missing data from Seoul and the metropolitan area surrounding Seoul lines were excluded in data analysis due to no information being available for the season and the installation of a screen door.
[*] Results from other cities were indicated in the supplementary material.

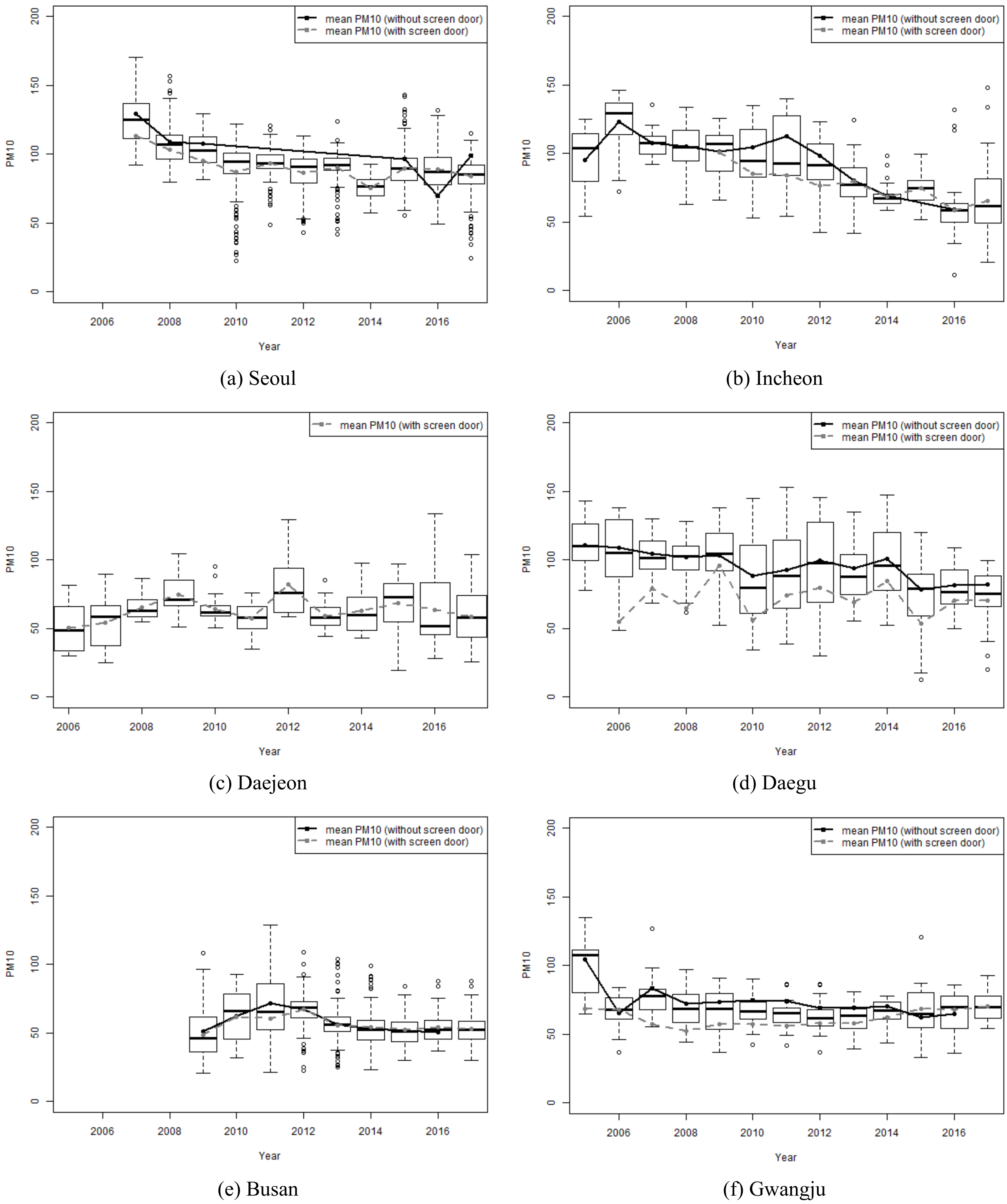


**Fig. 2.** Comparison of distribution of $PM_{10}$ levels (µg $m^{-3}$) on platforms by presence of screen door and year.

102.4 µg $m^{-3}$ prior to 2010, a 35.6% decrease. This trend is observed in all cities' subways, although the levels of decrease differ. Our results are far below the results reported by several studies conducted in Seoul. Park and Ha reported that $PM_{10}$ levels inside Subway Lines 1, 2, and 4 exceeded the Korean IAQ standard of 150 µg $m^{-3}$. Their average $PM_{10}$ concentration as monitored inside trains (144.0 µg $m^{-3}$) was far higher than the 125.8 µg $m^{-3}$ on platforms ($p = 0.026$) and the concentration range (35–81 µg $m^{-3}$) measured in outdoor air in Seoul from January to November in 2004 (SAMC, 2004). The oldest line, Line 1 in Seoul, showed concentration levels in 10 of 12 of its investigated stations that exceeded the

IAQ standard for $PM_{10}$. The highest monitored concentration was 207.5 µg $m^{-3}$ inside an underground station on Line 1.

Regardless of country, city, or location within the system, it has been characteristic for high concentrations of PM to be measured in subway systems, such as in London (Adams *et al.*, 2001), Stockholm (Johansson and Johansson, 2003), Prague (Braniš, 2006), Rome (Ripanucci *et al.*, 2006), Berlin (Fromme *et al.*, 1998), Seoul (Kim *et al.*, 2008), and Beijing (Li *et al.*, 2007). Levels of $PM_{10}$, $PM_{2.5}$, and nanoparticles in the subway environment have all been reported to be far higher than those monitored in the outside environment. When the average annual atmospheric concentration of $PM_{10}$ (KMOE, 2017) is compared with annual average concentrations measured in the subway, we also found the subway concentration to be higher than the atmospheric concentrations in all cities (Fig. 3). These results demonstrate that the amount of fine and ultrafine dust absorbed into the respiratory system in subway systems can generally be far higher than the amount from outdoors based on both exposure time and exposure level.

Generalizing factors that may influence $PM_{10}$ levels measured under specific circumstances are very difficult to specify because of the subway characteristics, surrounding environments, and environment measured (i.e., the types of subway, location measured, age of subway, number of subway users). We found that several subway characteristics significantly influence the level of $PM_{10}$ in subway stations. Year was found to be significantly associated with change in $PM_{10}$ level. The level of $PM_{10}$ reduces markedly with year, something statistically detected for all cities and all stations (Fig. 1 and Tables 3 and 4). However, the $PM_{10}$ levels measured in subway stations are still far above the Korean atmospheric environmental standard for $PM_{10}$ (yearly average: 50 µg $m^{-3}$; daily average: 100 µg $m^{-3}$) intended to protect the general public, including children and elderly people, even though other pollutants such as ozone and nitrogen dioxide ($NO_2$) are not substantially different (KMOE, 2018a). The Korean Ministry of Environment also adopted a $PM_{2.5}$ standard for the first time in 2015 (yearly average: 25 µg $m^{-3}$; daily average: 50 µg $m^{-3}$) and strengthened the standard in March 2018 (yearly average: 15 µg $m^{-3}$; daily average: 35 µg $m^{-3}$) (KMOE, 2018b). However, IAQ regulations lacked a standard for $PM_{2.5}$, even though it accounts for most of the $PM_{10}$ generated in the subway environment. IAQ standards for $PM_{2.5}$ in subway stations are scheduled to be set as a daily average of 50 µg $m^{-3}$ for the first time from 2019 (KMOE, 2018c). Many countries' national health organizations and influential global organizations such as the World Health Organization (WHO) have stipulated a standard or guideline value for indoor hazardous pollutants (Abdul-Wahab *et al.*, 2015). Air quality standards have been adopted as measures enforceable by a regulatory authority, including in Korea, Taiwan, and Japan. On the other hand, air quality guidelines are designed to offer guidance for reducing adverse health impacts from air pollution, and many countries such as the USA suggest their IAQ values only as guidelines. Generally, IAQ standards except for $PM_{10}$ are set to be similar to outdoor atmospheric standards (Vahlsing and Smith, 2012). Many people use the subway, including not only adults but also pollutant-sensitive groups such as children, medical patients, elderly people, and pregnant women. Also, people who routinely use a subway system for commuting can be exposed to the air in the subway for much longer periods than to outdoor air. This indicates that IAQ standards for $PM_{10}$ and $PM_{2.5}$ should be modified to match atmospheric standards.

In general, subway stations with transfer lines have more PM sources compared with stations without transfer lines, including a greater number of passengers, number of entrances and exits, and frequency of maintenance work. In addition, the passageways of transit stations are often connected to underground shopping areas, and thus, the possibility of the inflow of pollutants from the outside is greater. Therefore, transfer stations should be managed first to reduce fine dust concentrations. This study recommends the installation of boards that display real-time levels of $PM_{10}$ and $PM_{2.5}$ on some subway platforms on transfer lines so that citizens can be aware of the quality of subway air.

Several mitigation measures have been developed to reduce PM concentrations in subway systems; Korean researchers conducted most of the evaluations in this field. PSDs were recognized as one of the most efficient measures to improve underground air quality in subways. The average $PM_{10}$ concentration measured on the platforms after the installation of PSDs significantly reduced by 16% (Kim *et al.*, 2012) and 38% (Han *et al.*, 2014), respectively, compared to the earlier period. In this study, the presence of a PSD was also found to be a significant factor in reducing $PM_{10}$ levels on platforms (Fig. 2); this is considered true despite the city of Busan (Fig. 2(e)) and specific years not following this trend. However, the mean $PM_{10}$ concentration measured inside trains after the installation of PSDs increased significantly by 29.9% compared to the concentration before the installation (Son *et al.*, 2014). Son *et al.* (2014) suggest that air mixing between the platform and the tunnel was extremely restricted after the installation of the PSDs. Kown *et al.* (2016) investigated the change of PM size distribution in an underground station with PSDs; their results showed that the PM that was suspended in the tunnel flowed into the platform area even in a subway station where the effect of train-induced wind was blocked by the installed PSDs, as this flow occurred when the PSDs were opened. Despite the installation of completely sealed PSDs, the inflow of coarse mode particles from the tunnel seems unavoidable, indicating the need for measures to decrease the generated PM in order to lower subway user exposure.

Mechanical ventilation has been recognized as a key factor affecting indoor air quality in subway systems. Juraeva *et al.* (2016) experimentally investigated the effects of the train wind, the air curtain, and electric precipitators as well as the proper conditions for electric precipitator operation to decrease the PM concentration. Their results indicated that the average velocity of the airflow in the shaft increased when the velocity of the air curtain increased. The PM concentration after ventilation was reduced significantly in the tunnel when the air curtain and train wind were operated. Station design is also related to the influence of tunnel ventilation and the train piston effect. The effects of

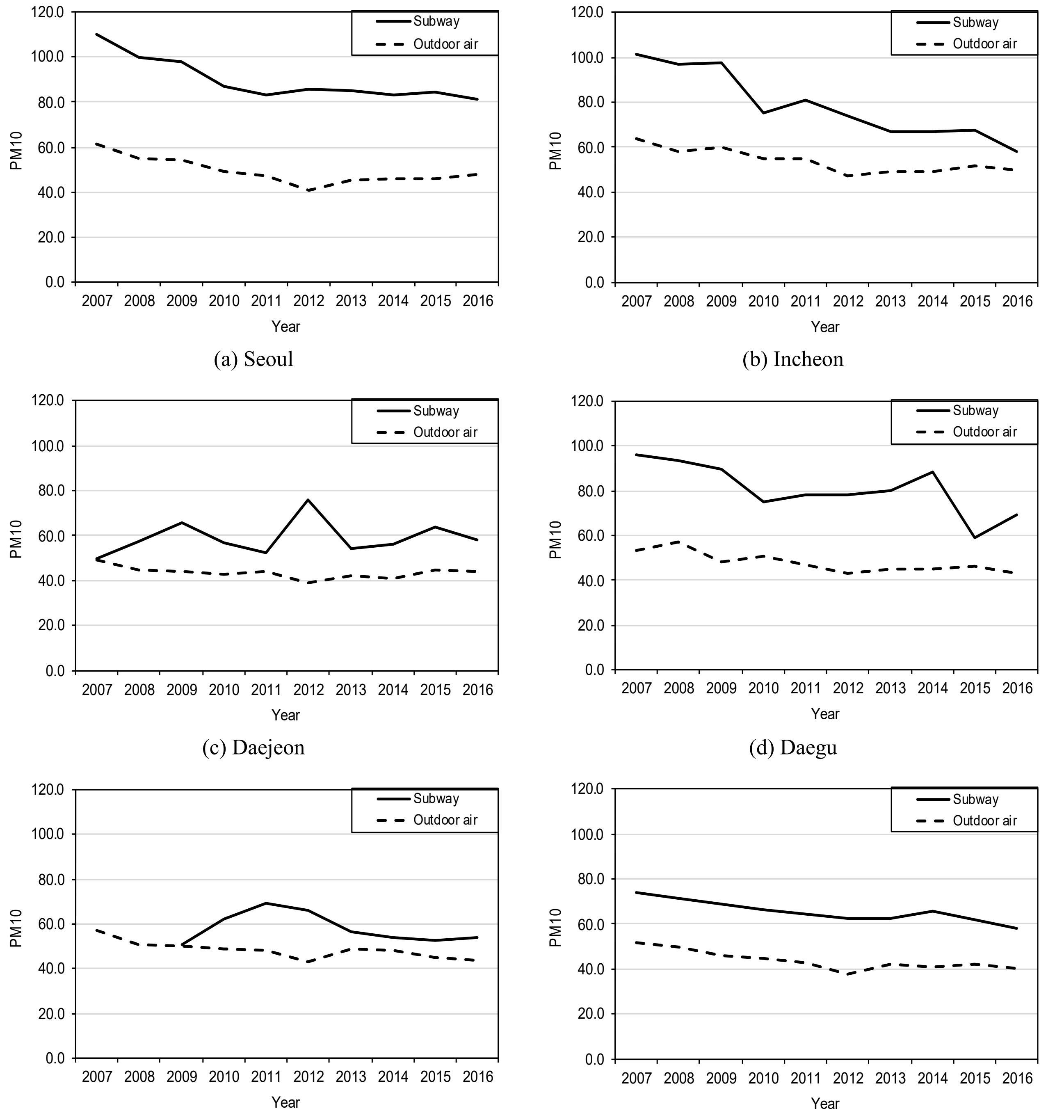


**Fig. 3.** Comparison of distribution of yearly average $PM_{10}$ levels ($\mu g\ m^{-3}$) monitored in subway stations and outdoor air.

ventilation conditions and station design on underground air quality were investigated in the Barcelona subway system. Narrow platforms served by single-track tunnels were dependent on forced tunnel ventilation and could not rely on the train piston effect alone to reduce platform PM concentrations. The PM concentrations of stations with spacious double-track tunnels were not significantly affected when tunnel ventilation was switched off (Moreno *et al.*, 2014). To reduce PM concentration in subway cabins, the subway cabin air purifier (SCAP) was developed and evaluated for its effectiveness (Kim *et al.*, 2014); it was found that the $PM_{10}$ concentrations inside cabins were reduced by 15.5–26.0% after the SCAP system was installed.

In order to improve indoor air quality in subways, it is important to identify the main sources of air pollution. Several studies in identifying the chemical composition of subway PM demonstrated that Fe was the most abundant metal element of $PM_{2.5}$ (Aarnio *et al.*, 2005; Loxham *et al.*, 2013; Lee *et al.*, 2018; Minguillón *et al.*, 2018) and $PM_{10}$ (Jung *et al.*, 2010; Park *et al.*, 2012; Loxham *et al.*, 2013;

Moreno *et al.*, 2015; Lee *et al.*, 2018), accounting for 30% and 80% of PM content, respectively. Jung *et al.* (2010) clearly identified indoor sources of subway PM in comparing four sets of samples collected in tunnels, on platforms, near ticket offices, and outdoors. Fe-containing particles predominated in the samples collected in tunnels, with relative abundances of 75–91% for the four stations. In addition, the amount of Fe-containing particles decreased as the distance of sampling locations from the tunnel increased. These results clearly indicated that Fe-containing subway particles were generated in the tunnel. Park *et al.* (2012) characterized $PM_{10}$ sources by positive matrix factorization; railroad-related sources such as the abrasion of the railroad tracks, brakes, and power supply or draft lines during subway operation contributed the most $PM_{10}$ to subway cabin air. Studies in both New York City (Vilcassim *et al.*, 2014) and Shanghai (Guo *et al.*, 2017) indicated that a potential source of fine particles in subways was the diesel engine cleaning and maintenance vehicles that operated during the night in the underground facilities. Recently, Choi *et al.* (2019) also identified that the use of diesel engine vehicles in tunnel maintenance was a key contributor to both $PM_{2.5}$ and black carbon (BC) exposure levels among subway workers. The use of diesel engine vehicles in semi-confined underground environments causes not only exposure to high levels of diesel engine exhaust emissions but also an increase in $PM_{2.5}$ on subway platforms or in waiting rooms. Therefore, proactive measures, including the installation of diesel particulate filters (DPFs) on diesel engine maintenance vehicles in tunnels, are urgently suggested in order to reduce subway workers' exposure to both $PM_{2.5}$ and BC. In addition, after the enforcement of the EURO engine emission standard, $NO_2$ emissions for recent diesel engines are becoming a significant concern in diesel engine exhaust (Grice *et al.*, 2009; Carslaw and Rhys-Tyler, 2013). Electric-battery equipped vehicles, which would be effective in reducing the levels of airborne particles and $NO_2$, should be introduced to improve air quality in subways. In particular, diesel vehicles without diesel exhaust-reducing air treatment systems should be phased out of use in subways.

This study has several limitations. One major limitation is that it is not possible to know how representative these findings obtained from various locations are with regard to subway characteristics that involve various types of physical environments and ventilation levels. Our $PM_{10}$ measurements were compilations of data measured once in a specific area and on a specific day during the year, which may likely be affected by not only subway characteristics but by outdoor conditions as well. The number of passengers, which likely is associated with the level of $PM_{10}$, was not examined in this study. It is impossible to obtain the number of passengers who used the stations where $PM_{10}$ levels were measured. In addition, this study did not examine the impact on $PM_{10}$ by engineering control measures designed to reduce the infiltration of air pollutants in subways, including fine and ultrafine particles, from the outdoor environment, which is likely one of the factors increasing the level of fine particles in a subway. The facilities for supplying outdoor air were all found to be installed on a street at the same level as a road bearing traffic. The air cleaners are not able to remove fine particles exhausted from vehicles and the outdoor environment. In addition, the non-designed data collection resulted in some potential environmental factors partially crossing, implying that not all the effects of these influential factors were fully estimated and tested within the linear mixed models. For example, all of the $PM_{10}$ data for Daejeon for the years 2012–2014 were collected in the autumn, and therefore, it was impossible to separate the effect of autumn from that of the years 2012–2014. Although we successfully took into account the correlation structure among $PM_{10}$ measurements due to their being measured over time at several locations within a station through the use of a linear mixed model, it is assumed that spatial correlations among adjacent stations were not large enough to be considered under the condition that the ventilation system in a tunnel connecting any two stations worked well. This assumption needs to be investigated thoroughly in a future study.

Nevertheless, our results are useful not only for characterizing the level of $PM_{10}$ in the subway environment but also for identifying specific factors that may significantly influence $PM_{10}$ concentrations and for recommending mitigation procedures. The general variations in $PM_{10}$ levels over more than a decade were also characterized. Based on our results, a number of appropriate engineering, administrative, and regulatory measures could be taken to reduce exposure to fine and ultrafine PM in subway stations. Further study is required to monitor $PM_{2.5}$ and the diesel engine exhaust concentrations in subway air considering several subway characteristics including maintenance at tunnel.

In conclusion, even though the $PM_{10}$ concentrations in subways have been decreasing over time, they are still higher than outdoor levels and far exceed the yearly atmospheric environmental standard (50 $\mu g\ m^{-3}$). We found that several factors, including the specific year, the location of the station, and the presence of a PSD, significantly influenced the amount of $PM_{10}$.

## ACKNOWLEDGMENTS

This study was supported by the 2018 Extramural Research Fund of the Occupational Safety and Health Research Institute, KOSHA (2018-OSHRI-796).

## DISCLAIMER

All authors declare there is no financial/personal interest or belief that could affect their objectivity.

## SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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*Received for review, May 22, 2019*
*Revised, August 19, 2019*
*Accepted, October 9, 2019*