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# Indoor air quality control for improving passenger health in subway platforms using an outdoor air quality dependent ventilation system

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ABSTRACT

Indoor air quality (IAQ) ventilation systems are widely used to control air pollutants in subway platforms. When outdoor air is heavily contaminated by particulate matters (PMs), it enters the subway platform through the ventilation system, resulting in the deterioration of platform IAQ and adverse effects on passenger health. In this study, a new IAQ ventilation system that takes into account the outdoor air quality used for ventilating platform is proposed to control the platform $PM_{10}$ concentration. For this, the amount of $PM_{10}$ that flows from the outdoors into the subway platform is considered a manipulated variable of the proposed ventilation system. The influence of the platform $PM_{10}$ on passengers' health risk is evaluated using a comprehensive indoor air-quality index (CIAI). The CIAI level of platform $PM_{10}$ is compared using the manual and proposed ventilation systems, where the manual system operates at fixed ventilation inverter frequency without regard to the outdoor air quality. Experimental results from an underground subway platform showed that the proposed ventilation system can improve the platform $PM_{10}$ level, leading to the passengers' exposure to the reduced $PM_{10}$ concentration (i.e., health risk reduction), and reduce the ventilation energy compared to the manual system by adjusting the ventilation inverter frequency and inflow of outdoor $PM_{10}$ into the subway platform depending on the outdoor air quality.



## 1. Introduction

Millions of people in metropolitan areas depend on the convenience of subway systems for transportation, which have been described as the "lifeline of urban development" by reducing traffic congestion above ground and providing environment-friendly transit [1–3]. Notwithstanding these advantages, there has been a growing concern over indoor air quality (IAQ) in subway systems, since people spend a considerable amount of time in the subway systems daily [4,5]. Most subway systems are underground in a confined space where air pollutants are generated internally as well as enter from the outside atmosphere. Furthermore, due to heavy use and overcrowding, various types of hazardous pollutants which present a health risk to passengers and subway working staff are accumulated in subway systems [3,6]. Therefore, to ensure passengers and subway workers good health, ventilation systems are necessary for controlling hazardous air pollutants in the subway systems.

Recently, several studies on ventilation of indoor air pollutants in different building spaces have been reported [7–12]. Chao and Hu [8] have established a dual-mode demand control ventilation strategy that maintains the occupant-related and non-occupant-related indoor air pollutants at acceptable levels. Kolokotsa et al. [9] have proposed a bilinear model-based ventilation system to achieve the optimum indoor environmental conditions while minimizing energy cost. Liu et al. [10] have developed a model predictive control (MPC) based ventilation system in the subway station. They also have applied a multi-objective optimization algorithm to determine optimal set-points of the ventilation system which concurrently improve the IAQ and ventilation energy efficiency. Lim et al. [12] have proposed a new ventilation index, Net Escape Velocity (NEV), which directly provides information in behavior of the contaminants to the ventilation system. These researchers have assumed that the polluted indoor air is replaced with clean outdoor air by increasing the ventilation rate. In fact, if the outdoor air is strongly contaminated due to aeolian

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transportation of dust particles or yellow dust, its entry into the building spaces through the ventilation systems increases the air pollutants inside the building spaces [13,14]. This article proposes a new approach that considers the outdoor air quality used for diluting indoor air pollutants. The development of ventilation control system, which takes the changes of outdoor air quality into account, is the central theme of the present study.

The ventilation under contaminated outdoor air conditions can increase the potential that the passengers in the subway systems will be exposed to health risk. Suppose the concentration of particulate matters (PMs) in the outdoor air is higher than usual (for example on megacities where the PMs concentration is far above the recommendations due to yellow dust etc., see Refs. [15,16]). If the ventilation system is operated with the identical ventilation rate to the usual, then a larger amount of PMs enters the subway system through the ventilation under such contaminated outdoor air conditions [14,17]. The PMs with aerodynamic diameters less than 10 μm ($PM_{10}$) and 2.5 μm ($PM_{2.5}$) deposit to trachea-bronchial compartment of the human respiratory system, and then, cause respiratory illnesses such as bronchial asthma, rhinitis and chronic bronchitis [18,19]. As such, the ventilation with contaminated outdoor air has a large influence on the passengers' health risk. Therefore, to protect the passengers' health inside the subway systems, it is necessary to evaluate the influence of IAQ that is ventilated with the contaminated outdoor air. Another theme of this study is the evaluation of the influence of the ventilated IAQ on the passengers' health risk depending on the consideration of outdoor air quality.

In the first part of this study, the ventilation control system is developed to keep the $PM_{10}$ concentration in the subway system at a comfortable and healthy range. To take the changes of outdoor air quality into account, the amount of $PM_{10}$ that is introduced from the outdoors to the subway system is used for developing the ventilation control system. Feedback and feed-forward ventilation control strategies are proposed to compensate for dynamic variations of the $PM_{10}$ concentration in the subway systems and effects of disturbances on the subway system's $PM_{10}$ concentration, respectively (for background on feedback and feed-forward control, see Bequette [20] and Seborg et al. [21]).

This article uses a comprehensive indoor air-quality index (CIAI) to evaluate the influence of the ventilated IAQ on the passengers' health risk inside the subway system. The CIAI describes ambient air quality based on the health risk of the air pollutants [18]. The variations of $PM_{10}$ level in the subway system are evaluated using the ventilation control system with and without the consideration of outdoor air quality, respectively. Then, the influence of $PM_{10}$ level on the passengers' health risk is investigated using the CIAI. These methods are applied to an underground subway station at Seoul Metro, South Korea.

## 2. Comprehensive indoor air-quality index (CIAI)

A comprehensive indoor air-quality index (CIAI), of which the aim is to help the public understand the condition of current indoor air and the associated health effects, determines the health risk of indoor air pollutants using six levels of concern (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous) [18,22]. The CIAI value of each indoor air pollutant is represented as:

$$\mathrm{CIAI} = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}}(C_P - BP_{LO}) + I_{LO} \tag{1}$$

where $C_P$ is the current concentration of air pollutants (μg/m$^3$); $BP_{LO}$ and $BP_{HI}$ are the concentration breakpoints of each health concern level (μg/m$^3$); and $I_{LO}$ and $I_{HI}$ are the index breakpoints of each health concern level [18]. Specifications of the CIAI are shown in Table 1.

## 3. Description of the IAQ ventilation control system

Fig. 1 shows a schematic diagram of the IAQ ventilation control system in a subway platform. The ventilation control system generates control signals to ventilation inverter frequency to control the air pollutants inside the platform, where the inverter is an electronic device that regulates revolution speed of ventilation fan motor. Then, depending on the controlled inverter frequency, outdoor air with the massive PMs filtered out is distributed to the platform to dilute the polluted indoor air [23].

In this study, a controlled variable taken for the ventilation control system is the $PM_{10}$ concentration at the subway platform. A manipulated variable is the amount of $PM_{10}$ (mg/h) introduced from the outdoors to the platform through the ventilation system, which is calculated as:

$$PM_{10}\,\text{amount} = \left(Q\frac{Hz}{Hz_{max}}\right)n(1-\alpha)PM_{10}\,\text{conc. in outdoor air}/10^3 \tag{2}$$

where $Q$ is the air volume of the ventilation system (m$^3_{\text{outdoor air}}$/h); Hz is the inverter frequency of the ventilation system; $Hz_{max}$ is the maximum inverter frequency of the ventilation system; $n$ is the number of ventilation systems installed in the subway platform; $\alpha$ is an average filter efficiency; and $PM_{10}$ conc. in outdoor air is the outdoors $PM_{10}$ concentration (μg/m$^3$). In Eq. (2), the filter efficiency $\alpha$ dependent on the filters' efficiencies could be an important factor, since it affects both of the IAQ and filtration cost in the subway platform. Table 2 compares the filtration cost of $PM_{10}$ filters with

**Table 1**
Comprehensive indoor air quality index (CIAI) suggested by the U.S. Environmental Protection Agency.

| Level of health concern | Good | | Moderate | | Unhealthy for sensitive groups | | Unhealthy | | Very unhealthy | | Hazardous | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CIAI | 0-50 | | 51-100 | | 101-150 | | 151-250 | | 251-350 | | 351-500 | |
| ILO | 0 | | 51 | | 101 | | 151 | | 251 | | 351 | |
| IHI | 50 | | 100 | | 150 | | 250 | | 350 | | 500 | |
| Conc. level | $BP_{LO}$ | $BP_{HI}$ | $BP_{LO}$ | $BP_{HI}$ | $BP_{LO}$ | $BP_{HI}$ | $BP_{LO}$ | $BP_{HI}$ | $BP_{LO}$ | $BP_{HI}$ | $BP_{LO}$ | $BP_{HI}$ |
| $NO_2$ (ppm) | 0 | 0.03 | 0.031 | 0.05 | 0.051 | 0.15 | 0.151 | 0.25 | 0.251 | 0.5 | 0.501 | 2 |
| CO (ppm) | 0 | 5 | 5.01 | 10 | 10.01 | 20 | 20.01 | 30 | 30.01 | 40 | 40.01 | 50 |
| $CO_2$ (ppm) | 0 | 500 | 501 | 1000 | 1001 | 1500 | 1501 | 2000 | 2001 | 3000 | 3001 | 5000 |
| $PM_{10}$ (ppm) | 0 | 50 | 51 | 150 | 151 | 250 | 251 | 350 | 351 | 450 | 451 | 600 |
| PM2.5 (ppm) | 0 | 15 | 16 | 40 | 41 | 140 | 141 | 250 | 251 | 350 | 351 | 500 |

Note: $I_{LO}$ is the index breakpoint corresponding to $BP_{LO}$, $I_{HI}$ is the index breakpoint corresponding to $BP_{LO}$, and $BP_{LO}$ and $BP_{HI}$ are the concentration breakpoints of each health level.