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# A dynamic gain-scheduled ventilation control system for a subway station based on outdoor air quality conditions

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A B S T R A C T

Within subway stations, the use of a mechanical ventilation system is a common strategy for improving the indoor air quality (IAQ). These ventilation systems use outdoor air to dilute pollutants on the subway platforms. However, a fixed fan speed in manual subway station ventilation systems does not consider variations in IAQ dynamics caused by disturbances yielded by the outdoor air quality (OAQ). Since the IAQ in subway stations has become a major public health concern, this study aims to analyze the IAQ dynamics at different OAQ conditions to design a new dynamic ventilation control system. The proposed method implemented a Gain Scheduling control strategy over OAQ variations at the D-Subway Station in the Seoul metropolitan area. A set of one feedback (FB) and two feedforward (FF) controllers was implemented. The results showed that the proposed control system tuned with the internal model control (IMC) method achieved an energy saving of 9% in comparison to the manual ventilation system. It was estimated a decrease in energy consumption of 158 kWh/day, representing an emission reduction of 268 $kgCO_2$/day. Following, an energy cost reduction of 4325 USD yearly was estimated. Additionally, the indoor particulate matter level is maintained below a control limit considered to be unhealthy for sensitive groups (150 μg/$m^3$).

## 1. Introduction

Over the past few decades, underground transportation has become increasingly important in metropolitan areas worldwide due to its high efficiency, extensive capacity, traffic relief, and low emissions operation [1]. Millions of people depend on these transportation systems for their daily routines, resulting in considerable time spent in subway stations [2]. However, despite the benefits of subway transport systems, indoor air pollutants are a potential health risk to commuters [3]. Urban subway systems are confined, poorly ventilated microenvironments with unique emission sources (friction in the rail-wheel-brake interaction) of particulate matter (PM) [1,3,4].

Prior studies focused on the monitoring and control of PM generated in subway stations [2,3,5–11]. The levels of this pollutant in subway microenvironments are generally higher than at ground level, creating the potential for hazardous health exposure to commuters [12,13]. Furthermore, PM in subway stations differs from that in other environments due to shape, distribution, and composition (dominantly Fe) [4]. Pope and Dockery [14] concluded that long-term PM exposure is associated with increased cardiovascular mortality. In Seoul, there are nine lines that are used daily by approximately four million people [2]. The Korean Ministry of Environment has declared subway stations as harmful spaces for public health, motivating the establishment of regulations for the control of these indoor hazardous pollutants [5,6]. For these reasons, this study uses particulate matter smaller than 10 μm ($PM_{10}$) to quantify the indoor air quality (IAQ) in the subway station.

IAQ levels in urban subway systems depend on several factors such as humidity, internal temperature, crowding level and ventilation conditions [1,6]. In this context, mechanical ventilation systems are commonly used to improve IAQ by supplying the indoor space with fresh air from outside [15]. Moreno et al. [3] concluded that subway platforms are heavily dependent on forced tunnel ventilation to maintain low levels of PM. Nonetheless, Kukadia and Palmer [16] conducted a pilot study concluding that IAQ follows the outdoor air quality (OAQ) trend to which it is exposed; therefore, IAQ is mainly dependent on OAQ.

Although a mechanical ventilation system helps in the dilution of contaminants, it increases the building energy consumption [15,17]. Air conditioning and ventilation systems consume between 35% and 50% of the total electricity in a building space [6,18]. Despite this, ventilation systems in underground stations are considered to have the greatest potential for energy savings [19]. The reduction of the demand

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in energy consumption in the building sector has been considered as an important goal suggested by the Intergovernmental Panel on Climate Change [18]. Furthermore, some studies have directly related the current energy and transportation systems to $CO_2$ discharge over the next 50 years [20]. In South Korea, there are 20 subway lines and 577 subway stations; it is estimated that subway ventilation systems consumption is approximately greater than 1800 KWh/day per station [5,6]. For these reasons, studies have been conducted to improve IAQ while saving energy in ventilation systems [2–6,12–14].

Ventilation systems in subway stations work at fixed fan speeds according to a schedule, regardless of variations in IAQ that manifest as time-variant disturbance factors. For example, IAQ levels are lowest during morning rush hours due to overcrowding and heavy use [6]. Additionally, periodic events such as seasonal changes and yellow sand storms may alter the IAQ conditions [6,21]. Modeling of an IAQ system comprises all disturbance factors, and it is commonly used as a strategy to simulate the actual process through mathematical algorithms [2–5,22].

Previously, to control the IAQ in subway stations, researchers have carried out several studies using mathematical models. Lee et al. [6] implemented a gain-scheduled ventilation control system relying on variations in the IAQ dynamics according to rush and non-rush hours. Additionally, they proposed a combination of feedback (FB) proportional-integral-derivative (PID), and feedforward (FF) controllers as a control strategy. The implementation of this system reduced the ventilation energy by 4% maintaining a comfortable IAQ level ($PM_{10}$ under 120 $\mu g/m^3$). Kim et al. [5] proposed an OAQ-dependent ventilation system wherein, the amount of $PM_{10}$ flowing indoors was used as a manipulated variable. An FB proportional-integral (PI) and an FF controller were used as a control strategy. This proposed strategy achieved a reduction in energy consumption of 39% while maintaining a healthy IAQ level. Vaccarini et al. [23] developed a model-based predictive control algorithm coupled with a monitoring platform. This study achieved a greater than 30% energy savings in a Barcelona subway ventilation system while maintaining comfort levels.

Most of the research considering IAQ has focused on decreasing the concentration of pollutants in building spaces and on the development of energy saving strategies. However, considering disturbances as a control tool for varying IAQ dynamics has not been studied in depth. The main objective of the present study is to develop a ventilation control system based on the differentiation of the IAQ system according to OAQ variations. Hence, IAQ systems and their controllers are updated according to an OAQ signal and specific corrective actions to the ventilation system are performed for each OAQ condition. As a result, an energy efficient ventilation system must be generated while maintaining comfortable IAQ levels.

This paper consists of three major sections. First, the relationships between indoor $PM_{10}$ concentration (namely $PM_{10}$ concentration inside the subway platform), ventilation system, and disturbances are analyzed to identify the IAQ system. Second, two IAQ control systems are defined: one that is derived from the manual ventilation system and the other from OAQ conditions. In addition, a set of FB and FF controllers are applied to both systems. In the third section, both ventilation control systems are simulated, and their performance is compared using the average indoor $PM_{10}$ concentration, energy consumption, and occurrence of $PM_{10}$ concentrations exceeding the control limit.

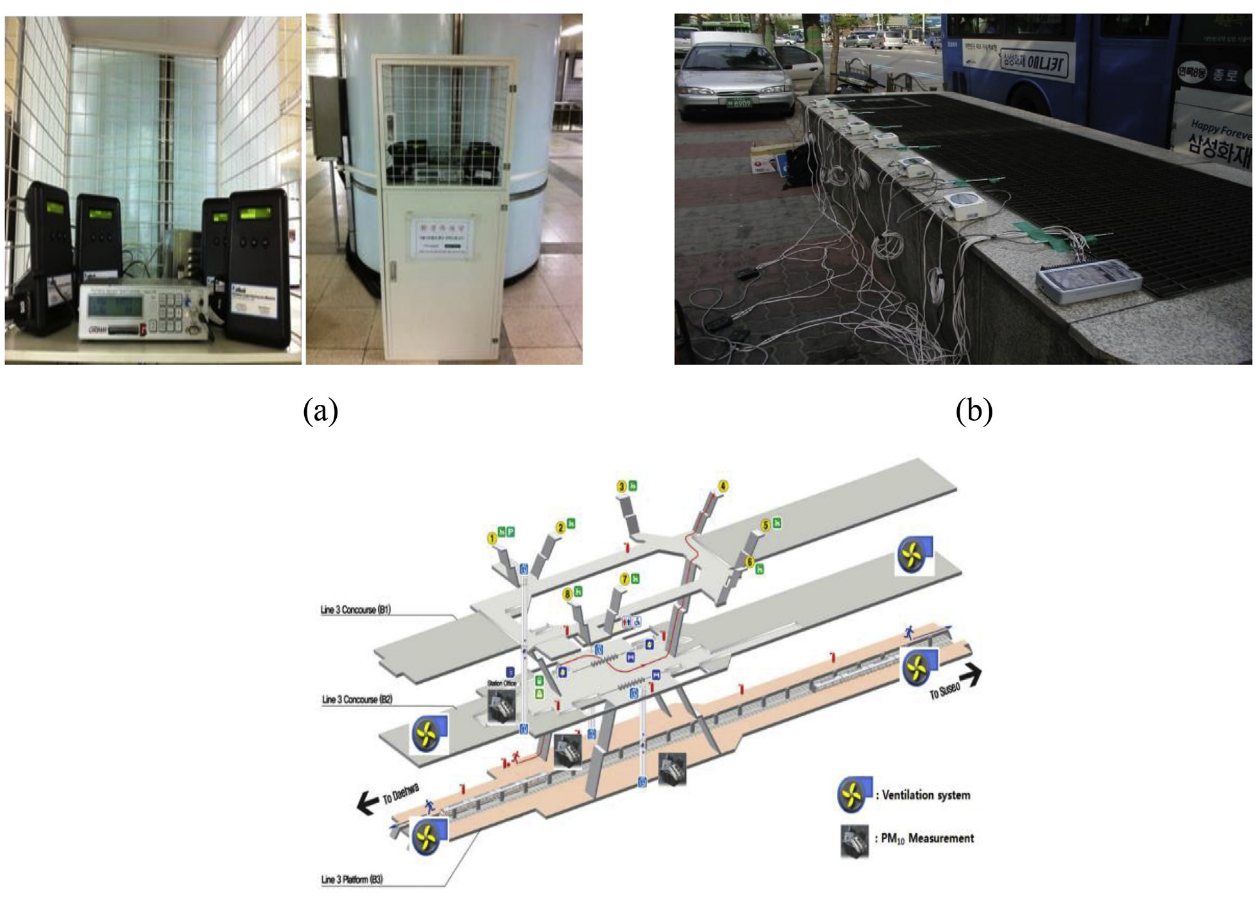


**Fig. 1.** Data measurement in D-Subway station: (a)Tele-monitoring system for IAQ measurements, (b) outdoor ventilators, and (c) location of IAQ measurement stations.