World Academy of Science, Engineering and Technology
International Journal of Architectural and Environmental Engineering
Vol:9, No:7, 2015

# Optimal Trajectory Finding of IDP Ventilation Control with Outdoor Air Information and Indoor Health Risk Index

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Open Science Index, Architectural and Environmental Engineering Vol:9, No:7, 2015 publications.waset.org/10002352.pdf

***Abstract*—**This study was carried out for an underground subway station at Seoul Metro, Korea. The optimal set-points of the ventilation control system are determined every 3 hours, then, the ventilation controller adjusts the ventilation fan speed according to the optimal set-point changes. Compared to manual ventilation system which is operated irrespective of the OAQ, the IDP-based ventilation control system saves 3.7% of the energy consumption. Compared to the fixed set-point controller which is operated irrespective of the IAQ diurnal variation, the IDP-based controller shows better performance with a 2% decrease in energy consumption, maintaining the comfortable IAQ range inside the station.

***Keywords*—**Indoor air quality, iterative dynamic algorithm, outdoor air information, ventilation control system.

## I. INTRODUCTION

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 [1]. To maintain the IAQ at a comfortable and healthy range, mechanical ventilation systems that dilute the indoor air pollutants with outdoor air have been widely used [2]. Conventional researches on the mechanical ventilation system have assumed that the polluted indoor air is replaced with clean outdoor air by increasing the ventilation rate [3], [4]. In fact, if the outdoor air is contaminated due to dust particles or yellow dust, its entry into buildings through the ventilation system increases the air pollutants inside the building spaces [5]. Therefore, a new ventilation control system that adjusts the ventilation rate taking *outdoor air information* (e.g., concentration of outdoor air pollutants, temperature) into account is necessary.

A trajectory of set-point of ventilation control systems plays an important role for efficient ventilation inside subway stations since it affects the level of indoor air pollutants and ventilation energy consumption. To maintain Indoor Air Quality (IAQ) at a comfortable range with lower ventilation energy consumption, the optimal trajectory of the ventilation control system needs to be determined. The concentration of air pollutants inside the station shows a diurnal variation in accordance with the variations in the number of passengers and subway frequency. To consider the diurnal variation of IAQ, an Iterative Dynamic Programming (IDP) that searches for a piecewise control policy by separating whole duration into several stages is used. When outdoor air is contaminated by pollutants, it enters the subway station through the ventilation system, which results in the deteriorated IAQ and adverse effects on passenger health. In this study, to consider the influence of outdoor air quality (OAQ), a new performance index of the IDP with the passenger health risk and OAQ is proposed [6].

The objective of this study is to determine a trajectory of optimal set-points of the ventilation control system that considers (1) *outdoor air quality* used for diluting indoor air pollutants and (2) *IAQ diurnal variation*. In the subway systems, it is not feasible to ventilate the IAQ with the fixed value of set-point, since the concentration of air pollutants inside the subway system shows a periodic diurnal variation depending on the changes in the number of passengers and subway frequency [7]. At morning and evening rush hours (when the indoor pollutants are in high concentration), the set-point of the ventilation control system is set at a low value for maintaining IAQ at the healthy range and reducing pollutant's risk to the passengers. On the other hand, at non-rush-hour times (when the indoor pollutants are in low concentration), the set-point is set at a high value for reducing ventilation energy consumption [8]. It implies that, to balance the pollutant's risk reduction and ventilation energy saving in the subway systems, the set-point of the ventilation control system needs to be reset in accordance with the IAQ diurnal variation [9]. Therefore, this study proposes the methodology that finds the trajectory of optimal set-points of the ventilation control system considering the outdoor air quality and IAQ diurnal variation concurrently.

This study uses an iterative dynamic programming (IDP) to determine the optimal set-points trajectory of the ventilation control system. IDP is a powerful technique that searches for the optimal control policy by separating whole control duration into several time stages [10]. First, to find the set-points that is balanced for the pollutant's risk reduction and ventilation energy saving, performance index used by the IDP is newly proposed. The amount of outdoor pollutants that are flowed into the subway system through the ventilation is varied depending on the outdoor air quality, and it consequently influences the passenger health [5]. Therefore, the different performance index is proposed for two conditions of the

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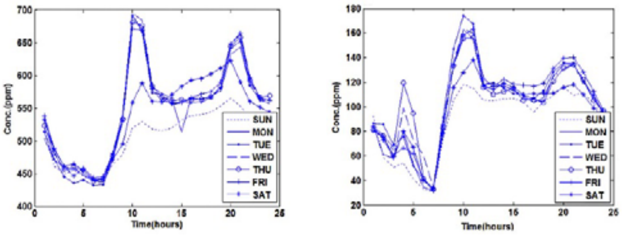
outdoor air quality, which are moderate and contaminated outdoor air conditions. Then, the IDP method is applied to determine the optimal set-points trajectory under the moderate and contaminated outdoor air conditions, respectively. For this, the IDP method is applied to one-day ventilation duration of which the set-point determining interval is 3-hour and 1-hour, respectively. It resets the optimal set-point every time intervals, which are able to satisfy the performance index considering the outdoor air quality and IAQ diurnal variation. This study is carried out in an underground subway station at Seoul Metro, Korea.

## II. ITERATIVE DYNAMIC PROGRAMMING

Since the concentration of air pollutants inside the subway station is varied with the periodic diurnal patter (as shown in Fig. 1), iterative dynamic programming (IDP) is used to determine the optimal set-points of the ventilation control system every IAQ changing intervals. In this implementation, IDP searches for the optimal values of set-point for one-day ventilation duration separated into several stages of equal length [10].



(a) (b)

Fig. 1 Diurnal variation of indoor air pollutants in subway station: (a) $CO_2$ and (b) particulate matter ($PM_{10}$)

Using an IDP algorithm, a piecewise constant control policy (instead of a continuous control policy) is chosen over the stages as shown in Fig. 2, where **x** is the state vector and **u** is the control vector bounded by $u_H$ and $u_L$ [9]. For more details on the IDP algorithm, refer to [11].

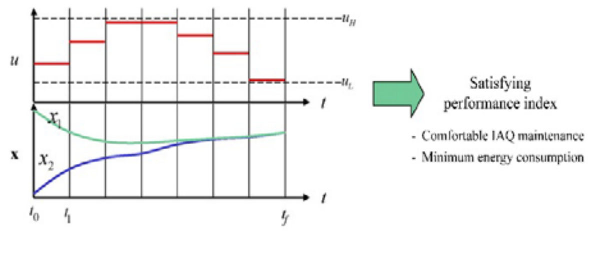


Fig. 2 Basic scheme of iterative dynamic programming (IDP)

## III. MATERIAL AND METHODS

### A. IAQ Ventilation Control System

Fig. 3 shows a block diagram of the IAQ ventilation control system developed in the present study. A controlled variable taken for the ventilation control system is the $PM_{10}$ concentration in the subway station. In actual ventilation control systems, the physical manipulated variable is the ventilation fan speed [4]. However, to consider the outdoor air quality used for ventilating the IAQ, it is convenient to formulate the ventilation control design in terms of the amount of $PM_{10}$ that is introduced from the outdoors to the station through the ventilation system. Therefore, the $PM_{10}$ amount fed into the station through the ventilation system is considered a surrogate manipulated variable, which is calculated as:

$$\mathrm{PM}_{10}\ \text{amount} = \left( Q \frac{\mathrm{RPM}}{\mathrm{RPM}_{\max}} \right) n (1-\alpha) \cdot \left( \mathrm{PM}_{10}\ \text{conc. in outdoor air} \right) \tag{1}$$

where $Q$ is the capacity of the ventilation system [$m^3_{\text{outdoor air}}$/hour], $RPM_{max}$ is the maximum fan speed of the ventilation system, $n$ is the number of ventilation systems installed in the subway station, and $\alpha$ is a filter efficiency. One of disturbance variables of the ventilation control system is the $PM_{10}$ concentration in the waiting room, since it flows into the station by passengers' movement and affects the station $PM_{10}$ level [7]. The other disturbance variable is the subway frequency, since the motion of subway trains pushes the $PM_{10}$ in tunnel toward the station by a piston effect [12].

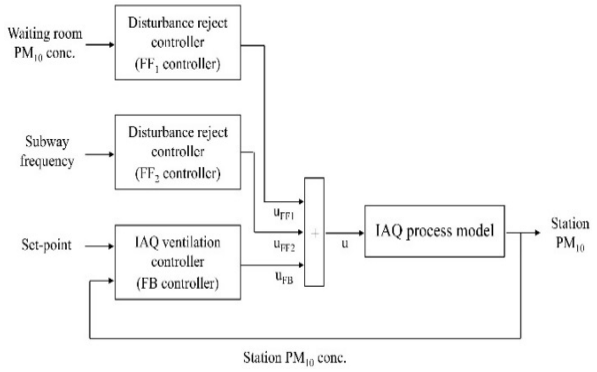


Fig. 3 Block diagram of the IAQ ventilation control system

The IAQ ventilation control system consists of two control strategies, which are feedback (FB) and feed-forward (FF) control. To reduce a difference between the set-point and the measured station $PM_{10}$ value (i.e., control error), the FB based ventilation control system is designed [13]. The FF control makes the control action before the disturbances upset the process. Thus, to suppress the effects of the disturbances on the station $PM_{10}$ concentration, the FF based ventilation control system is designed [13].

### B. The Proposed Method

The proposed framework to determine the optimal set-points trajectory of the ventilation control system using the IDP algorithm is shown in Fig. 4. The implementation of the proposed method consists of two parts: (1) formulation of the performance index of IDP algorithm under moderate and contaminated outdoor air condition and (2) determination of the best set-points of ventilation control system considering the outdoor air quality and IAQ diurnal variation.

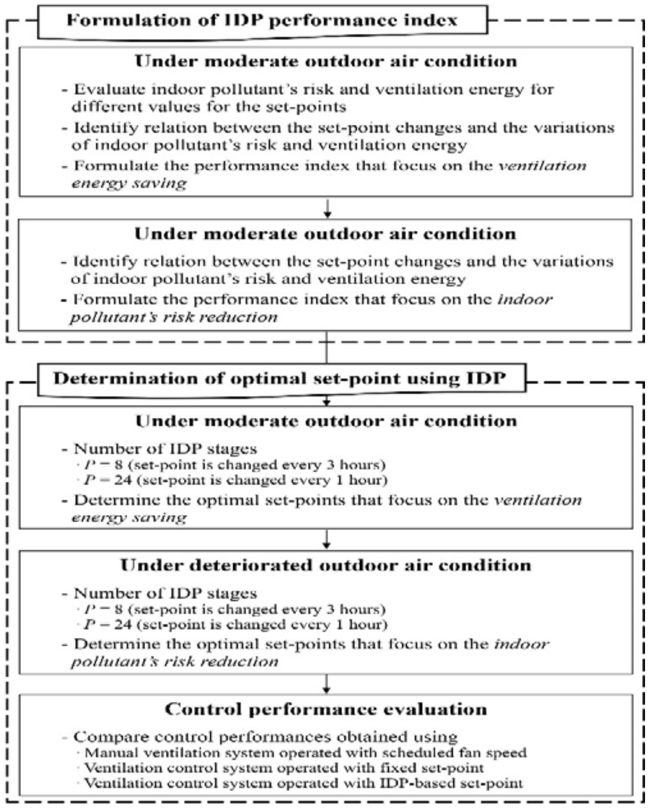
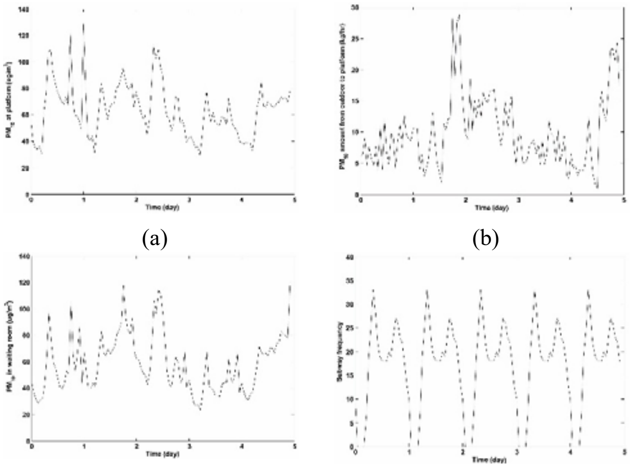


Fig. 4 The framework for determination of the optimal set-points of the ventilation control system considering outdoor air quality and IAQ diurnal variation

First, the performance index of the IDP algorithm is proposed under two different outdoor air conditions. To consider the indoor pollutant's risk to the passenger health, a comprehensive indoor air-quality index (CIAI) that evaluates the health risk of indoor air pollutants using six levels of concern (good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous) is considered the first term of the performance index [1]. The ventilation energy consumption is considered the second term, since the energy for maintaining IAQ comfort comprises 40% of the residential energy use [14]. Once the outdoor air pollutants are at low concentration, the station IAQ level is not greatly influenced by the outdoor pollutants that flow into the station through the ventilation system. It results in less risk to the passenger health [5]. Therefore, under the moderate outdoor air condition, the performance index that focuses on the ventilation energy savings rather than pollutant's risk reduction is formulated. Once the outdoor air is contaminated, its entry into the station through the ventilation systems increases the air pollutants inside the station, which results in the increase of pollutant's risk to the passenger [5]. Thus, under the contaminated condition, the performance index that emphasizes the pollutant's risk reduction is formulated. Then, the IDP algorithm is applied to determine the optimal set-points trajectory for the moderate and contaminated outdoor air conditions using the proposed performance index. Since the concentration of air pollutants inside the subway station shows the periodic diurnal variation, the ventilation duration of the applied IDP algorithm is set one day (i.e., 24 hours). The algorithm is carried out with 8-stage time interval, where the optimal value of set-point is determined every 3 hours. In order to confirm the robustness of the proposed ventilation control strategy, the ventilation performances obtained using three ventilation systems are compared: (1) manual ventilation system operated with the scheduled fan speed, (2) ventilation control system operated with the fixed set-point and (3) ventilation control system operated with the IDP-based optimal set-points.

### *C. Underground Subway Station in Seoul Metro System*

This study is carried out for the underground D-subway station at Seoul Metro, Korea. Diurnal variations of the controlled, manipulated, and disturbance variables collected from a real-time tele-monitoring system (TMS) in the D-station are shown in Fig. 5.



(a) (b)

(c) (d)

Fig. 5 Variations of IAQ measurements from underground D-subway station: (a) $PM_{10}$ concentration in the station (controlled variable), (b) $PM_{10}$ amount introduced from the outdoors to the station (manipulated variable), (c) $PM_{10}$ concentration in the waiting room (disturbance variable) and (d) subway frequency (disturbance variable)

To investigate the variations of optimal set-points trajectory depending on the outdoor air quality, the data for two conditions are compared: (1) moderate outdoor $PM_{10}$ data and (2) deteriorated outdoor $PM_{10}$ data. The moderate outdoor data was collected from November 21, 2011 to November 25, 2011. The average value of the outdoor $PM_{10}$ was 31 μg/m$^3$, and all outdoor $PM_{10}$ samples belong to the 'moderate' level of health concern suggested by Ministry of Environment of South Korea [1]. The deteriorated outdoor data was collected from May 26, 2014 to May 30, 2014 when the yellow sand storm occurred. The average outdoor $PM_{10}$ value is 117 μg/m$^3$, and 61 samples exceed a threshold for the 'unhealthy for sensitive group' level (which is 120 μg/m$^3$).

## IV. RESULT AND DISCUSSION

### *A. Formulation of Performance Index of IDP Algorithm*

To search for the optimal set-points of the ventilation control system that reduces the indoor pollutant's risk with lower ventilation energy, the performance index used by the IDP is proposed. Fig. 6 shows the ventilation energy consumption and CIAI value of the $PM_{10}$ at the subway station measured for some different values for the set-point of the ventilation control system. While the position of the points will vary somewhat from one experiment to the next due to time-varying disturbances, the tradeoff between the ventilation energy and pollutant's risk to the passenger can be clearly seen in the plot. More energy of the ventilation system is required to supply more fresh air into the station for diluting the polluted indoor air, which results in the reduction of indoor pollutant's risk [15]. To take this tradeoff into account, both the ventilation energy and CIAI value of the station $PM_{10}$ are incorporated into the performance index.

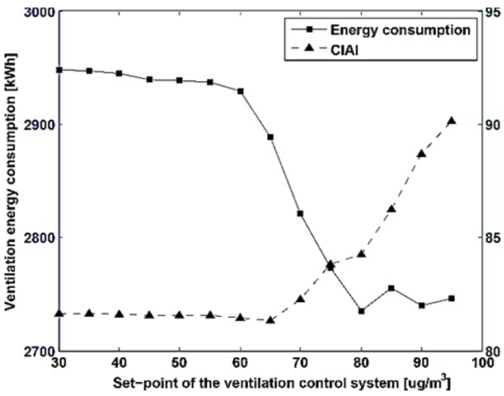


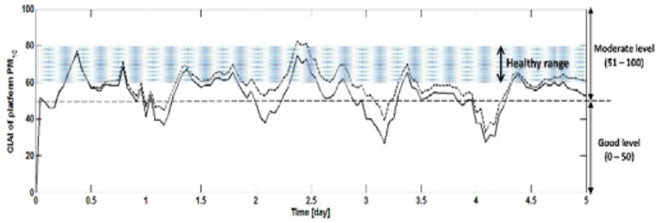
Fig. 6 Measured variations of the ventilation energy consumption and CIAI of station $PM_{10}$ to changes in the set-point of the ventilation control system

Fig. 7 (a) shows the variation in the CIAI value of station $PM_{10}$ for two different values for the set-point under the moderate outdoor air condition. The CIAI of all $PM_{10}$ samples that are ventilated with two set-points belongs to 'good' and 'moderate' levels of health concern (where the CIAI range of the good and moderate levels is 0-50 and 51-100, respectively). Under these two levels of health concern, a smaller value of CIAI does not represent a good ventilation control strategy, since the ventilation energy increases in accordance with the decrease of CIAI value (as shown in Fig. 6). It implies the set-point that maintains the comfortable CIAI range, which can balance the pollutant's risk reduction and ventilation energy saving, is reasonable rather than the set-point that makes the CIAI minimize [4]. Therefore, in the present study, to find the set-points that make the CIAI located within (or near) the comfortable range, a difference between the CIAI of station $PM_{10}$ and comfortable range (i.e., $|\text{CIAI of station } PM_{10} - \text{average of comfortable range}|$) is used for formulating the performance index. Note that we consider the comfortable range of CIAI as 60-80.

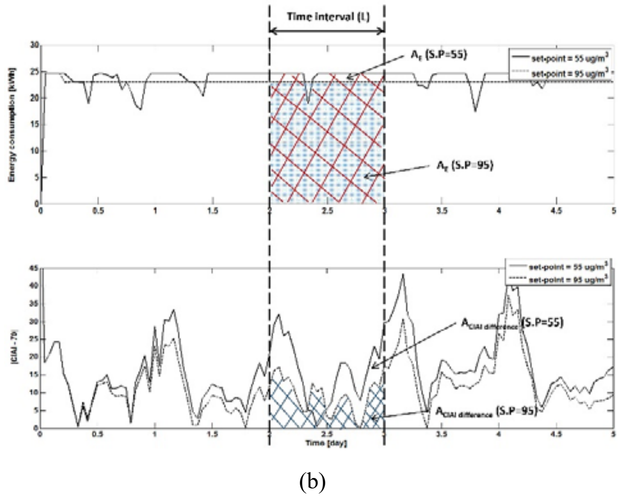
Now, let us consider the areas of the ventilation energy consumption ($A_E$) and CIAI difference from comfortable range ($A_{CIAI\ difference}$), which are shown in Fig. 7 (b). These areas are integrals of the respective variables over a specified time interval. For the specified time interval, the area $A_E$ is proportional to the energy consumption, thus, a smaller area $A_E$ means less consumption of the ventilation energy. In terms of the CIAI difference from comfortable range, a smaller value of difference means that the CIAI of the ventilated $PM_{10}$ is closer to the comfortable range. Accordingly, a smaller area $A_{CIAI\ difference}$ indicates more reasonable CIAI for balancing the pollutant's risk reduction and ventilation energy saving. Hence, for the moderate outdoor air condition, the performance index of the IDP algorithm is selected as a weighted combination of the $A_E$ and $A_{CIAI\ difference}$ [10]:

$$J = \sum_{k=0}^{N} \left( QA_E + RA_{CIAI\ difference} \right) = \sum_{k=0}^{N} \left( Q \cdot \text{energy}(k) \cdot L + R \cdot \left| \text{CIAI}(k) - 70 \right| \cdot L \right) \tag{2}$$

where $Q$ and $R$ are weights on the ventilation energy and CIAI of station $PM_{10}$, respectively, $N$ is the number of IDP stages, and $L$ is the length of the IDP stage.



(a)



(b)

Fig. 7 Influence of set-point changes on the ventilation energy and CIAI of station $PM_{10}$ under moderate outdoor air condition: (a) Measured variation in the CIAI of station $PM_{10}$, (b) Areas of the ventilation energy consumption ($A_E$) and CIAI difference from comfortable range ($A_{CIAI\ difference}$) for two values for the set-point (S.P = 55 and 95 μg/m$^3$)

Fig. 8 shows the $A_E$ and $A_{CIAI}$ for two different values for the set-point under the contaminated outdoor air condition. The CIAI values under this condition are higher than those under the moderate condition, since a larger amount of outdoor $PM_{10}$ enters the station through the ventilation system under the contaminated air condition. Nonetheless, most of the $PM_{10}$ samples that are ventilated with two set-points belong to the healthy range of CIAI. Within the healthy CIAI range, a smaller area $A_{CIAI}$ means less risk of the station $PM_{10}$ to the passenger. Hence, for the contaminated condition, the performance index is selected as the weighted combination of the $A_E$ and $A_{CIAI}$:

$$\begin{aligned} J &= \sum_{k=0}^{N}\left(QA_E + RA_{CIAI}\right) \\ &= \sum_{k=0}^{N}\left(Q\cdot \text{energy}(k)\cdot L + R\cdot \text{CIAI}(k)\cdot L\right) \end{aligned} \tag{3}$$

At each stage, the IDP algorithm determines the set-point that gives the minimum value of performance index, which becomes the optimal set-point of the ventilation control system at the corresponding stage [10]. Furthermore, by increasing the value of $Q$ relative to $R$, the set-point of the ventilation control system focuses more on the ventilation energy savings than the pollutant's risk reduction, and vice versa. This proposed performance index takes into account the tradeoff between the ventilation energy consumption and pollutant's risk reduction through the weight factors $Q$ and $R$ [10].

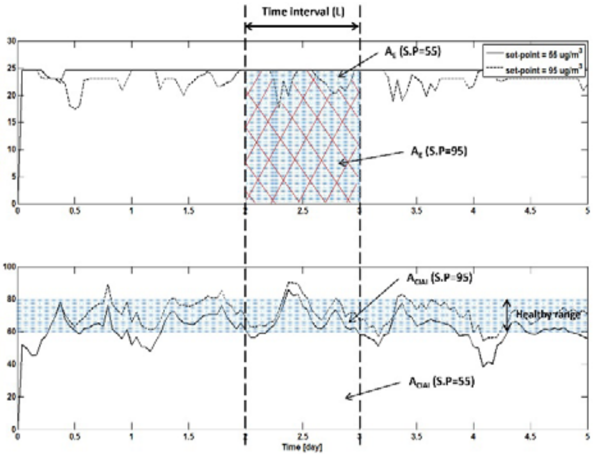


Fig. 8 Areas of the ventilation energy consumption ($A_E$) and CIAI value of station $PM_{10}$ ($A_{CIAI}$) for two different set-points under contaminated outdoor air condition (S.P = 55 and 95 μg/m$^3$)

### B. Determination of the Optimal Set-Points under the Moderate Outdoor Air Condition

Once the outdoor $PM_{10}$ is at low concentration, its entry into the station through the ventilation system and passengers' movement does not significantly affect the station $PM_{10}$ level [5]. Therefore, the diurnal trajectory of the optimal set-points that is able to save ventilation energy (rather than to decrease the pollutant's risk to passenger) is searched using the IDP algorithm. Specifications of the applied IDP method are an initial set-point of 84 μg/m$^3$, a region size of the set-point ($r$) of 5, a number of iterations of 5, and a set-point reduction factor ($\gamma$) of 0.8.

Table I summarizes the ventilation performances obtained using three different ventilation systems. Compared to the manual system, the ventilation control systems that consider the outdoor air quality show less ventilation energy consumption. The reason is explained by Fig. 9, which displays the variations of $PM_{10}$ amount flowed from the outdoor to the station and ventilation fan speed once the ventilation control system with the IDP-based optimal set-points is applied. For the manual system, the ventilation fan speed is kept at 45 Hz from 12 am to 5 pm, 60 Hz from 5 pm to 9 pm, and 40 Hz from 9 pm to 12 am without regard to the outdoor air quality. On the other hand, the ventilation control system slows down the ventilation fan speed once the outdoor $PM_{10}$ is in high concentration (shown in the solid circle in Fig. 9), which leads to the less consumption of ventilation energy. The ventilation controller picks up the ventilation rate when the outdoor $PM_{10}$ is in low concentration (shown in the dotted circle in Fig. 9), which results in the increased ventilation energy, but, the inflow of fresh outdoor air into the station. Overall, compared to the manual system, the proposed ventilation control system flexibly regulates the ventilation fan speed within 20-60 Hz depending on the outdoor air quality. Consequently, the ventilation energy in the target subway station can be reduced.

TABLE I
PERFORMANCE EVALUATION OF THE MANUAL AND PROPOSED VENTILATION CONTROL SYSTEMS IN TERMS OF AVERAGE CONCENTRATION OF STATION $PM_{10}$ AND VENTILATION ENERGY CONSUMPTION

| Ventilation system configuration | | Average $PM_{10}$ concentration | Ventilation energy consumption |
|---|---|---|---|
| Manual ventilation system | | 74.40 | 571 |
| Ventilation control system | Fixed set-point | 72.18 | 561 |
| | IDP-based set-point | 75.27 | 550 |

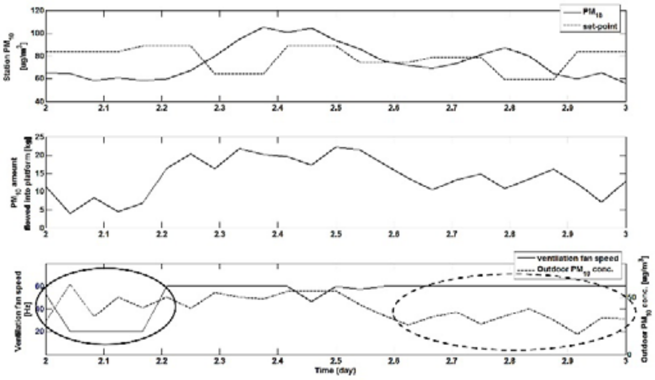
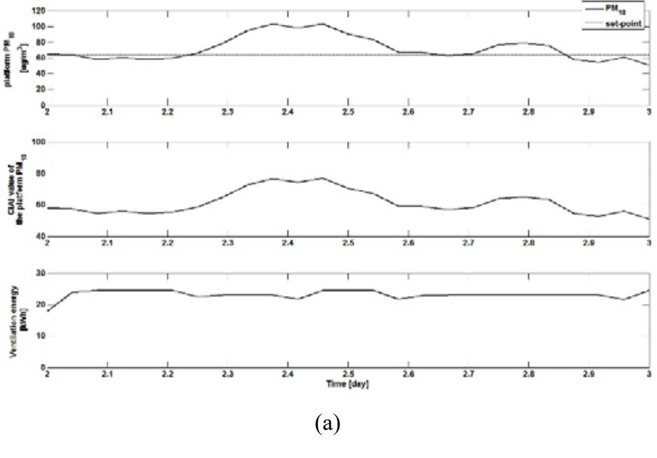


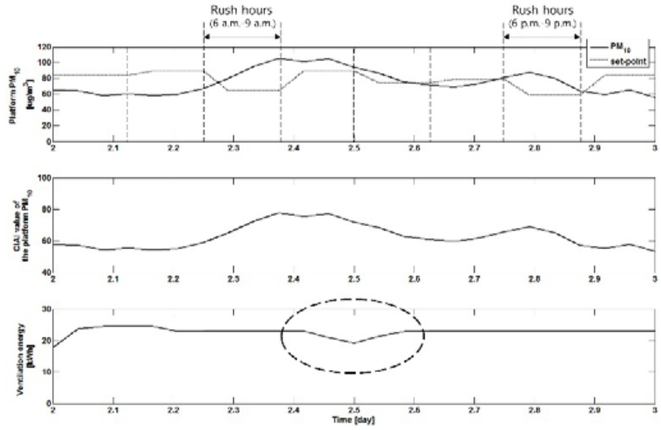
Fig. 9 Station $PM_{10}$ value (upper plot), amount of $PM_{10}$ flowed into the station from the outdoors (middle plot) and ventilation fan speed (lower plot) obtained using the ventilation control system with IDP-based optimal set-point

Figs. 10 (a) and (b) show the variations of the station $PM_{10}$ concentration, CIAI level of station $PM_{10}$, and ventilation energy consumption once the ventilation control system with the fixed and IDP-based optimal set-points is applied. Once the IDP-based set-points are applied, the ventilation energy is conserved compared to the ventilation control system with the fixed set-point. The reduced energy usage is associated with the reset of set-points considering the $PM_{10}$ diurnal variation in the subway station. At the rush hours (6 a.m.-9 a.m. and 6 p.m.-9 p.m.), the station $PM_{10}$ concentration increases in accordance with the increase of passengers and subway frequency [6]. Therefore, the IDP algorithm searches for the set-points that focus on the pollutant's risk reduction rather than ventilation energy saving. Accordingly, lower values of the set-point are allocated to the ventilation control system during the rush hours, which results in the speedup of the ventilation rate. During the non-rush hours, the IDP-based set-points are kept at similar or higher value than the fixed set-point. In this timeslot, the station $PM_{10}$ is in moderate concentration, since the factors which increase the station $PM_{10}$ level (number of passengers, subway frequency) are less than those at the rush hours. Thus, the IDP algorithm determines the set-points that focus on the ventilation energy saving rather than pollutant's risk reduction. It leads to the allocation of high values for the set-point, which results in the reduction of ventilation rate, that is, the less consumption of ventilation energy (shown in the dotted circle in Fig. 10(b)). Consequently, when the set-points of the ventilation control system are changed depending on the IAQ diurnal variation, the ventilation energy consumption is decreased from 561 to 550 kWh (i.e., 2% conservation of the ventilation energy). This result demonstrates that the ventilation control system which updates the optimal set-point in each time interval can improve the ventilation energy efficiency inside the subway station.

In terms of the IAQ, the average $PM_{10}$ concentration that is obtained using the ventilation controller with the IDP-based set-points is higher than the others (shown in Table I). Nonetheless, most of the $PM_{10}$ samples ventilated using the IDP-based control system belongs to the comfortable range of CIAI (i.e., 60-80). The reason is that, under the moderate outdoor air condition, the performance index which keeps the CIAI at the comfortable range with lower ventilation energy is applied to the IDP algorithm. Therefore, these results highlight that the ventilation control system with the IDP-based optimal set-points is able to reduce the pollutant's risk to passenger health and conserve the ventilation energy by considering the outdoor air quality as well as IAQ diurnal variation, and then, contribute to the economic and health-friendly IAQ ventilation in the subway stations.



(a)



(b)

Fig. 10 Station $PM_{10}$ value (upper plot), CIAI of the station $PM_{10}$ (middle plot) and ventilation energy consumption (lower plot) obtained using the ventilation control system with (a) fixed set-point and (b) IDP-based optimal set-point

## V. CONCLUSIONS

To maintain the $PM_{10}$ concentration inside subway stations at a comfortable range and save on ventilation energy consumption, optimal set-points of a ventilation control system were determined using an iterative dynamic programming (IDP) method. The main contribution of this study is a consideration of outdoor air quality, of which entry into the station influences the indoor pollutants level of the station. A different performance index of the IDP algorithm was proposed for moderate and contaminated outdoor air condition, respectively. Moreover, to take a diurnal variation of station $PM_{10}$ into account, a diurnal trajectory of the optimal set-points was searched by separating one-day ventilation duration into several time stages. The results of this study showed that, under the moderate outdoor air condition, the ventilation control system with the IDP-based optimal set-points saves about 2% of the ventilation energy compared to that with the fixed set-point. Furthermore, the station $PM_{10}$ that is ventilated using the proposed ventilation controller belongs to the comfortable range of health concern. Therefore, we can conclude that the ventilation control system operated with the IDP-based optimal set-points affords robust ventilation performance to reduce the pollutant's risk to passenger health and save the ventilation energy in subway stations. This study was carried out by applying 8-stage IDP algorithm where the set-points are reset every 3 hours. For further study, an application of the proposed method to 12-stage and 24-stage IDP algorithms will be carried out to capture properties of the $PM_{10}$ diurnal variation more dynamically.

## ACKNOWLEDGMENT

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (No. 2015R1A2A2A11001120).

## REFERENCES

[1] M. Kim, H. Liu, J. T. Kim, C. Yoo, "Evaluation of passenger health risk assessment of sustainable indoor air quality monitoring in metro systems based on a non-Gaussian dynamic sensor validation method," *J. Hazard. Mater.,* vol. 278, pp. 124-133, June 2014.

[2] C. K. H. Yu, M. Li, V. Chan, A. C. K. Lai, "Influence of mechanical ventilation system on indoor carbon dioxide and particulate matter concentration," *Build. Environ.*, vol. 76, pp. 73-80, June 2014.

[3] S. Wang, Z. Sun, Y. Sun, N. Zhu, "Online optimal ventilation control of building air-conditioning systems," *Indoor Built Environ.*, vol. 20, pp. 129-136, Dec. 2010.

[4] H. Liu, S. Lee, M. Kim, H. Shi, J. T. Kim, K. L. Wasewar, C. Yoo, "Multi-objective optimization of indoor air quality control and energy consumption minimization in a subway ventilation system," *Energy Build.*, vol. 66, pp. 553-561, Nov. 2013.

[5] A. T. Chan, "Indoor-outdoor relationships of particulate matter and nitrogen oxides under different outdoor meteorological conditions," *Atmos. Environ.*, vol. 36, pp. 1543-1551, Mar. 2002.

[6] M. Kim, R. Braatz, J. T. Kim, C. Yoo, "Economical control of indoor air quality in underground metro station using an iterative dynamic programming based ventilation system," *Indoor and Built Environment ,* in press, August 2015.

[7] S. Lee, H. Liu, M. Kim, J. T. Kim, C. Yoo, "Online monitoring and interpretation of periodic diurnal and seasonal variations of indoor air pollutants in a subway station using parallel factor analysis (PARAFAC)," *Energy Build.,* vol. 68, pp. 87-98, Feb. 2013.

[8] X. Xu, S. Wang, Z. Sun, F. Xiao, "A model-based optimal ventilation control strategy of multi-zone VAV air-conditioning systems," *Applied Thermal Eng.*, vol. 29, pp. 91-104, Jan. 2009.

[9] A. Keblawi, N. Ghaddar, K. Ghali, "Model-based optimal supervisory control of chilled ceiling displacement ventilation system," *Energy Build.,* vol. 43, pp. 1359-1370, June 2011.

[10] Y. Kim, C. Yoo, I. Lee, "Optimization of biological nutrient removal in a SBR using simulation-based iterative dynamic programming," *Chem. Eng. J.,* vol. 139, pp. 11-19, May 2008.

[11] R. Luus, *Iterative Dynamic Programming.* USA: Chapman & Hall/ CRC, 2000, Ch. 4.

[12] T. Moreno, N. Perez, C. Reche, V. Martins, E. Miguel, M. Capdevila, S. Centelles, M. Minguillon, F. Amato, A. Alastuey, X. Querol, W. Gibbons, "Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design," *Atmos. Environ.*, vol. 92, pp. 461-468, Aug. 2014.

[13] D. Seborg, T. Edgar, D. Mellichamp, F. Doyle, *Process Dynamics and Control.* USA: Wiley & Sons Inc., 2010, pp. 185-388.

[14] J. K. Joo, Q. Zheng, G. J. Lee, J. T. Kim, S. K. Kim, "Optimum energy use to satisfy indoor air quality needs," *Energy Build.,* vol. 46, pp. 62-67, Mar. 2012.

[15] M. Kim, H. Liu, J. T. Kim, C. Yoo, "Sensor fault identification and reconstruction of indoor air quality (IAQ) data using a multivariate non-Gaussian model in underground building space," *Energy Build.,* vol. 46, pp. 48-55, Nov. 2013.