VENTILATION DEMAND IN A SUBWAY TRAIN
- Based on CO_2 Bioeffluent from Passengers

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ABSTRACT

The air quality in a subway-train was studied to suggest optimal design criteria and operation conditions based on the ventilation demand by passengers. The CO_2 emitted from the passengers was the tracer for this study. The CO_2 bioeffluent from a human body was firstly quantified and used for the data analysis. Then the CO_2 concentration was monitored in a subway-train being operated. The number of passenger was also recorded with the tracer gas measurement over the selected subway route in Seoul.

From the measurement of human CO_2 bioeffluent, it was found that the emission rate is dependent on the body position. Especially, a standing person generates more CO_2 by 29% than a sitting person. The correlation between the measured CO_2 concentrations and the passenger numbers is significantly high. It implies that the passenger number could be a proper parameter for designing air-conditioning systems for subway-trains. Finally the introduction of demand control, based on the passenger number, to maintain required air quality is suggested.

KEYWORDS
Demand Control; Field Study; Human Subjects; Underground Space; Ventilation

NOMENCLATURE

C	: CO_2 concentration in a train	[*ppm*]
C_0	: CO_2 concentration in supply air	[*ppm*]
C_{mi}	: measured CO_2 concentration at $(i)^{th}$ station	[*ppm*]
C_{mi-1}	: measured CO_2 concentration at $(i-1)^{th}$ station	[*ppm*]
C_{ti}	: calculated CO_2 concentration at $(i)^{th}$ station	[*ppm*]
Q	: ventilation air flow rate	[m^3/hr]
V	: inner volume of a train (=132 m^3)	[m^3]
V_e	: effective volume of a train ($=V - n \cdot b$)	[m^3]
a	: CO_2 bioeffluent per capita	[$m^3/p \cdot hr$]
b	: body volume of a passenger	[0.07 $m^3/person$]
n	: number of passenger	[*person*]
t	: run time from $(i)^{th}$ station to $(i+1)^{th}$ station	

INTRODUCTION

Many of metropolitan cities over the world are suffering from the problems such as their overpopulation, traffic jam, etc., and the cities in Korea are not exceptional. Especially for the traffic, the usage of underground spaces such as subway systems, underground roads, and underground passages, is a possible way of improving transport efficiencies. Since the first subway route in Korea was opened in 1974, approximately 1,000 *km* of subway system has been running or constructing at present. In case of Seoul, the subway system occupies 34% of transportation, and it is predicted to go up to 45% in 2000 [1]. As a reference, in some countries it goes up to 75%. It implies that subway systems could be further expanded.

Recently Yoo et al. [2] have studied the air quality problem in underground roads and underground passages in Seoul. They measured the air quality with the traffic running and made suggestions to be considered for improving the air quality in such underground spaces. Lee [3] conducted scale-model tests to study the effect of subway-trains in a subway station on the airflow. The piston ventilation air flow occurred by the subway train approaching to the station was quantified and it exchanges 26% of the air in the subway station tested. Fukuyo et al. [4] also numerically simulated the airflow in a subway station and the U.S. Department of Transportation [5] developed the program to analyze the environment in a subway station, named Subway Environment Simulation. In addition, it is necessary to study and improve the air quality surrounding passengers in a subway-train.

In this study, field measurements were conducted to study the parameters which may affect the ventilation demand in a subway train. The number of passenger on board was the major parameter investigated. It is also aimed to suggest the optimal conditions of ventilation system to match the air quality criteria for the passengers. The CO_2 generated by the passenger was the tracer of this study.

METHODS

A subway route among eight routes in Seoul was selected for this study. The route has 25 stations including six stations above the ground and nineteen stations under the ground. It takes about two hours to finish a journey from one end to the other. Figure 1 shows the inner structure of the train tested. It has four doors on each side and connection-doors at the ends. It also has the dimension of 2.94 *m* (W) x 2.35 *m* (H) x 19.05 *m* (L) which confines 132 m^3 of air volume inside. There are 54 seats for passengers. For the calculation, the first 54 passengers were considered as sitting and the rest of passengers were standing.

Seat	Door	Seat	Door	Seat ⑤	Door	Seat	Door	Seat
	①		②	Passage	③		④	
Seat	Door	Seat	Door	Seat	Door	Seat	Door	Seat

Figure 1. Plan view of a passenger train.

The train has two air-conditioning systems on the ceiling. They supply air through the openings on the ceiling for cooling and the openings under the passenger bench for heating. It has four different operation modes dependent on the weather condition and the air condition inside. The individual capacity is 30,000 *kcal/hr* (≈34.7 *kW*) for cooling and 720 m^3/hr for ventilation. The two air-conditioning systems are capable to be operated at 10.9 *ACH* (air changes per hour) for an empty train. The CO_2 bioeffluent, which was the tracer for this study, was measured to have more reliable values based on Korean people. Five males and five females were selected and tested for the study. The respiration gas analyzer (Model Q4500, Quinton, USA) was used for the measurement with five different body positions; sitting, standing, slow-walking, fast-walking, and running.

Four volunteers have monitored the number of passengers taking on and off the train, ①,②,③,④ in Figure 1. The CO_2 analyzer (Model COX-2, Sibata, Japan) was placed at ⑤ in Figure 1 and read the CO_2 concentration every 10-second for the test. The sampling height was 1.8*m* which was in the space between the ceiling and the passengers. The operation time and the door opening were also recorded with the tracer gas reading. The tests were conducted for the commuting time, i.e. in the morning and the evening, when there exists significant change on the passenger number.

The CO_2 removal by the ventilation, including air-conditioning and in-/ex-filtration in a running train, is estimated by considering the CO_2 bioeffluent (*a*) and the measured concentration as follows:

$$CO_2 \text{ Removal} = \frac{C_{ti} - C_{mi}}{C_{ti}} \times 100\,[\%] \tag{1}$$

$$C_{ti} = C_{mi-1} \times \frac{V_e}{V} + \frac{a \cdot n \cdot t}{V} \tag{2}$$

The mass conservation for a control volume, in Figure 2, can be expanded into the inner space of a subway-train with the fully-mixing assumption. In the process, knowing the tracer gas concentration and the passenger number makes it possible to estimate the amount of ventilation air [6].

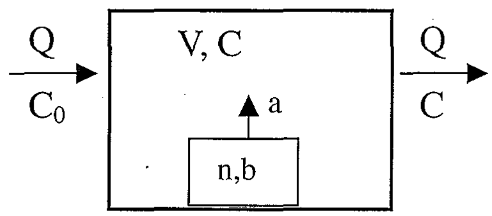

Figure 2. Mass balance on a control volume.

$$\frac{dC}{dt}(V - n \cdot b) = C_0 \cdot Q - C \cdot Q + a \cdot n \tag{3}$$

where, C_0 was measured at the tunnels and the platforms, 370 *ppm*. When the 'C' at the right-hand side of Equation (3) is replaced by 'C_{m-1}' and it gives the following:

$$C = \frac{a \cdot n + C_0 \cdot Q}{Q}\left[1 - e^{-\frac{Q}{V - n \cdot b}t}\right] + C_{mi-1} \cdot e^{-\frac{Q}{V - n \cdot b}t} \tag{4}$$

The equation indicates that the ventilation demand can be calculated by using the measured CO_2 concentration and the recorded passenger number. The CO_2 concentration is also possible to get by using the CO_2 bioeffluent with the passenger number. Therefore, the ventilation demand will be the function of the passenger number on board, which could be used to control the air-conditioning system on a subway-train.

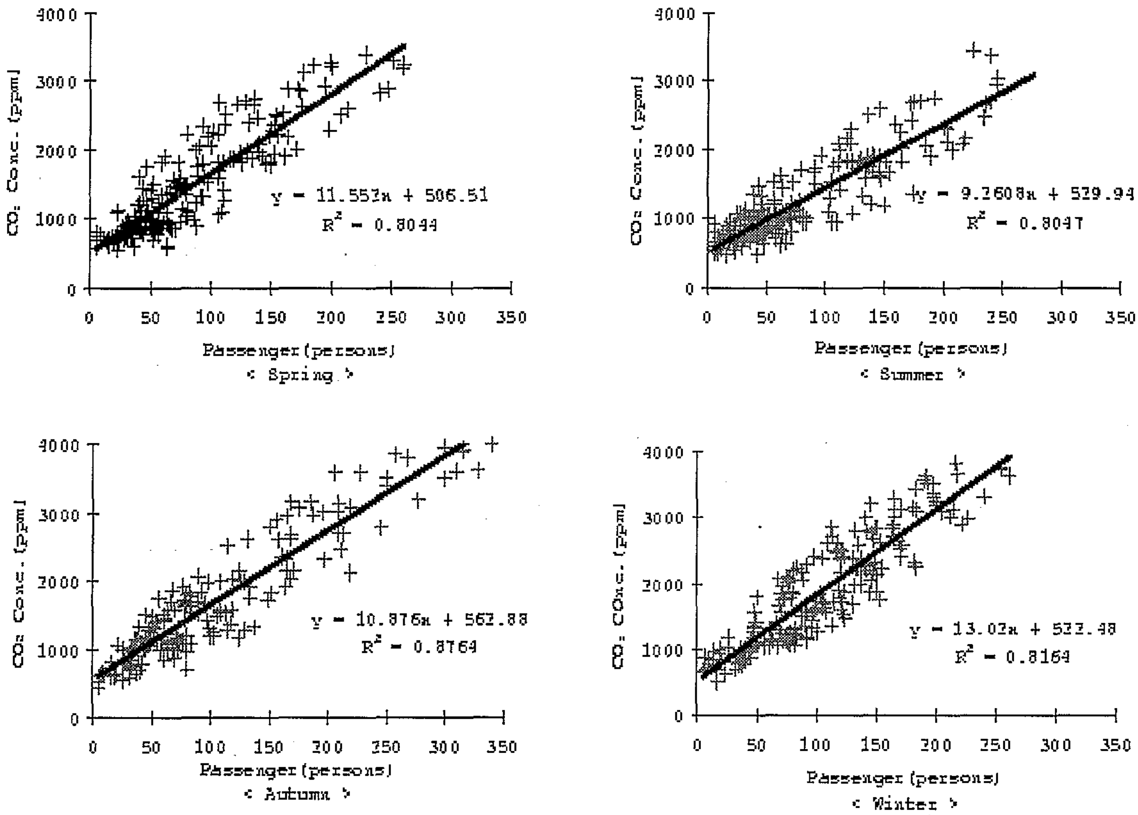

Figure 3. CO_2 concentration vs. passenger number.

RESULTS AND DISCUSSION

The air quality in a subway-train was monitored with the passenger number and the operation conditions. The CO_2 bioeffluent from a human body was also measured for the data analysis. Table 1 shows the results according to the different body positions for Korean males and females. The male generates more CO_2 by 29% than the female tested. The measured emission rate for a sitting person is lower by 23% than that for a standing person. The ratio of a sitting person over a standing is 0.78 and also applied for the calculation.

Table 1. CO_2 bioeffluent from a human body with different body positions.

Sex	Male	Female	Male	Female
Body Position	Standing		Sitting	
CO_2 Bioeffluent (*L/p·hr*)	19.4	14.7	15.1	11.5
Average	17.1		13.3	

To cover the seasonal variations, the tests were conducted over a year. The measured CO_2 concentrations are plotted with the passenger number in Figure 3. The CO_2 concentration was approximately 600~800 *ppm* at beginning and was recorded up to 3000~4000 *ppm* dependent upon the passenger number on board. The slopes of the relations in the plots show each individual's contribution on the CO_2 concentration in the train. They are ranked in the order of 'summer < autumn < spring < winter', which implies that the concentration in summer is less affected by a passenger than in other seasons. This may be possible because the windows are usually opened when it is hot inside, especially in summer. The plots also show the correlation between the CO_2 concentration and the passenger number. The correlation coefficients are ranged from 0.80~0.87 and also significant. It also implies that the passenger number could be a suitable parameter to decide the ventilation demand in a subway-train. The CO_2 removal and the ventilation in a running train is calculated by using Equation (1) and (2) and summarized in Table 2. The annual removal rate is 22.5%, which indicates the demand of more ventilation air. There exists the highest value in summer and the lowest value in winter, which is discussed in terms of a passenger's contribution on the CO2 concentration.

Table 2. CO_2 removal and ventilation in a running train.

Season	Spring	Summer	Autumn	Winter	Annual
CO_2 Removal (%)	22.6	24.8	22.2	20. 6	22.5
Ventilation [m^3/h]	1,247	1,309	1,215	1,081	1,213

The ventilation air flow rate to satisfy the air quality criteria for underground spaces, which is 1,000 *ppm* of CO_2 in Korea, is calculated by using Equation (4). When considering 350 passenger's body volume for the maximum loading, 9,180 m^3/hr (70 *ACH*) of ventilation is demanded. This demand will be varied with the season, even with same passenger number, which may need to be counted in the design of air-conditioning system.

Besides the passenger number, there are other factors such as in-/ex-filtration, door opening at a station, usage of connection door, etc., which also affect the air quality. The temperature and humidity in a train is other environmental parameters to be studied to provide comfortable indoor environment to the passenger. However, the change on CO_2 concentration, in general, is dominated by the passenger number, which could be used for the demand control on ventilation by introducing variable-air volume (VAV) system.

CONCLUSION

The air quality in a subway-train was studied to understand the major parameters for ventilation design and to suggest the optimal conditions of ventilation system to match the air quality criteria for the passengers on board. The remarking conclusions from this study are as follows.

- A male generates more CO_2 by 27~28% than a female in the study; the CO_2 bioeffluent is dependent on the body positions. People generate more CO_2 in standing position by 28% than in sitting position.
- The CO_2 concentration in a subway-train is less affected by a passenger in summer than

in other seasons. In other words, a passenger's contribution on the CO_2 concentration is less in summer than other seasons. The passenger number could be a suitable parameter to consider the design or modification of the ventilation systems on subway-trains.

- Introduction of VAV (Variable Air Volume) system based on the ventilation demand by passenger number is recommended to design and improve the air quality in a subway-train effectively.

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