International Journal of Environmental Monitoring and Analysis
2015; 3(1): 17-21
Published online January 23, 2015 (http://www.sciencepublishinggroup.com/j/ijema)
doi: 10.11648/j.ijema.20150301.13
ISSN: 2328-7659 (Print); ISSN: 2328-7667 (Online)

Prediction of CO_2 concentration in Korea train express (KTX) cabins

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To cite this article:

Yong-Il Lee, Duckshin Park, Do-Yeon Hwang, Won-Seog Jeong, Mona Loraine Barabad. Prediction of CO_2 Concentration in Korea Train Express (KTX) Cabins. *International Journal of Environmental Monitoring and Analysis.* Vol. 3, No. 1, 2015, pp. 17-21.
doi: 10.11648/j.ijema.20150301.13

Abstract: The forced ventilation in high-speed trains makes air quality control in railway cabins of importance. Ventilation is used for controlling various contaminants, along with the temperature and the humidity, keeping them at comfortable levels for passengers. Express trains travel to their destinations at high speeds, and given Korea's mountainous terrain, must go through many tunnels along the way. Korea's tunnel rate is in fact much higher than other countries. Because the HVAC system blocks off outdoor air when entering a tunnel, a high tunnel rate has a negative impact on railway cabin ventilation. To meet the air quality standards for public transportations, CO_2 concentration in high speed railway cabins should be strictly managed. In this study, changes in CO_2 concentration in railway cabins were predicted through a simulation on a route that has not yet in service.

Keywords: Korea Train Express (KTX), Cabin, Carbon Dioxide, Indoor Air Quality (IAQ)

1. Introduction

Korea Train Express (KTX) began its service in 2004 and within its first year had carried 1.96 million passengers. The amount has increased every year since, reaching 4.97 million passengers in 2012 [1]. The Korean government has revised its "Master Plan for Indoor Air Quality Management" every 5 years since 2004 [2]. In March 2014, the government changed the name from "Guideline on the Indoor Air Quality of Public Transportation" to "Recommendation Criteria for the Indoor Air Quality of Public Transportation Vehicles" in an effort to maintain the air quality of railway cabins at an appropriate level. Also, earlier in 2003, Hong Kong had announced a similar guideline for its railway cabins [3].

As the latest high-speed trains have sealed windows and provide forced ventilation [4], controlling the ventilation rate is very important for indoor air quality management. The ventilation rate is adjusted to control the CO_2 exhaled by passengers and the various volatile organic compounds (VOCs) generated by interior materials in the cabin and keep them at appropriate levels. The heating, ventilation and air-conditioning (HVAC) system regulates air quality within railway cabins by automatically controlling ventilation, heating and cooling based on the fresh air temperature, to maintain comfortable conditions [4].

When a high-speed railway track is constructed in a mountainous region, there is by a necessity of a high tunnel rate. Tunnels in Japan and Germany comprise 23-50% of the total high-speed railway tracks of both countries. The tunnel rate affects ventilation in the cabin. Studies that carried out in Korea has shown a correlation between tunnel rate and CO2 [5] and those carried out in China have pointed tunnels as one of the causes of increased CO_2 [6].

A pressure control system is installed in high-speed railway cabins to ease the ear discomfort of passengers, which is caused by the generation of high pressure waves when a train enters a tunnel. A previous study reported that indoor air quality was impacted by the activation of the flaps by the pressurization system [7].

This study selected the Honam high speed railway line, service on which has not operated yet, for simulation. The main factors of the CO_2 concentration prediction formula for the cabins of Honam high speed railway line were calculated, and the actual measured values of the Gyeongbu (Seoul-Busan) high speed railway line were compared to verify the variables of the prediction formula and the predicted values.

2. Method

From December 18 to 21, 2012, CO_2 concentration was measured in KTX cabins operating on the Seoul-Busan high speed railway line using a dual wavelength-type CO_2 meter (SM-2100, Korea Digital). The meter was installed on a shelf in the center of the KTX cabin for measurement every 30 seconds. For stabilization, it was set for 30 minute warm up time before train departure.

Many studies have been carried out on CO_2 prediction. Cho et al. [8] used Equation (1) to predict changes in CO_2 concentration over time.

$$C_t = C_0 + \frac{M}{Q}(1 - e^{-\frac{Q}{V}t}) \tag{1}$$

The C_0 is the of outdoor CO_2 concentration at 600 ppm. The M is emitted CO_2 ratio and the Q is the fresh air supply ratio as the number of passengers in cabin (L/s). The V is the Volume in cabin excluded from the volume of passengers.

So and Yoo [9] predicted CO_2 concentration on subway trains using Equations (2) to (4), verifying their predictions with actual measured performance.

$$m = m_\infty \left(1 - e^{-at}\right) + m_0 e^{-at} \tag{2}$$

$$C_t = C_0 + \left(\frac{M \times t}{V \times C_{2,density}}\right) \times 10^6 \tag{3}$$

$$C_t = \frac{M}{Q}\left[1 - e^{\left(-\frac{Q_{freshair}}{V}t\right)} + C_0\left(\frac{M \times t}{V \times CO_{2,density}}\right)e^{\left(-\frac{Q_{freshair}}{V}t\right)}\right] \times \left(\frac{10^6}{V \times CO_{2,density}}\right) \tag{4}$$

Whereas, the m_0 and m_∞ is the initial and final CO_2 mass in cabin. The C_0 is the CO_2 Concentration in supply air while C_t is the CO_2 Concentration (m^3/ m^3) after t time (h). The M is the emitted CO_2 volume per hour in cabin (m^3/h). The Q is the total supply air while $Q_{freshair}$ is fresh air (m^3/h). The V is the Volume in the cabin (m^3).

Kwon et al. [3] predicted the reduction of CO_2 concentration by the opening and closing of subway train doors using Equation (5).

$$CO_{2,i} = \left[\frac{M \times N_i \times t_i}{\left(V_c - N_i \times V_b\right)} \times 10^6 + \Delta CO_{2,i-1}\right] \times \left(1 - D\right) + CO_{2,bg} \tag{5}$$

Whereas, the M is the CO_2 emission per person (m^3/h). And the N_i is the number of passenger from i^{th} to $(i+1)^{th}$ station. And the Ti is time from i^{th} to $(i+1)^{th}$ station. And the V_c is volume of cabin (m^3). And The V_b is average body volume of passenger (m^3). And the $\Delta CO_{2,i-1}$ is CO_2conc.differential rate compare to ambient conc. and the D is cabin CO_2 conc. reduction rate between two stations. And the CO_2,bg is ambient conc.

The present study used Equation (5) as its basic prediction formula. For the reduction rate (D), is an important variable for predicting CO_2 concentration, the reduction rate of CO_2 concentration according to the operation of a flap installed to supply fresh outside air to the high-speed trains was applied.

3. Results and Discussion

Table 1 shows the measured CO_2 concentrations and the number of passengers in a KTX cabin operating on the Seoul-Busan line. The average CO_2 concentration in KTX cabins for Busan was 1,558 ppm while the average CO_2 concentration in KTX cabins for Seoul was 1,482 ppm.

Table 1. *Measured CO_2 concentrations in KTX cabins.*

Data	Station		CO_2 (ppm)	Temp (℃)	Humidity(%)	No. of passengers
12/18	Seoul → Busan	Max	2,104	26.1	27.9	54
		Min	720	21.3	21.7	33
		Mean	1,558	24.8	25.1	36
	Busan → Seoul	Max	2,214	26.9	26.9	54
		Min	629	23.6	12.8	21
		Mean	1,482	26.0	20.0	40
12/21	Seoul → Busan	Max	2,558	26.7	35.0	57
		Min	814	24.5	19.0	33
		Mean	1,608	26.1	29.3	49
	Busan → Seoul	Max	2,341	28.6	45.7	60
		Min	707	26.0	29.4	22
		Mean	1,565	28.1	33.8	47

Table 2. *Measured and predicted CO_2 concentrations between Seoul and Busan.*

		Measured CO_2 concentration(ppm)	Predicted CO_2 concentration(ppm)	Reduction rate (%)	Passengers
Seoul → Busan	Seoul - Gwangmyeong	922.4	1,515.2	25	40
	Gwangmyeong - Osong	1,529.2	1,607.1	20	57
	Osong - Daejeon	1,883.2	1,844.9	10	54
	Daejeon - Dongdaegu	1,794.0	1,785.4	15	57
	Dongdaegu - Ulsan	1,423.0	1,781.4	10	53
	Ulsan - Busan	1,713.3	1,508.7	10	33
	Total	1,604.1	1,714.3	-	-
Busan → Seoul	Busan - Ulsan	924.2	1,031.7	15	22
	Ulsan - Dongdaegu	1,721.8	1,186.1	10	43
	Dongdaegu - Daejeon	1,652.5	1,646.0	15	53
	Daejeon - Osang	1,430.5	1,552.3	25	59
	Osang - Gwangmyeong	1,818.5	1,729.3	15	60
	Gwangmyeong - Seoul	1,453.7	1,754.4	25	46
	Total	1,560.6	1,451.0	-	-

Table 2 shows the measured values, predicted values and reduction rate of average CO_2 concentration in KTX cabins on the Seoul-Busan line. The reduction rate was deduced by applying the main factors gathered during the measurement of the prediction formula. It was calculated by reflecting the opening and closing of the flap and the outside air influx rate of the HVAC. Outside air flows in when the flap is opened, but the HVAC manipulates the outside air influx rate in order to control the temperature and humidity inside the train. The outside air influx rate of the HVAC was set for the four steps of 10, 15, 20 and 25%, and the outside air influx rate was assumed to be 0 when the flap was closed. The flap is a device to prevent ear discomfort of passengers when high pressure waves flow into the cabin when a high-speed train enters a tunnel. The measured values and predicted values were similar with an error rate within ± 8%.

The main factors of the CO_2 concentration prediction formula were obtained, and the indoor air quality in the cabin operating on the Seoul-Busan Line was measured to verify the predicted values. The most substantial variable is the reduction rate (D), which represents the dilution of CO_2 by the inflow of outside air. The tunnel rate used to calculate the reduction rate is one of the variables that greatly impacts CO_2 concentration in the cabin. If the tunnel rate is high, the reduction rate (D) decreases. On the other hand, if the tunnel rate is low, the reduction rate (D) value increases and the outside air influx rate is raised thus slowing down the increasing CO_2 concentration. The total length of the Seoul-Busan line is 397.4 km, and the total length of the tunnels is 150.6 km, thus the tunnel rate is 37.9%. Equation (6) expresses the reduction rate according to the tunnel rate.

$$Reduction\ Rate(D) = -(0.1810 \times Tunnel\ Rate) + 0.2325 \quad (6)$$

Tables 3 show the main factors and CO_2 prediction result of the Suseo-Gwangju line and the Suseo-Busan line, both services have not yet in operation. The average CO_2 concentration of the Suseo-Gwangju Line was 1,712.2 ppm in the train for Gwangju and 1,422.1 ppm for Suseo. They are both lower than 2,000 ppm, which is the recommended non rush-hour concentration cited in the “Recommendation Criteria for Indoor Air Quality of Public Transportation Vehicles.” However, the Iksan → Gongju section (2,028.9 ppm) in the train bound for Suseo exceeded the non rush-hour recommendation, while the Dongtan → Osong section (2,745.4 ppm) bound for Gwangju, and the Dongtan → Suseo section (3,355.4 ppm) bound for Suseo both exceeded 2,500 ppm, which is the recommended rush-hour limit. The average CO_2 concentration of the Suseo-Busan line was 1,623.1 ppm inside heading to Busan and 1,566.4 ppm bound for Suseo, indicating somewhat lower levels than usual. However, the Busan → Ulsan section (2,065.9 ppm) heading to Suseo was slightly higher than the recommended non rush-hour limit, while the Dongtan → Osong section (2,745.4 ppm) inside the cabin bound for Busan, and the Dongtan → Suseo section (3,409.4 ppm) heading to Suseo exceeded 2,500 ppm, which is the recommended rush-hour limit. The Suseo-Osong sections on both the Suseo-Gwangju line and the Suseo-Busan line were similar. It was predicted that CO_2 concentration would continuously increase as tunnel rates in the Suseo-Dongtan section and in the Dongtan-Osong section are high, at 97% and 66%, respectively.

Table 3. *Simulation results of CO_2 between Suseo and Gwangju, Suseo and Busan.*

		Distance (km)	Tunnel rate (%)	Reduction rate (%)	Predicted CO_2 conc.(ppm) (southbound)	Predicted CO_2 conc.(ppm) (northbound)
Suseo-Gwangju	Suseo–Dongtan	31.7	97	$6^{*}(10^{**})$	1,857.8	3,355.4
	Dongtan–Osong	51.5	66	$11^{*}(15^{**})$	2,745.4	1,516.5
	Osong–Gongju	44.1	63	$12^{*}(15^{**})$	1,641.7	1,452.1
	Gongju–Iksan	45.7	2	$23^{*}(25^{**})$	1,256.7	2,028.9
	Iksan - Jeongeup	39.8	3	$23^{*}(25^{**})$	1,853.3	1,295.7
	Jeongeup - Gwangju	53.6	30	$18^{*}(20^{**})$	1,177.5	964.4
Total section		266.4	42	-	1,712.2	1,422.1
Suseo-Busan	Suseo - Dongtan	31.7	97	$6^{*}(10^{**})$	1,857.8	3,409.4
	Dongtan - Osong	51.5	66	$12^{*}(15^{**})$	2,745.4	1,637.6
	Osong– Daejeon	30.8	32	$19^{*}(20^{**})$	1,782.9	1,699.4
	Daejeon –Gimcheon	67.6	36	$18^{*}(20^{**})$	1,541.2	1,361.0
	Gimcheon - Dongdaegu	54.8	26	$20^{*}(20^{**})$	1,345.7	1,471.0
	Dongdaegu - Singyeongju	46.1	44	$17^{*}(20^{**})$	1,418.6	1,207.8
	Singyeongju - Ulsan	24.2	59	$14^{*}(15^{**})$	1,180.7	1,379.2
	Ulsan – Busan	52.2	75	$10^{*}(10^{**})$	1,580.1	2,065.9
Total section		359.0	52	-	1,623.1	1,566.4

- Initial CO_2 concentration in cabin is 1,000 ppm between Suseo–Gwangju, number of passengers in cabin is 60 (full load). Background CO_2 concentration is 468 ppm [10].

* Decrease rate calculated by equation 6.

** Decrease rate used by in this study.

4. Conclusion

The main factors in the prediction formula for the concentration of CO2 in KTX cabins on the Seoul-Busan line were concluded, and the values calculated by the prediction formula were verified with actual measurements. The most important factor of the prediction formula is the dilution by inflow of outside air defined as reduction rate (D). This value varies greatly according to the opening or closing of the door and the opening and closing of the flap during train operation. It was confirmed that the reduction rate depended on the tunnel rate of the operating line, and Equation (6) was deduced to calculate the reduction rate according to the tunnel rate. Using Equation (6), the reduction rates of the Suseo-Gwangju line and the Suseo-Busan line, were determined and the predicted values were calculated through simulation. The average concentration of each line was 1,422.1-1712.2 ppm, indicating that both were below 2,000 ppm, which is the recommended non rush-hour time concentration limit as cited in the "Recommendation Criteria for the Indoor Air Quality of Public Transportation Vehicles." However, the sections showing the highest concentration in each line: the Dongtan → Suseo section at 3,409.4 ppm bound for Suseo on the Suseo-Busan line, and the Dongtan → Suseo section at 3,355.4 ppm headed for Suseo on the Suseo-Gwangju Line, both exceeded 2,500 ppm, which is the recommended peak time concentration limit as cited in the "Recommendation Criteria for the Indoor Air Quality of Public Transportation Vehicles." The concentration presented in the criteria is the average value for one operation of a line, and each line showed average values below recommended non-peak time limits. However, there were sections in the lines that were 36% higher than recommended rush-hour limits. Thus it is recommended that CO_2 concentration should be lowered by increasing the ventilation rate through adjustment of the flap and HVAC on trains.

Acknowledgements

The work described in this paper was supported by research grants on the Railway Technology Research Project by Minister of Land, Infrastructure and Transport (14RTRP-B081249-01) and the Basic Research Project of Korea by Ministry of Science, ICT, and Future Planning.

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