

# Carbon dioxide (CO<sub>2</sub>) concentrations and activated carbon fiber filters in passenger vehicles in urban areas of Jeonju, Korea

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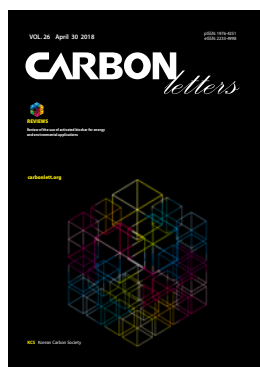
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## Abstract

The South Korean Ministry of the Environment has revised the laws relating to the management of interior air quality for multiple use facilities, and recommends maintaining carbon dioxide (CO<sub>2</sub>) concentration in passenger vehicles below 1000 ppm during operation in urban areas of large cities. However, the interior CO<sub>2</sub> concentration of passenger vehicles can rapidly increase and exceed 5000 ppm within 30 min, as observed when two passengers are traveling in urban areas of the South Korean city of Jeonju with the air conditioner blower turned off and the actuator mode set to internal circulation mode. With four passengers, CO<sub>2</sub> concentration can reach up to 6000 ppm within 10 min. To counter this, when the actuator is set to external mode, CO<sub>2</sub> concentration can be maintained below 1000 ppm, even after a long period of running time. As part of the air conditioning system, alkali-treated activated carbon fiber filters are considered to be far superior to the commercial non-woven filters or combination filters currently commonly in use.

**Key words:** carbon dioxide, passenger vehicle, air cleaning filter, activated carbon filter

## 1. Introduction

Due to the relatively recent increase of energy consumption and number of vehicles in big cities, air pollution becomes ever more severe. The continuous emission of carbon dioxide (CO<sub>2</sub>) in particular is linked to the rapid acceleration in global warming [1,2]. Yi and Shin [3] reported that the air temperature in the year 2100 will be 2°C greater than current temperatures, which will increase sea levels by an average of 50 cm, and this 2°C increase of temperature may also cause wider changes to land and ocean ecosystems, resulting in the extinction of many species and posing a great threat to humankind. Humans are not greatly impacted when the surrounding CO<sub>2</sub> concentration is below 400 ppm. However, when CO<sub>2</sub> concentration exceeds 1000 ppm, there is a marked difference. At levels of 2000 ppm and above, a person may experience muscle pain, headaches and dizziness, or even death. Interior air CO<sub>2</sub> concentration provides an important index of interior air quality (IAQ). Yoon et al. [4] warn about the danger of CO<sub>2</sub> in confined spaces, and reveal that the measured CO<sub>2</sub> concentration in a passenger vehicle with one passenger typically reaches about 5000 ppm after 1 h. Lee et al. [5] report that in the case of two passengers in a vehicle, the concentration becomes close to 5000 ppm after 20 min. Shin et al. [6] report that CO<sub>2</sub> concentration in express buses typically satisfies level 1 (2000 ppm) and level 2 (3000 ppm) in the South Korean Ministry of the Environment guideline for measurements in the summer and the fall seasons, while the measurement result for other seasons is shown to exceed level 1 in certain cases. Jung et al. [7] investigated the concentration of CO<sub>2</sub> in public transportation vehicles (express

bus, normal train, high-speed KTX train, and subway) during the rush hour and non-rush hour in Korea. They reported that the average CO<sub>2</sub> concentration was about 2500 ppm for the non-rush hour and about 3000 ppm for the rush hour. Of course, the concentration was dependent on operating conditions and the type of vehicle. Kim et al. [8] reported that if the interior is confined to increase the energy efficiency, the CO<sub>2</sub> concentration increases to threaten the health of persons present in the interior so that symptoms such as those of sick building syndrome may result. To date, studies related to air quality have been conducted mostly only on large cities (the Seoul Metropolitan region, Gyeonggi-do, and other large cities). Zhao et al. [9] have also studied CO<sub>2</sub> concentration while walking along streets in urban Guangzhou, China. Lee et al. [10] conducted a study of IAQ of domestic and imported automobiles. However, that study was limited to the Seoul area. There is now greater necessity to investigate the concentrations of ultrafine particles and CO<sub>2</sub> and improve air quality in vehicles in small and medium cities having populations of 60 thousand or fewer.

Jeonju (population 650,000) is a historical city 250 km southwest of Seoul. The city used to be an agricultural region, emphasizing traditional culture. However, due to recent industrialization, the city's environment has gradually degraded. In particular, in the central area, the increase of automobiles has caused the rapid increase of air pollutions. Therefore, it becomes pressing to examine the measurement of changes of ultrafine particles and CO<sub>2</sub> concentration in automobiles running on the central streets of Jeonju and to consider some ways to effectively lower pollution levels. Moon et al. [11] measured the change of ultrafine particle (PM<sub>2.5</sub>) concentration in running vehicles, and reported that activated carbon fiber (ACF) filters show a better removal effect of PM<sub>2.5</sub> than commercial air filters for automobiles due to their large surface micropores. Also, they reported the removal capacity of ACF filters on toluene to be excellent, and that the improved capacity depended on the micropore size being in the range of 2–5 nm [12]. Kwon and Ahn [13] also reported on CO<sub>2</sub> concentration in vehicle interiors.

In consideration of enclosed vehicles, removal of CO<sub>2</sub> can be done by using proper adsorbents such as zeolite, activated carbon, and ACFs. Among them, Hwang et al. [14] reported that nitrogen functionalized ACF is the best adsorbent for low-level CO<sub>2</sub> capture due to its well-developed micropore size distribution on the surface. CO<sub>2</sub> capture was much improved by using impregnation of nitrogen-functionalized ACF. Therefore, proper surface modification of an ACF can be useful for the removal of CO<sub>2</sub> in running vehicles.

In this paper, the purpose of the study is the investigation of CO<sub>2</sub> concentration in running passenger vehicles in urban areas of Jeonju. To achieve this purpose, 1) CO<sub>2</sub> concentrations in vehicles were measured under various conditions such as considering the number of passengers, window opening or closing, and different air cleaning filters, 2) an efficient method to reduce the concentration of the interior source is proposed by finding a correlation between the running condition and the interior pollution based on the measurement results.

## 2. Experimental

### 2.1. Experimental vehicles and measurement devices

Two types of popular vehicles, a used vehicle (KIA's K5) bought in 2010 and having the mileage of 70,000 km and another used vehicle (Hyundai's Avante MD) bought in 2012 and having a mileage of 25,000 km are selected for the experiment. Table 1 shows the specifications of the vehicles used for the experiment. CO<sub>2</sub> measurements were conducted in a similar fashion to the measurement method of CO<sub>2</sub> concentration in vehicle interiors as performed by Kwon and Ahn [14]. A GFC Infrared Analyzer (Model 7200FM, Signal Group Ltd., UK), which is a CO<sub>2</sub> measurement device was used. The GFC Infrared Analyzer was installed in the middle of the backseat, and the probe was installed 10 cm below the front passenger mirror. The GFC Infrared Analyzer was powered by installing an AC-DC Trans1000A at the vehicle's battery, and the probe was connected to store measured data. Three types of CO<sub>2</sub> removing filters were prepared. Two commercial air filters for an automobile are 1) a genuine PP non-woven air filter (80 g, 1100 cm<sup>2</sup> filtering rate, 3.7 MPa internal intensity test; HD-Mobis Co, Korea), 2) a combination filter (127 g, glass fiber+chemical filter; WoorhiTech Co, Korea), and 3) a woven ACF (76 g, 1500 m<sup>2</sup>g<sup>-1</sup>; Toyobo Co. Japan) the same size as the PP non-woven filter was prepared.

### 2.2. Experiment method

The experiment was conducted in April 2016, a total of 91 times, 13 times a day for 7 d referring to the conditions suggested by Lee et al. [10]. The vehicles were driven in suburban and urban areas of Jeonju between 11:00–19:30 for 8–9 hours each day. CO<sub>2</sub> measurements were made by alternating between window open and window close, passenger number, vehicle type, the actuator's internal circulation and external mode, the air conditioner's blower operation being on and off, and the filter type. Fig. 1 shows the driving route through the urban and the suburban areas of Jeonju. The driving distance in the urban and the suburban areas totaled approximately 15 km. The speed was 30 km h<sup>-1</sup> in the urban area and 70 km h<sup>-1</sup> in the suburban area. The interiors of the experiment vehicles were ventilated for 5 min by opening the windows before the experiment to maintain the same environment. While each vehicle was driven, the experiment was conducted for a total of 30 min by activating the monitor and measuring the data at 1 min intervals. CO<sub>2</sub> concentration was measured around the seats of the vehicle by one or three

**Table 1.** Specifications of the test cars

Unit (mm)	K5 (2000 cc midsize car)	MD (1600 cc small car)
Whole length	4845	4530
Whole piece	1835	1775
Overall height	1455	1435
Wheel base	2795	2700

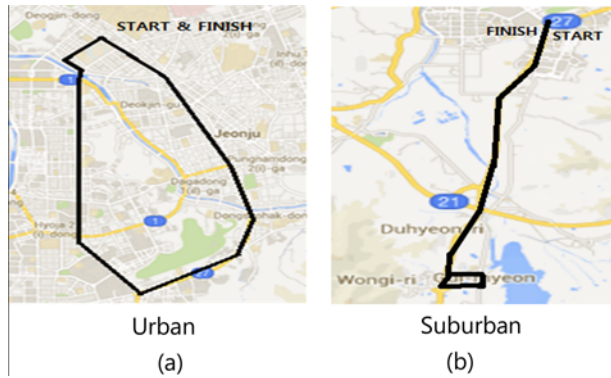


Fig. 1. Driving route in the urban (a) and suburban (b) areas of Jeonju.

persons other than the driver. The average value of CO<sub>2</sub> concentration for each experimental condition was obtained from seven measurements. Table 2 shows the experimental conditions.

### 3. Results and Discussion

#### 3.1. Change of CO<sub>2</sub> concentration in the passenger vehicles between morning (AM) and afternoon (PM)

Fig. 2 illustrates the timely changes of CO<sub>2</sub> concentration in the passenger vehicles running in the mornings and afternoons in an urban area of Jeonju. According to the graph, the first CO<sub>2</sub> concentration before the vehicle running was 800±50 ppm in the morning (AM) and 790±50 ppm in the afternoon (PM), showing

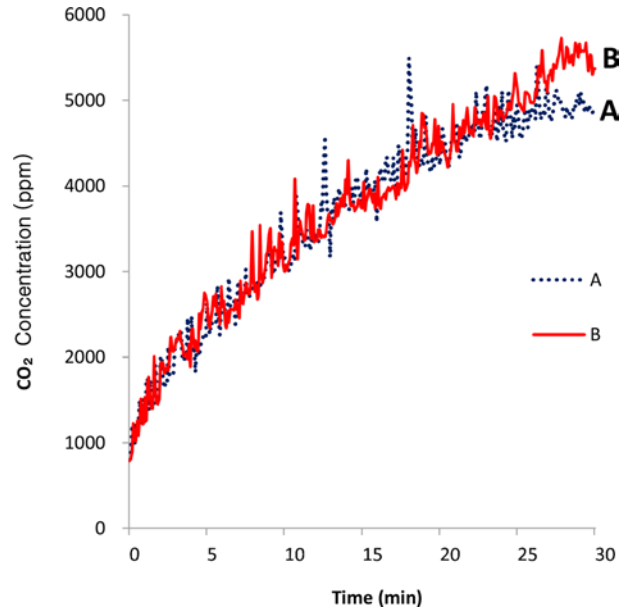


Fig. 2. CO<sub>2</sub> concentrations in the passenger vehicles during the (A) morning and (B) afternoon in urban area of Jeonju.

only a 6% difference. The study regarding the changing characteristic of CO<sub>2</sub> concentration in the background atmosphere of the Korean Peninsula, reported by Park et al. [15], also states that the reason for the small differences shown in hourly concentrations is determined to be influenced by the busy activity of people’s commuting and plants’ photo-synthesis, and no significant difference is found between the morning and the afternoon. The result of CO<sub>2</sub> concentration measurements in 18 locations in

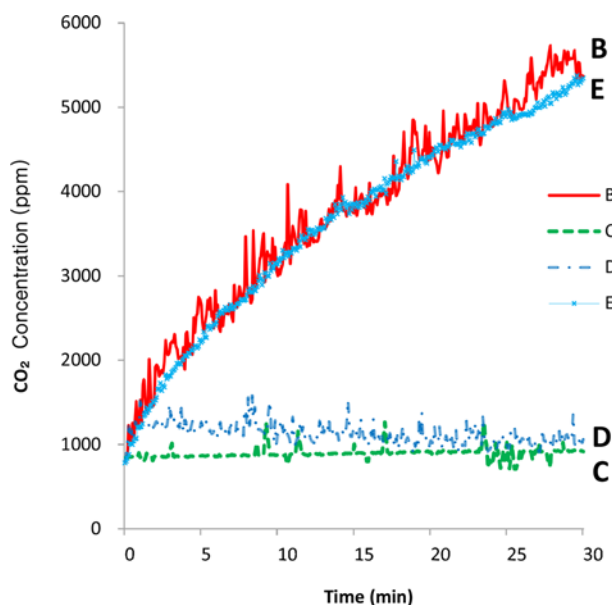
Table 2. Experimental conditions									
Item	Time	Actuator	Window	Persons	Urban/suburban	Blower	Filter	Model	Diagram
A	AM	Inside air	Close	2	Urban	Off	Non-woven	K5	..... A
B	PM	Inside air	Close	2	Urban	Off	Non-woven	K5	———— B
C	PM	Outside air	Close	2	Urban	Off	Non-woven	K5	----- C
D	PM	Outside air	Close	2	Urban	2	Non-woven	K5	- . - . D
E	PM	Inside air	Close	2	Urban	2	Non-woven	K5	==== E
F	PM	Inside air	Front windows open	2	Urban	Off	Non-woven	K5	---- F
G	PM	Inside air	All windows open	2	Urban	Off	Non-woven	K5	—— G
H	PM	Inside air	Close	4	Urban	Off (probe front)	Non-woven	K5	—— H
I	PM	Inside air	Close	4	Urban	Off (probe rear)	Non-woven	K5	- . - . I
J	PM	Inside air	Close	2	Urban	Off	Non-woven	MD	—— J
K	PM	Inside air	Close	2	Suburban	Off	Non-woven	K5	—— K
L	PM	Inside air	Close	2	Urban	2	Combination	K5	—— L
M	PM	Inside air	Close	2	Urban	2	ACF	K5	---- M

ACF, activated carbon fiber.

Seoul conducted in April 2013 showed a daily average of 706 ppm. This value was much higher than the measurement of 396 ppm at Anmyeondo, the background measurement location in Korea. In this study, a 790 ppm CO<sub>2</sub> concentration on the street in Seoul's urban areas was higher than in residential areas (683 ppm) and school areas (649 ppm). Kwon and Ahn [13] report CO<sub>2</sub> concentration in the range of 580–760 ppm, with an average of 670 ppm in the central city area, and being in the range of 500–600 ppm with an average of 550 ppm so that the central area is about 1.2 times greater. The fact that the first concentration at street side in the central area of Jeonju city was 800 ppm and a higher value than central Seoul's average of 706 ppm demonstrates that the air in the central area of Jeonju is as polluted as Seoul's air. In another study, Zhao et al. [9] reported the CO<sub>2</sub> concentration in central urban areas of Guangdong, China, was 786 ppm on average, which is very similar to that of the urban area of Jeonju. The result of change of CO<sub>2</sub> concentration in passenger vehicles running in the central area of Jeonju setting the actuator to internal circulation mode and having the blower turned off showed no influence of external air in the internal circulation mode during the morning [A] and the afternoon [B]. The reason for such a result was determined to be that CO<sub>2</sub> exhaled by the passengers is not discharged to the outside of the passenger vehicle. The CO<sub>2</sub> concentration initially was approx. Eight hundred parts per million, and this rapidly increased to 5000 ppm after 25 min. Such a result is almost identical to the results reported by Yoon et al. [4] and Lee et al. [5].

### 3.2. CO<sub>2</sub> concentration change in the passenger vehicle according to actuator and blower operation

Fig. 3 illustrates the CO<sub>2</sub> concentration changing over 30 min in one of the passenger vehicles, varying the actuator and the



**Fig. 3.** CO<sub>2</sub> concentration in passenger vehicle K5 with respect to actuator and blower condition; conditions B, C, D, and E (see Table 2).

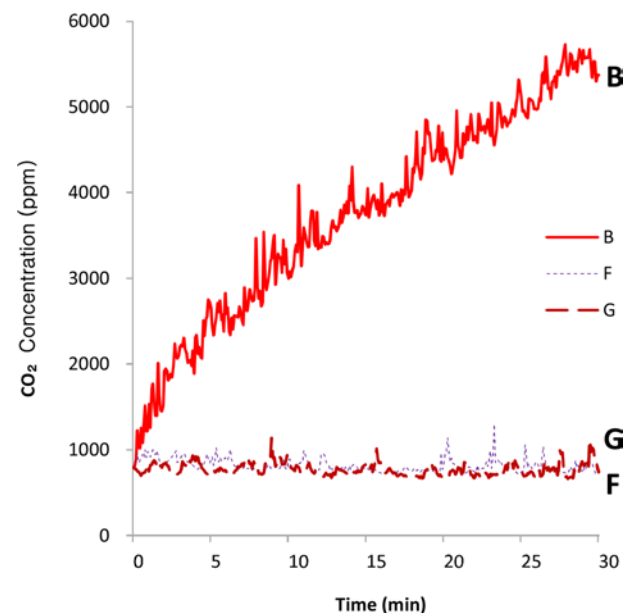
blower operations (experiment key: B, C, D, E).

When the actuator was set to external air mode and the blower was set to off (C) or level 2 (D), concentration increased to approx. Five hundred parts per million during the first 1–2 min and gradually decreased as time passed to maintain the initial CO<sub>2</sub> level continuously. In the case of (E), which maintains the internal circulation mode at level 2 of the blower, and CO<sub>2</sub> concentration increases continuously similarly to (B) having the blower turned off and, after 30 min, the initial CO<sub>2</sub> concentration was continuously maintained as (D). This shows that the ventilation through the actuator and the blower is critical in reducing CO<sub>2</sub> concentration in a passenger vehicle. Also, when the actuator was set to external air mode, an adequate air inflow during the vehicle running seemed to result. Such a result emphasizes the necessity for fresh air inflow and the installation of an excellent air cleaning filter. Research conducted by Wargocki et al. [16] also reported that as air inflow speed increases, CO<sub>2</sub> concentration reduces, and an air inflow amount of 2.5 L s<sup>-1</sup> for each person is required.

### 3.3. CO<sub>2</sub> concentration change in the passenger vehicle according to window opening and closing

Fig. 4 shows the results of observation on the interior CO<sub>2</sub> concentration changes when the passenger vehicle's window was opened [F, G] and closed [B] while the actuator was set to internal circulation mode and the blower was turned off.

When the window was closed, the interior CO<sub>2</sub> concentration reached 5000 ppm within 30 min. This was caused by the gradual increase of CO<sub>2</sub> concentration due to CO<sub>2</sub> creation by breathing and the space restriction. Both the case of only front windows opened [F] and the case of opening

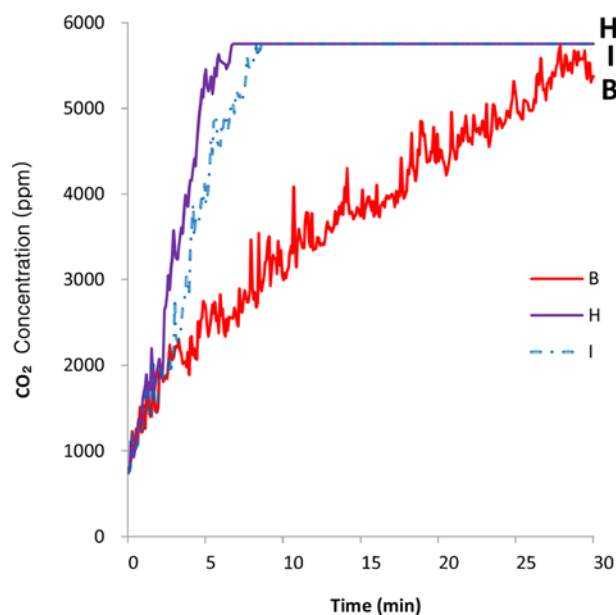


**Fig. 4.** CO<sub>2</sub> concentration in passenger vehicle K5 with respect to window opening and closing; conditions B, F, and G (see Table 2).

all four windows showed interior CO<sub>2</sub> concentration reduced to a small degree, eventually becoming the same as the CO<sub>2</sub> concentration outside. Zhao et al. [9] also reported that air conditioned transportation modes circulate and cool only the air inside the vehicle compartment, with limited air exchange with outdoor air. Therefore, air ventilation by opening the windows of the passenger vehicle to reduce CO<sub>2</sub> concentration is acquired. Such a result is also confirmed through Shin et al. [6] who also discussed the status of IAQ in public transportation. Since conditions such as winter weather often do not permit the opening of windows, the importance of excellent air cleaning filters is emphasized again, and the connection to the interior of public transportation where the external air inflow is limited becomes greater. Shin et al. state that the necessity of ventilation during public transportation operation becomes more important.

### 3.4. CO<sub>2</sub> concentration change in the passenger vehicle according to the number of passengers

Fig. 5 shows the results of the investigation on CO<sub>2</sub> influence on the passenger vehicle according to the number of passengers. Previously, it was shown that when two passengers are in a vehicle in the condition of [B], CO<sub>2</sub> concentration rapidly increased. In the case of four passengers, CO<sub>2</sub> concentration rapidly increased up to 5700 ppm no matter how the measurement was made at the front seat [H] or at the rear seat [I] area, and those concentration levels could not be measured by this detector. Zhu et al. [17] reported CO<sub>2</sub> concentration rapidly rose to 4500 ppm over 10 min for three passengers in a vehicle. The measurement of air quality and CO<sub>2</sub> concentration in a vehicle's interior presented by So and Yoo [18] also shows that the interior CO<sub>2</sub> concentra-



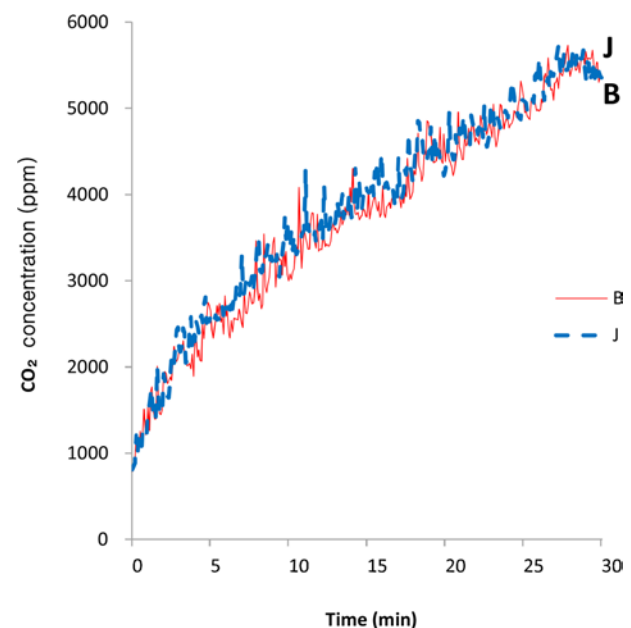
**Fig. 5.** CO<sub>2</sub> concentration in passenger vehicle K5 with respect to number of person; condition B, H, and I (see Table 2).

tion is proportional to the number of passengers. Therefore, CO<sub>2</sub> concentration in the passenger vehicle is found to be influenced most greatly by the number of passengers. Shin et al. [6] also report that since the number of passengers riding intercity buses is higher on average, the CO<sub>2</sub> concentration in intercity buses (1460 ppm) is somewhat higher than that of express buses (1185 ppm).

### 3.5. CO<sub>2</sub> concentration change in the passenger vehicle according to vehicle type

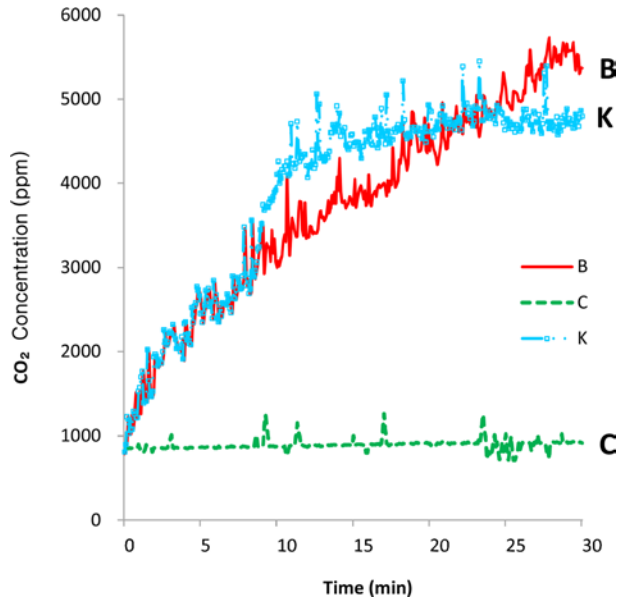
Fig. 6 shows the results of measurement on the change of CO<sub>2</sub> concentration in passenger vehicles for each type. The figure shows that CO<sub>2</sub> concentration in the general mid-sized passenger vehicle (K5, 2000 cc) largely increased as [B] and exceeded 5000 ppm within about 25 min. In the case of the small-sized passenger vehicle (MD, 1600 cc), the significant increase of CO<sub>2</sub> concentration showed a similar pattern to the mid-sized passenger vehicle, but the concentration was found to be a little less with the mid-sized passenger vehicle, which had a slightly wider interior space compared to the small-sized one. Therefore, CO<sub>2</sub> concentration can be considered to be influenced by the size of the interior space. Jung et al. [7] report that taxis are mostly operated having windows closed so that higher CO<sub>2</sub> concentration can result in comparison with buses or subway trains.

Fig. 7 shows the results of CO<sub>2</sub> change in the passenger vehicle when the vehicle was running at a speed of 30 km h<sup>-1</sup> in an urban area and at the speed of 70 km h<sup>-1</sup> in a suburban area of Jeonju.



**Fig. 6.** CO<sub>2</sub> concentration in passenger vehicle K5 (B) and vehicle MD (J); condition B and J (see Table 2).





**Fig. 7.** CO<sub>2</sub> concentration in passenger vehicle K5 with respect to urban (B, C) and suburban (K).

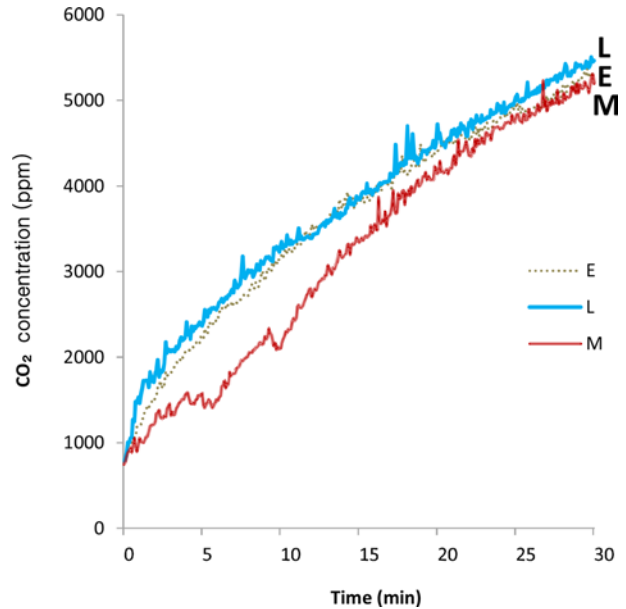
### 3.6. CO<sub>2</sub> concentration change in the passenger vehicle according to area

In the case of running at low speed in the urban area, CO<sub>2</sub> concentration increased continuously. However, in the case of running in the suburban area, the increase was faster during the first 7 min compared with that of running in the central area, but the CO<sub>2</sub> concentration stabilized to some degree after about 10 min. This may have been because the CO<sub>2</sub> concentration increase was stopped by the gradual increase of external air inflow to the interior as the speed increased. The case of [K] shows that although the actuator was set to internal circulation mode, a small quantity of air inflow occurred from the vehicle's running speed, and the air inflow seemed to stabilize or reduce CO<sub>2</sub> concentration. Therefore, the change was considered to be based on the level of external air flow rather than on the area. Kwon and Ahn [13] also confirm that even in the case of a vehicle having the ventilation amount set to 0, external air inflow occurs. They also report that when a vehicle is driven in an area with a faster speed limit, the ventilation rate becomes higher than in a slower area so that the IAQ is maintained at a better state.

Fig. 8 illustrates the change of CO<sub>2</sub> concentration with each type of air cleaning filter in the vehicle. The illustration shows that CO<sub>2</sub> concentration continuously increased for all three filters. However, in spite of a small amount of ACF filter (76 g) than

### 3.7. CO<sub>2</sub> concentration change in the passenger vehicle according to different air cleaning filters

the other two filters, the ACF filter showed a far more effective CO<sub>2</sub> adsorption in the passenger vehicle, especially under 15 min. If the amount of ACF filter is increased, the



**Fig. 8.** CO<sub>2</sub> concentration in passenger vehicle K5 with respect to type of filter; (E) PP non-woven filter, (L) combination filter, and (M) ACF filter.

removal efficiency will obviously increase. Ryu et al. [19] report that as-prepared ACF shows some amount of CO<sub>2</sub> adsorption at room temperature due to its large micropores. Hwang et al. [14] report that ammonia-treated ACF shows far greater CO<sub>2</sub> adsorption capacity. Adelodun et al. [20,21] studied the modification of an ACF surface with ammonia, and obtained a much improved CO<sub>2</sub> capture. Yuan et al. [22] also modified the graphite nanofibers with KOH to obtain the CO<sub>2</sub> adsorbent. On the other hand, Moon et al. [12] showed that ACF has a particularly high adsorption performance on volatile organic materials such as toluene in passenger vehicles. Ryu [23] also reports the removal capacity of ACF on volatile organic materials. Therefore, an ACF filter which is properly alkali treated can be used for the effective removal of CO<sub>2</sub> in passenger vehicles.

## 4. Conclusions

In passenger vehicles, greater stability can be obtained from the actuator being set to external mode than set to internal circulation mode. In the case of the internal circulation mode, CO<sub>2</sub> concentration reaches 5000 ppm within 30 min when two passengers are riding, and 6000 ppm within 10 min when four passengers are riding. When the air conditioner blower is turned off, and the actuator is set to external mode, the interior's CO<sub>2</sub> concentration with two passengers remains continuously at 1000 ppm or below for the outside air inflow. This suggests that outside fresh air should be continuously inflowing when passengers are riding in a passenger vehicle.

A surface-modified and controlled pore size distributed ACF filter is advantageous for the removal of particulate matter (PM<sub>2.5</sub>), carbon dioxide, and VOCs compared with commercial combination filters or PP non-woven filters due to the large mi-

crotopes which are completely exposed on the surface. Alkali-modified ACF filters are promising for removing interior pollution sources in passenger vehicles.

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### Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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