AJAE

Open Access

Vol. 14, No. 2, pp. 146-154, June 2020
doi: https://doi.org/10.5572/ajae.2020.14.2.146
ISSN (Online) 2287-1160, ISSN (Print) 1976-6912

Research Article

In-car and Near-road Exposure to $PM_{2.5}$ and BC

Chang-Jin Ma, Gong-Unn Kang[1),*]

Department of Environmental Science, Fukuoka Women's University, Fukuoka 813-8529, Japan
[1)]Department of Medical Administration, Wonkwang Health Science University, Iksan 54538, Republic of Korea

***Corresponding author.**
Tel: +82-63-840-1286
E-mail: gukang@wu.ac.kr

Received: 20 April 2020
Revised: 23 May 2020
Accepted: 4 June 2020

ABSTRACT The current study aims to characterize the $PM_{2.5}$ and the equivalent black carbon (eBC) inside/outside vehicles (hereafter called "in/out-cabin") and near roadway, and to estimate their personal exposure to the driver himself as well as the school-aged children. Based on the $Dose_{DEP}$ of a mouse reaching the 90% polymorphonuclear leukocytes ($PMNs_{90\%}$) (Stoeger *et al.*, 2006), the time (day) to reaching the $PMNs_{90\%}$ in the blood of a male resident who lives around the roadway was newly calculated. Five independent measurements of $PM_{2.5}$ and eBC were intensively taken in May 2019 using the monitors attached to the interior and exterior of the vehicle, respectively. In-cabin and out-cabin $PM_{2.5}$ on the course of driving measurement ranged from 29.4–47.4 μg/m^3 with an average of 34.4 μg/m^3 and 32.5–56.0 μg/m^3 with an average of 45.6 μg/m^3, respectively. The eBC in/out-cabin ratio during idling on a busy road ranged from 22% to 86% depending on the windows open/close and ventilation on/off. The in-cabin $Dose_{PM2.5}$ (ng) for 30 seconds on the test driving route ranged from 166–240 ng with an average of 190.4 ng. The average in-school $Dose_{PM2.5}$ (μg) for the schoolchild attending the school near a bus stop is 1.2 times higher than that of schoolchild attending the school away from a bus stop. The time (day) to reaching the $PMNs_{90\%}$ due to DEP inhalation for the male resident who lives around the roadway was estimated as 113 days.

KEY WORDS $PM_{2.5}$, eBC, Exposure, Car, Road, Dose, Idling

1. INTRODUCTION

The personal car is by far one of the common means of commuting in the urban cities of many countries because it is practical and convenient. The emission from an individual vehicle is generally lower than that of a large-scale fixed source such as incinerator. But in numerous cities of any country in the world, the personal car is the single greatest contributor to air pollution, as emissions from a huge number of cars on the road add up. Whether it is personal or business, driving a private car is certainly a typical citizen's most polluting daily activity (US EPA, 1994).

Vehicle emission results in small-scale spatial variations and can have an adverse effect on the health of not only drivers and passengers, but also on residents around the road (Barnes *et al.*, 2018). There is growing evidence that people living or otherwise spending a lot of time within the contaminated downwind region of main roads are seriously exposed to pollutants emitted by cars (Barnes *et al.*, 2018).

Exposure to air pollutants, especially diesel exhaust particles (DEP), has been linked to chronic respiratory diseases. Numerous epidemiologic studies have consistently suggested that children, older adults, and people with preexisting cardiopulmonary disease are particularly susceptible to health impacts associated with living close to busy roads (Barnes *et al.*, 2018; Ma, 2015). Thurston (2000) suggested that elementary and middle school children have high inhalation rates and lung surface area per body weight, and it makes them especially vulnerable to ultrafine particles. If they attend school close to busy roads, the concern will grow even more.

Through the study on the relationship between diesel vehicle emission and death rates in Tokyo, Japan, Yorifuji *et al.* (2011) reported that daily $PM_{2.5}$ concentration increase of 10 μg/m^3 was associated with 1.3% increase in cerebrovascular mortality rate. According to the World Health Organization (WHO), air pollution is responsible for 0.49 million deaths per annum and many of these fatalities have been linked to exposure to high levels of airborne particulates, such as DEP.

It is significantly meaningful to assess the personal exposure $PM_{2.5}$ and BC in-cabin and near-road through a real-time measurement with a high time resolution.

Although a lot of research on the air pollution of car driving and near road has been reported, there have been very few studies of the exposure to $PM_{2.5}$ and BC during vehicle running (Stoeger *et al.*, 2006). Furthermore, only a limited number of studies has been conducted on the estimation of the $PM_{2.5}$ exposure dose ($Dose_{PM2.5}$ (μg)) in the alveolar interstitial (AI) region for 10-year and 15-year child attending the school around the road according to their activities (Stoeger *et al.*, 2006).

The goal of this study is to assess the characteristics of $PM_{2.5}$ and eBC in/out-cabin and near road, and their personal exposure to the driver himself as well as the resident and the school-aged children near a roadway.

2. EXPERIMENTAL METHODS

2.1 Study Design

Driving and idling measurements for $PM_{2.5}$ and eBC were conducted on the bus route crossing Iksan City, Korea. Iksan City is located in the southwest part of Korea, and it is one of modern industrial cities with many factories producing textiles, jewelry, and electrical products. A large-scale industrial complex, residential region, and farmland are located at the outskirts of Iksan City.

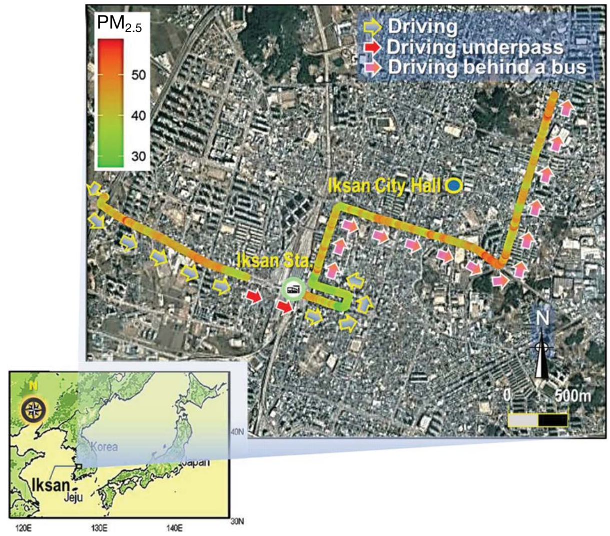

Fig. 1. The selected driving route on the map of Iksan City, Korea and the out-cabin $PM_{2.5}$ measured every 30 seconds.

Fig. 1 shows the map showing the Iksan City and the course of driving measurement. The out-cabin $PM_{2.5}$ measured every 30 seconds during a driving test is also drawn on the map. As shown in Fig. 1, the selected route crosses Iksan City from west to east through near Iksan City Hall via Iksan Station. This route passing through the residential and commercial districts is the representative of typical commuting routes for the students and workers in Iksan City.

The average traffic volumes of gasoline and diesel cars were 1,236/hour and 90/hour, respectively during our field measurements. The average journey time on the selected route was 23 minutes and the average journey distance was 8 km. The car used driving measurement in this study was a five-seater Santa Fe SUV (Hyundae, 2009) (1.885 m × 4.905 m × 1.690 m), and its fuel, displacement, fuel efficiency, and a car year are diesel, 1990 cc, and 13.2 km/L, and 10 years old, respectively.

Five independent measurements of $PM_{2.5}$ and eBC were intensively taken in May 2019 using the monitors attached to the interior and exterior of the vehicle, respectively. Monitoring was conducted at the time when elementary and middle school students left school. It was possible to carry out the bus-following measurement during the afternoon rush hour. During driving measurement, the windows were closed, and the air conditioning/ventilation were off. None of the participants (two passengers and a driver) smoke in the test car.

2.2 Real-time $PM_{2.5}$ and eBC Measurements

$PM_{2.5}$ concentration was measured using a portable real-time sensor called as the AirBeam (HabitatMap, Inc., V3). According to the manufacturer specifications (HabitatMap, 2016), air introduced in the aerosol sensor of a single-bin OPC (Shinyei PPD60PV-T2, Shinyei technology Co., LTD) via an internal pump. Then the sensor voltage created by scattered light by the particles can be converted to $PM_{2.5}$ mass concentrations using a linear regression model, developed in side-by-side tests of the AirBeam and a pDR (Thermo Scientific™), which is a rigorously proven device.

The single-bin OPC was calibrated by the manufacturer using polystyrene spherical latex particles with a known diameter, refractive index, and density (1.65 g/cm^3) (Mukherjee *et al.*, 2017).

Because the sensor voltage of OPC rely on the intensity of scattered light, the particles that are highly absorptive such as BC can affect the measurement results. Sousan *et al.* (2017) conducted the performance evaluation of AirBeam using both light scattering and light absorption aerosols. The aerosols were selected as the high light-absorbing particles were welding fume. Although their experiments included light-absorbing particles, the results demonstrated that the AirBeam exhibited a good linear relationship with the pDR for concentrations lower than 100 μg/m^3.

The measured data are communicated to the AirCasting Android app via Bluetooth, and then the data maps and graphs can be created on a martphone (AirBeam Technical Specifications, Operation & Performance, 2019). In this study, the data logging interval was set at 30 seconds. The measured data is sent to the Apples.

This AirBeam sensor method was used in many studies for measuring $PM_{2.5}$ at community sites (Badura *et al.*, 2018; Genikomsakis *et al.*, 2018; Zheng *et al.*, 2018; Mukherjee *et al.*, 2017; Jiao *et al.*, 2016). An EPA study thoroughly evaluated its precision by comparing the $PM_{2.5}$ data measured by AirBeam and a regulatory monitor, respectively. As the result, a strong correlation ($R^2=0.99$) between the two sets of data was obtained (Jiao *et al.*, 2016).

As a BC monitor, the Aethalometer® (AE51) was applied to the real-time analysis of the eBC mass concentration with the excellent sensitivity (0.001 μg/m^3), precision ±0.1 μg eBC/m^3, and time resolution (from 1 sec. to 5 min.). The MicroAeth AE51 (Aethlabs, USA) can quantify the eBC concentration by measuring the light attenuation induced by the accumulation of BC on a filter at a near-infrared wavelength of 880 nm.

The concept of eBC suggested by Petzold *et al.* (2013). For the precise use of the terms for BC, they first suggested that eBC should be used instead of BC for data derived from optical absorption methods, together with a suitable mass absorption coefficient (MAC). For the conversion of light absorption coefficient into mass concentration, 12.1 MAC ($m^2\ g^{-1}$) applied to AE51.

Both $PM_{2.5}$ and eBC monitors were placed inside and outside of the front window of the test car.

3. RESULTS AND DISCUSSION

3.1 Temporal and Spatial Variations of $PM_{2.5}$

The $PM_{2.5}$ concentration drawn on the Iksan City map in Fig. 1 at intervals of 30 seconds exhibits a highly variable distribution on the target route. The section of the red arrows marked at the Iksan Station underpass was not included in $PM_{2.5}$ mapping.

Fig. 2 shows the time series variation of in/out-cabin $PM_{2.5}$ while driving. In-cabin and out-cabin $PM_{2.5}$ ranged from 29.4–47.4 μg/m^3 with an average of 34.4 μg/m^3 and 32.5–56.0 μg/m^3 with an average of 45.6 μg/m^3, respectively. The average $PM_{2.5}$ out-cabin exceed that in-cabin by 1.3 times. The average in-cabin $PM_{2.5}$ is barely satisfactory for the recommended Indoor Air Quality (IAQ) level (35 μg/m^3) in medical institutions and kindergartens by the South Korea Environmental Protection Department.

The wide variability of out-cabin $PM_{2.5}$ on the driving route can be attributed to the differences in the traffic density and local atmospheric diffusion along the route.

Under the same conditions of measurement, namely with window closed and ventilation off, the average in-cabin $PM_{2.5}$ measured Ispra located in the province of Varese, Northern-Italy marked 26.9 μg/m^3 (Geiss *et al.*, 2010), meanwhile that measured in Northampton, UK was 15.1 μg/m^3 (Gulliver *et al.*, 2004). The average in-cabin $PM_{2.5}$ in Iksan City is 2.3 times and 1.3 times higher than those of Varese and Northampton, respectively.

Although the windows were closed during driving, the in-cabin $PM_{2.5}$ might be affected by out-cabin particles. To verify this possibility, the out-cabin $PM_{2.5}$ and the one minute later in-cabin $PM_{2.5}$ from the out-cabin data while driving behind a diesel-powered bus are plotted in Fig. 3. As shown in Fig. 3, some extremely high out-cabin

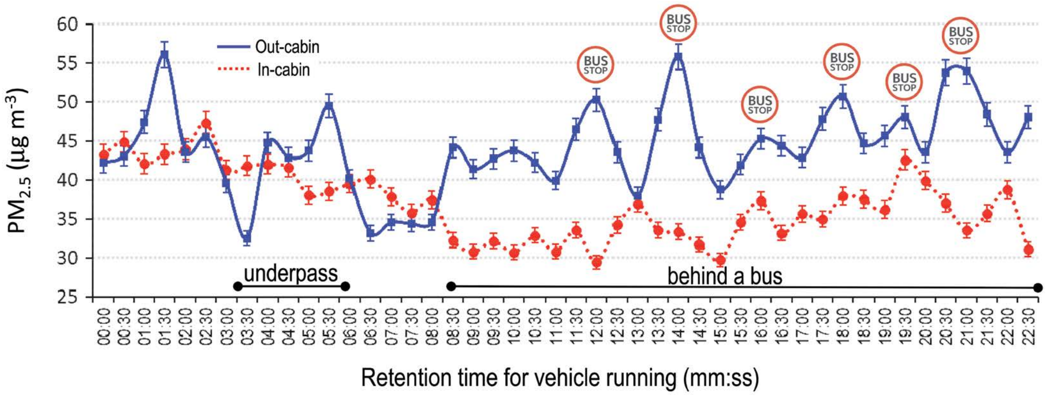

Fig. 2. Trend of in/out-cabin $PM_{2.5}$ while driving tests.

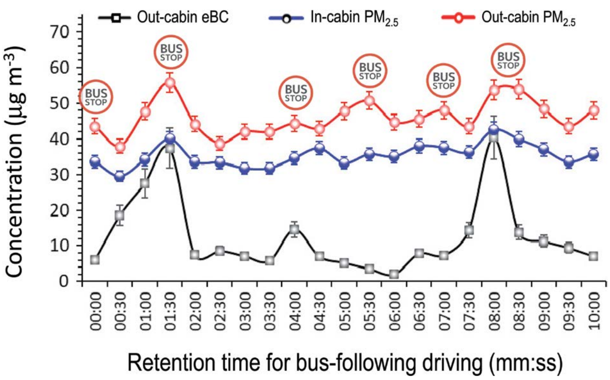

Fig. 3. Timely variation of in/out-cabin $PM_{2.5}$ and out-cabin eBC during a diesel-powered bus follow-up driving at the bus stop section. In-cabin $PM_{2.5}$ is the data after one minute of the out-cabin data.

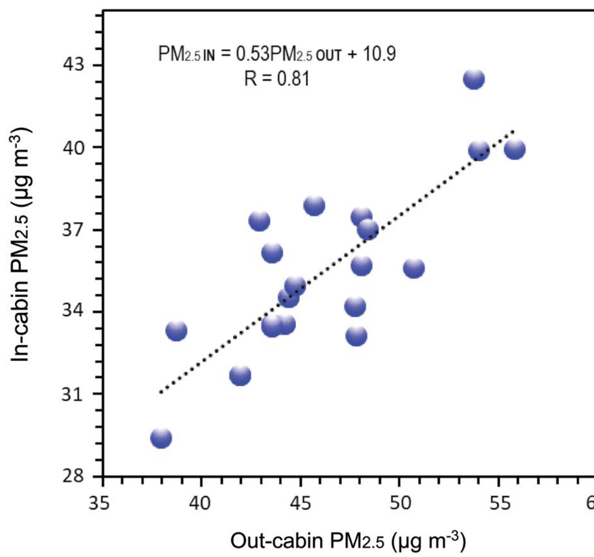

Fig. 4. The scattering plot between out-cabin $PM_{2.5}$ and in-cabin $PM_{2.5}$ measured after one minute of out-cabin measurement while driving behind a diesel-powered bus.

eBC were measured, and this greatly affected the in-cabin $PM_{2.5}$.

Fig. 4 shows the scattering plot between the out-cabin $PM_{2.5}$ and the one minute later in-cabin $PM_{2.5}$ from the out-cabin data while driving behind a diesel-powered bus. A strong correlation was found ($r = 0.81$). Although the windows are closed, this result indicates that the $PM_{2.5}$ outside vehicle will enter the vehicle in a minute while keeping a distance of 20 meters from the vehicle ahead. The effect of out-cabin particles on the in-cabin $PM_{2.5}$ is also probably affected by both the atmospheric diffusion on the side of the road and the mode of in-vehicle ventilation applied (Chan *et al.*, 2002).

3.2 eBC In/out-Cabin During Idling on a Busy Road

Excessive idling causes an unnecessary release of air contaminants including BC into the air, and it partially penetrated to inside the vehicles stopping from the rear.

Fig. 5 shows the eBC concentration in/out-cabin under the different conditions of window (open/close) and ventilation (on/off) during traffic signal waiting on a busy road. The in-cabin ratio (%) to out-cabin under different conditions is also exhibited. The ventilation setting in the car during the idling study was the circulation with the outdoor air with the medium speed. The eBC proportions of in-cabin to out-cabin ranged from 22% to 86%. The pattern most affected by the idling of the car ahead was the windows opening with ventilation off. The in-cabin ratio (%) to out-cabin during window opening

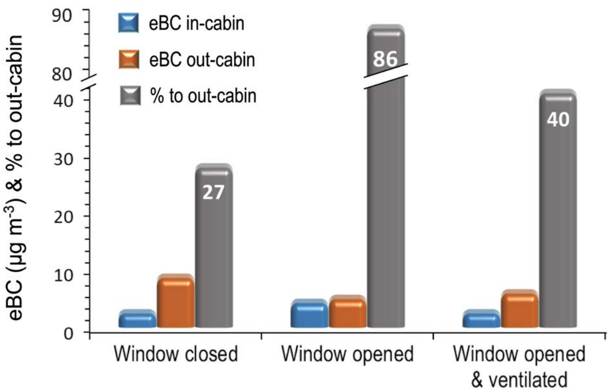

Fig. 5. eBC concentration in/out-cabin and the in-cabin ratio (%) to out-cabin under different conditions during traffic signal waiting on a busy road.

is 3.1 times higher than during window closing. Meanwhile, the circulation with the outdoor air with the windows opening greatly reduced eBC ratio (%) of in-cabin to out-cabin from 86% to 40%. Although research on eBC in/out-cabin during idling is hard to find, a similar result about $PM_{2.5}$ was revealed in other studies (Barnes *et al.*, 2018; Ding *et al.*, 2015).

3.3 Exposure Dose of $PM_{2.5}$

It is crucial to know how much $PM_{2.5}$ and BC actually penetrate the respiratory system of drivers, passengers, and residents around the road.

At first, to assess the $Dose_{PM2.5}$ per section of the driving route, the 30-second $Dose_{PM2.5}$ in the AI region of a male driver was estimated. The target driver was travelling at 20 meters from the rear of a diesel bus on a two-lane road, and just had to keep driving behind a diesel bus because it was not easy to overtake.

The in-cabin $Dose_{PM2.5}$ was determined by the real-time measurement $PM_{2.5}$ data (μg/m^3) ($C_{PM2.5}$) made every 30 seconds, the deposition fraction in the AI region ($f_{Dep.}$), exposure time ($t_{Exp.}$, h), and breathing rate ($r_{Bre.}$, m^3/h). The $r_{Bre.}$ (m^3/h) is the maximum deposition efficiency (%) in the AI region according to the activity patterns suggested by Yamada *et al.* (2007). The $r_{Bre.}$ (m^3/h) was assumed as an intermediate of sitting and light exercise. The $Dose_{PM2.5}$ (ng) was calculated by the below empirical equation proposed by Löndahl *et al.* (2007).

$$\textit{In-cabin } Dose_{PM2.5}\,(\mathrm{ng}) = C_{PM2.5} \times f_{Dep.} \times t_{Exp.} \times r_{Bre.}$$

The estimated in-cabin $Dose_{PM2.5}$ (ng) in the AI region of a male driver for 30 seconds was illustrated in Fig. 6. It

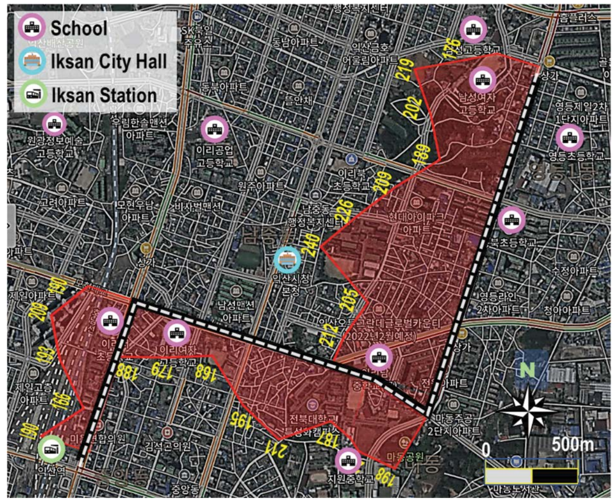

Fig. 6. In-cabin $Dose_{PM2.5}$ (ng) in the AI region of a male driver for 30 s when driving behind a diesel-powered bus.

ranged from 166–240 ng with an average of 190.4 ng.

Because there is no reference on the in-cabin $Dose_{PM2.5}$ under the same conditions, the in-cabin $Dose_{PM2.5}$ estimated in this study can be compared to that reported by Martins *et al.* (2015). The in-cabin $Dose_{PM2.5}$ in the present study is 3.7 times for their in-subway $Dose_{PM2.5}$ determined from the subway system of Barcelona, Spain that is one of the oldest underground transport systems in Europe.

Till now, the study on $Dose_{PM2.5}$ has typically been focused on adult subjects, little is known about that for children. According to the WHO's report (2018), every day around 1.8 billion children (93% of the world's children) under the age of 15 years breathe air that is so polluted. Tragically, many of them die from acute lower respiratory infections caused by polluted air (WHO, 2018).

As shown in Fig. 6, there are many elementary, middle and high schools around the target road. Many students will be exposed to a lot of car emissions pollutants in their daily lives. Assessing their $Dose_{PM2.5}$ is expected to contribute greatly to establishing the measures to maintain a healthy school life.

Table 1 summarizes the calculated in-school $Dose_{PM2.5}$ (μg) in the AI (alveolar interstitial) region for 10-year child and 15-year child attending the school around the road. In this study, their daily activity level was classified into three categories, namely sedentary (taking lessons), sedentary + 1 h light (simple movements during breaks or lunchtime), sedentary + 1 h heavy (sports activities during a P.E. class). The in-school $Dose_{PM2.5}$ was calculat-

Table 1. The in-school $DosePM_{2.5}$ (μg) in the AI (alveolar interstitial) region for 10-year child and 15-year child attending the school around the road.

	Sex	Stay/day (hour)	Activity patterns	$C_{PM2.5}$ (μg/m^3)		Maximum $f_{Dep.}$ in the AI	$r_{Bre.}$ (m^3/h)	$Dose_{PM2.5}$ (μg)/day		$Dose_{PM2.5}$ (μg)/week	
				Bus stop	Non-bus stop			Bus stop	Non-bus stop	Bus stop	Non-bus stop
10-year child	Male	6	Sedentary	51.09	44.03	0.37	0.38	43.10	37.14	215.52	185.70
		6	Sedentary + 1 h Light	51.09	44.03	0.46	1.12	157.60	135.80	788.00	678.98
		6	Sedentary + 1h Heavy	51.09	44.03	0.51	2.22	347.10	299.08	1735.48	1495.38
	Female	6	Sedentary	51.09	44.03	0.37	0.38	43.10	37.14	215.52	185.70
		6	Sedentary + 1 h Light	51.09	44.03	0.46	1.12	157.60	135.80	788.00	678.98
		6	Sedentary + 1 h Heavy	51.09	44.03	0.51	1.84	287.68	247.88	1438.41	1239.41
15-year child	Male	9	Sedentary	51.09	44.03	0.41	0.48	90.72	78.17	453.60	390.84
		9	Sedentary + 1 h Light	51.09	44.03	0.49	1.38	313.81	270.39	1569.03	1351.96
		9	Sedentary + 1 h Heavy	51.09	44.03	0.55	2.92	736.51	634.61	3682.53	3173.06
	Female	9	Sedentary	51.09	44.03	0.37	0.40	67.60	58.25	337.99	291.23
		9	Sedentary + 1 h Light	51.09	44.03	0.48	1.30	287.84	248.02	1439.22	1240.10
		9	Sedentary + 1 h Heavy	51.09	44.03	0.53	2.57	626.36	539.71	3131.81	2698.53

ed on the assumption there was no difference in the concentration of $PM_{2.5}$ indoor and outdoor because in Korea, the windows are wide open in May. The in-school $Dose_{PM2.5}$ (μg) in the AI (alveolar interstitial) region is even greater for children who take heavy exercise near severely polluted roadway. This is because children during periods of vigorous exercise breathe more than when they rest. In this study, regardless of age and behavior patterns, the average of in-school $Dose_{PM2.5}$ (μg) in the AI for the schoolchild attending a school near a bus stop is 1.2 times higher than that of schoolchild attending the school away from a bus stop.

According to the Korean exposure handbook (Jang *et al.*, 2002), the average daily $Dose_{PM2.5}$ for the women working at the outdoor of near roadsides was 4.6 μg/kg · day. They calculated $Dose_{PM2.5}$ under assumptions of 8 hours working time for 7 days, and there was little difference in the amount of breathing between a 15-year-old girl and an adult woman. The recalculated average daily $Dose_{PM2.5}$ (259.4 μg/day) considering the weight of an adult woman (56.4 kg) (Jang *et al.*, 2002) can be compared with the results of this study. The average daily $Dose_{PM2.5}$ for the women working at the outdoor of near roadsides turned out to be a moderate amount of $Dose_{PM2.5}$ for the 15-year-old female high school student who takes 8 hours of class and simple movements during breaks or lunchtime in the school located at halfway between bus stops and non-bus stops. Although the $Dose_{PM2.5}$ for 10-year-old students is lower compared to that for 15-year-old students, children's lung surface area per body weight makes them highly susceptible to $PM_{2.5}$ (Almeida *et al.*, 2011).

3.4 $PMNs_{90\%}$ $Dose_{DEP\text{-}Man}$

Polymorphonuclear Leucocytosis is characterized by increasing white blood cells, specifically polymorphonuclear leukocytes (PMNs) in the blood. They are called that because their nuclei are highly variable in shape by infection, tissue damage inflammatory diseases, kidney failure, and diabetic ketoacidosis. Therefore, the number (or content) of PMNs can be used as the marker of inflammation (Stoeger *et al.*, 2006).

To fine out the acute (24 hours after instillation) adverse effects of DEP, Stoeger *et al.* (2006) investigated the content of PMNs for the mouse that was instilled DEP into the alveolar space. According to their study, the 90% PMNs (PMNs contents of 90%) for a mouse ($PMNs_{90\%}$ $Dose_{DEP\text{-}Mouse}$) was 50 μg (2.5 mg/kg).

In this study, using their findings, we made a new attempt to estimate the 90% PMNs for the male resident with a weight of 60 kg ($PMNs_{90\%}\ Dose_{DEP\text{-}Man}$ (mg/kg)) who lives around the roadway.

The $Dose_{DEP}$ (mg/person·day) for the man around a road can be calculated by the sum of the $Dose_{DEP}$ (mg/person·daytime) and the $Dose_{DEP}$ (mg/person·nighttime). The detailed description is as following equation:

$$
\begin{aligned}
&Dose_{DEP}\,(\text{mg/person}\cdot\text{day})\\
&\quad=[(C_{eBC\text{-}day}\times f_{Dep.\ day}\times t_{Exp.\ day}\times r_{Bre.\ day}\times 12)\\
&\quad+(C_{eBC\text{-}night}\times f_{Dep.\ night}\times t_{Exp.\ night}\times r_{Bre.\ night}\times 12)]\\
&\quad\times R_{DEP/eBC}
\end{aligned}
$$

where $C_{eBC\text{-}day/night}$, $f_{Dep.\ day/night}$, $t_{Exp.\ day/night}$, and $r_{Bre.\ day/night}$ are the real-time measured eBC concentration, the deposition fraction in the AI region, exposure time, and breathing rate in the daytime and nighttime, respectively. The $R_{DEP/eBC}$ is the ratio (1.48) of DEP to BC for large cars (Yamamoto *et al.*, 2008).

Nair and Jacob (2016) introduced a simple equation for the dose conversion between mouse and human.

$$Dose_{Human}\,(\text{mg/kg}) = Dose_{Mouse}\,(\text{mg/kg})\times K_m\ \text{ratio}$$

where $K_m\ \text{ratio} = \dfrac{K_{m\ Mouse}}{K_{m\ Human}}$

Each K_m i.e., $K_{m\ Mouse}$ and $K_{m\ Human}$ can be calculated with following equation:

$$K_m = \frac{Weight\,(kg)}{BSA\,(m^2)}$$

where *BSA* is body surface area (m^2).

The K_m can be determined by dividing the average body weight (kg) of mouse and human by their body surface area (m^2). The $K_{m\ Human}$ (a weight of 60 kg and *BSA* of 1.62 m^2) (Lee *et al.*, 2007) and the $K_{m\ Mouse}$ (a weight of 0.02 kg and BSA of 0.0067 m^2) (Nair and Jacob, 2016) will be 37 and 3, respectively.

The 90% PMNs for a male resident who lives around the roadway with a weight of 60 kg by DEP inhalation can be estimated by following formula:

$$
\begin{aligned}
&PMNs_{90\%}\ Dose_{DEP\text{-}Man}\,(\text{mg})\\
&\quad= PMNs_{90\%}\ Dose_{DEP\text{-}Mouse}\,(2.5\ \text{mg/kg})\\
&\quad\times K_m\ \text{ratio}\left(\frac{3}{37}\right)\times 60\ \text{kg}
\end{aligned}
$$

where the $PMNs_{90\%}\ Dose_{DEP\text{-}Mouse}$ is the 90% PMNs for a mouse by DEP inhalation.

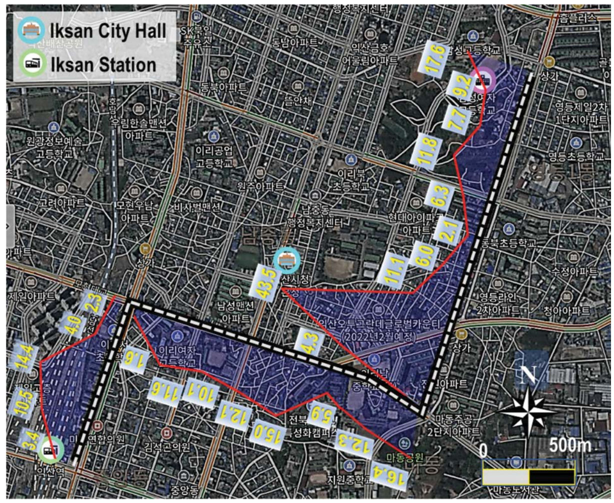

Fig. 7. The time ((×10) days) to reaching the $PMNs_{90\%}\ Dose_{DEP}$ for a male resident who lives around the roadway.

The calculated $PMNs_{90\%}\ Dose_{DEP}$ for a male resident who lives around the roadway shown in Fig. 7 was 12.16 mg.

Additionally, the time (day) to reaching the $PMNs_{90\%}\ Dose_{DEP\text{-}Man}$ can be calculated by dividing the $PMNs_{90\%}\ Dose_{DEP\text{-}Man}$ (mg) by the $Dose_{DEP}$ (mg/person·day).

The calculation results for each section of the bus tracking measurement are displayed in Fig. 7. The time to reaching the $PMNs_{90\%}\ Dose_{DEP\text{-}Man}$ ranged from 16 to 435 days with an average of 113 days. This result indicates that the male resident who lives around the roadway and inhales DEP for 113 days can have health problems caused by inflammation. In the worst case, the DEP inhalation for the people living near a road may make them likely to develop infections of respiratory system in two days after inhalation in the shortest. Therefore, although it cannot be definitely concluded that all residents get sick because of the inflammation caused by DEP inhalation, the people who live around the roadway should take care of their health.

4. CONCLUSIONS

Through the real-time measurements with a high time resolution during a vehicle running on the main bus route in Iksan City, it was possible to estimate the personal exposure $PM_{2.5}$ and eBC to the driver himself, the residents living near road, and the schoolchild attending the school near roadway. The effect of diesel bus origin $PM_{2.5}$ on in-school $Dose_{PM2.5}$ of the schoolchild was especially high during their strenuous physical activity. The measured eBC concentration in/out-cabin during traffic signal waiting on a busy road suggested that drivers can effectively reduce the exposure to on-road particle pollution by closing windows and ventilating the cabin. The people living and working near heavily traveled roadways can lead to higher exposures to elevated levels of DEP. In the worst case scenario, their respiratory system can be inflamed as early as two days.

ACKNOWLEDGEMENT

This paper was supported by Wonkwang Health Science University in 2020.

REFERENCES

AirBeam Technical Specifications, Operation & Performance. Available online: http://www.takingspace.org/airbeam-technical-specifications-operation-performance/ (accessed on 30 May, 2019).

Almeida, S.M., Canha, N., Silva, A., Freitas, M.D.C., Pegas, P., Alves, C., Evtyugina, M., Pio, C.A. (2011) Children exposure to atmospheric particles in indoor of Lisbon Primary Schools. Atmospheric Environment, 45, 7594–7599. https://doi.org/10.1016/j.atmosenv.2010.11.052

Badura, M., Batog, P., Drzeniecka-Osiadacz, A., Modzel, P. (2018) Evaluation of low-cost sensors for ambient $PM_{2.5}$ monitoring. Sensors, 2018, 1–16. https://doi.org/10.1155/2018/5096540

Barnes, N.M., Ng, T.W., Ma, K.K., Lai, K.M. (2018) In-cabin air quality during driving and engine idling in air-conditioned private vehicles in Hong Kong. Journal of Environmental Research and Public Health, 15, 611–624. https://doi.org/10.3390/ijerph15040611

BreatheLife air pollution campaign, WHO, Available online: https://www.who.int/news-room/detail/29-10-2018-more-than-90-of-the-worlds-children-breathe-toxic-air-every-day (accessed on 10 March, 2020).

Chan, L.Y., Lau, W.L., Lee, S.C., Chan, C.Y. (2002) Commuter exposure to particulate matter in public transportation modes in Hong Kong. Atmospheric Environment, 36, 3363–3373. https://doi.org/10.1016/S1352-2310(02)00318-7

Ding, H., Zhang, Y., Sun, H., Feng, L. (2015) Analysis of the $PM_{2.5}$ distribution and the transfer characteristic in a car-cabin. Procedia Engineering, 121, 875–880. https://doi.org/10.1016/j.proeng.2015.09.043

Geiss, O., Barrero-Moreno, J., Tirendi, S., Kotzias, D. (2010) Exposure to particulate matter in vehicle cabins of private cars. Aerosol and Air Quality Research, 10, 581–588. https://doi.org/10.4209/aaqr.2010.07.0054

Genikomsakis, K.N., Galatoulas, F.K., Dallas, P.I., Ibarra, L.M.C., Margaritis, D., Ioakimidis, C. (2018) Development and on-field testing of low-cost portable system for monitoring $PM_{2.5}$ concentrations. Sensors 18, 1056–1072. https://doi.org/10.3390/s18041056

Gulliver, J., Briggs, D.J. (2004) Personal exposure to particulate air pollution in transport microenvironments. Atmospheric Environment, 38, 1–8. https://doi.org/10.1016/j.atmosenv.2003.09.03

HabitatMap. 2016. http://www.takingspace.org/airbeam-technical-specifications-operation-performance/ (accessed on May 20, 2020).

Jang, J.Y., Jo, S.N., Kim, S.Y., Kim, S.J., Cheong, H.K. Korean exposure factors handbook. Available online: http://m.riss.kr/search/detail/DetailView.do?p_mat_type=d7345961987b50bf&control_no=1f310160f0f75c15ffe0bdc3ef48d419 (accessed on 10 March, 2020).

Jiao, W., Hagler, G., Williams, R., Sharpe, R., Brown, R., Garver, D., Judge, R., Caudill, M., Rickard, J., Davis, M., Weinstock, L., Zimmer-Dauphinee, S., Buckley, K. (2016) Community air sensor network (CAIRSENSE) project: Evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. Atmospheric Measurement Techniques, 9, 5281–5292. https://doi.org/10.5194/amt-9-5281-2016

Lee, J.Y., Choi, J.W., Kim, H. (2007) Determination of hand surface area by sex and body shape using alginate. Journal of Physiological Anthropology, 26, 475–483. https://doi.org/10.2114/jpa2.26.475

Löndahl, J., Massling, A., Pagels, J., Swietlicki, E., Vaclavik, E., Loft, S. (2007) Size-resolved respiratory-tract deposition of fine and ultrafine hydrophobic and hygroscopic aerosol particles during rest and exercise. Inhalation Toxicology, 19, 109–116. https://doi.org/10.1080/08958370601051677

Ma, C.-J. (2015) Modeling study on dispersion and scavenging of traffic pollutants at a region of near busy road. Asian Journal of Atmospheric Environment, 9, 272–279. https://doi.org/10.5572/ajae.2015.9.4.272

Martins, V., Minguillón, M.C., Moreno, T., Querol, X., Miguel, E., Capdevila, M., Centelles, S., Lazaridis, M. (2015) Deposition of aerosol particles from a subway microenvironment in the human respiratory tract. Journal of Aerosol Science, 90, 103–113. https://doi.org/10.1016/j.jaerosci.2015.08.008

Mukherjee, A., Stanton, L.G., Graham, A.R., Roberts, P.T. (2017) Assessing the utility of low-cost particulate matter sensors over a 12-week period in the Guyama Valley of California. Sensors, 17, 1805–1821. https://doi.org/10.3390/s17081805

Nair, A.B., Jacob, S. (2016) A simple practice guide for dose conversion between animals and human. Journal of Basic and Clinical Pharmacy, 7, 27–31. https://doi.org/10.4103/0976-0105.177703

Petzold, A., Ogren, J.A., Fiebig, M., Laj, P., Li, S.-M., Baltensperger, U., Holzer-Popp, T., Kinne, S., Pappalardo, G., Sugimoto, N., Wehrli, C., Wiedensohler, A., Zhang, X.-Y. (2013) Recommendations for reporting "black carbon" measurements. Atmospheric Chemistry and Physics, 13, 8365–8379. https://doi.org/10.5194/acp-13-8365-2013

Sousan, S., Koehler, K., Hallett, L., Peters, T.M. (2017) Evaluation of consumer monitors to measure particulate matter. Journal of Aerosol Science, 107, 123–133. https://doi.org/10.1016/j.jaerosci.2017.02.013

Stoeger, T., Reinhard, C., Takenaka, S., Schroeppel, A., Karg, E., Ritter, B., Heyder, J., Schulz, H. (2006) Instillation of six different ultrafine carbon particles indicates a surface area threshold dose for acute lung inflammation in mice. Environmental Health Perspectives, 114, 328–333. https://doi.org/10.1289/ehp.8266

Thurston, G.D. (2000) Particulate matter and sulfate: Evaluation of current California air quality standards with respect to protection of children, prepared for CARB and OEHHA.

US EPA (1994) Automobile emissions: An overview, FACT SHEET OMS-5, August.

World Health Organization. Ambient (outdoor) air quality and health. https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed on 20 May, 2020).

Yamada, Y., Fukutsu, K., Kurihara, O., Momose, T., Miyabe, K., Akashi, M. (2007) Influences of biometrical parameters on aerosol deposition in the ICRP 66 human respiratory tract model: Japanese and Caucasians. Aarozoru Kenkyu, 22, 236–243, https://doi.org/10.11203/jar.22.236

Yamamoto, K., Kuwana, J., Mizusawa, Y., Tohno, S. (2008) Estimation of elemental carbon emission and spatial distribution of atmospheric concentration in Kansai area. Journal of Japan Society for Atmospheric Environment, 43, 245–256.

Yorifuji, T., Kawachi, I., Kaneda, M., Takao, S., Kashima, S., Doi, H. (2011) Diesel vehicle emission and death rates in Tokyo, Japan: a natural experiment. Science of the Total Environment, 409(19), 3620–3627. https://doi.org/10.1016/j.scitotenv.2011.06.002

Zheng, T., Bergin, M.H., Johnson, K.K., Tripathi, S.N., Shirodkar, S., Landis, M.S., Sutaria, R., Carlson, D.E. (2018) Field evaluation of low-cost particulate matter sensors in high and low concentration environments. Atmospheric Measurement Techniques, 11, 4823–4846. https://doi.org/10.5194/amt-11-4823-2018