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Exposure to Fine Particle along Different Commuting Routes in Urban Area of Fukuoka, Japan

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ABSTRACT

The objective of the current study was to assess the comparative risk associated with exposure to particulate matter (PM) while commuting via different public transport modes in Fukuoka, Japan. For the given routes and measuring days, a trip-maker carried a lightweight portable bag loaded the real-time measurement devices which take simultaneous measurement for size-fractioned particle number concentration, $PM_{2.5}$ mass concentration, and total suspended particle (TSP) collection. The results of the present study have shown significant differences between public transports as commuting modes in Fukuoka. The PM exposure levels on subway platform and inside subway train were overwhelmingly higher than those of other points on commuting route. The relative ratio between modes (i.e., the ratio of $PM_{2.5}$ inside subway to that inside bus) provides an idea for choosing a right commuting mode for our health. This study clearly provided evidence of the extremely high levels of iron exposure by subway uses compared to bus uses. The result of theoretically reconstructed mass concentration of $PM_{2.0\text{-}0.3}$ collected on subway platform suggests that the PM of underground subway will be associated with PM both generated in subway system and inleakaged from outdoor environment.

Key words: Particulate matter, Exposure, Commuting, Subway, Indoor, $PM_{2.5}$, Element

1. INTRODUCTION

The data of monitoring networks are usually used to the risk assessment of ambient air quality to public health. However, it is doubtful whether these data measured on roof-tops of building can fairly assesses personal exposure to air pollutants. Even though the pollutants from our daily routines that include commuting, cooking, smoking, and so on are also sufficiently high to produce an adverse health effect, their exposure has not been fully estimated. Several pilot studies have provide the evidence of the extremely high levels of pollution experienced by our regular daily activities such as commuting (Tsai *et al.*, 2008; Päivi Aarnio *et al.*, 2005; Chan *et al.*, 2002a, b).

According to the report from the American Community Survey (American Community Survey (ACS) data, 2015), over 86 percent of workers commute to the office by car, train or bus, and the average commute lasts about 25 minutes. The Tokyo Metro and Toei networks together carry a combined average of over eight million passengers daily (Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2007).

Recently, experts in the field of public health have promoted formal health impact assessment as a process for encouraging transportation and urban planners to consider the health impacts of their decisions (National Research Council, 2011).

Using public transportation is a fair way to reach our destination (e.g., work, school, mall, gym, etc.) and contributive to helping greatly reduce air pollution and traffic congestion. However, underground railway systems (i.e., subway), which is one of the major transportations in most metropolitan areas worldwide, represent a major source of pollutants exposure to underground air pollution for millions of people daily. Moreover, the underground town generally used as a passage to subway platform and other underground spaces linked to subway system (e.g., shopping mall and platform) are also the confined place that may promote the concentration of pollutants both from the outside atmosphere and generated internally.

It is, therefore, extremely important to find out whether our daily commuting has an effect on our health. Moreover, since the exposure of pollutants is variable under the commuting modes, a comprehensive assessment of the exposures and the factors along different commuting modes is essential.

The purpose of this study is to assess the comparative exposure to PM while commuting via different transport modes in urban area of Fukuoka, Japan.

2. EXPERIMENTAL METHODS

2. 1 Description of the Selected City for Field Measurement

Fukuoka was selected to conduct the mobile and fixed field measurements for PM exposure along different commuting routes. Fukuoka is the capital city of Fukuoka Prefecture and is situated on the northern shore of the island of Kyushu in Japan. Kyushu is Japan's third largest island, located southwest of the main island, Honshu. The city of Fukuoka located in the northwest part of Fukuoka Prefecture is the Kyushu's largest and one of the Japan's ten most populated cities. Due to the city's constant expansion, many areas have now been constructed on reclaimed land and even man-made islands.

Fukuoka's subway system consists of three subway lines, the Kūkō (or Airport Line), the Hakozaki Line, and the Nanakuma Line. Its total length is 29.8 km (18.5 mi) and all stations are equipped with automatic platform gates. It carries more than 137.1 million passengers per year (Fukuoka Municipal Subway, 2014).

Details on Fukuoka were described in elsewhere (Ma and Kim, 2013).

2. 2 Designed Commuting Routes

In this study, the commuting routes were chosen on the presumption that a commuter moves from a heavily populated and congested downtown of Fukuoka City to an outskirts of city. Subway is the primary mode of transport in Fukuoka. Buses usually serve a secondary role, feeding bus passengers to and from subway stations.

We assigned a commuter to start her trip according to the predetermined commuting routes and the same scheduled time. This commuter used two different commuting routes i.e., [on foot - underground subway - aboveground electric train - on foot (a busy roadside)] and [on foot - underground subway - bus - on foot (a busy roadside)] on each day. The half-height platform screen doors (i.e., chest-height sliding doors) were installed at each station from the Fukuoka Airport station ((a) in Fig. 1) to the Kaizuka station ((d) in Fig. 1) to prevent passengers from falling off the platform edge onto the railway tracks. The commuting distance is about 28 km (the dotted line from "a" to "f" on Fig.

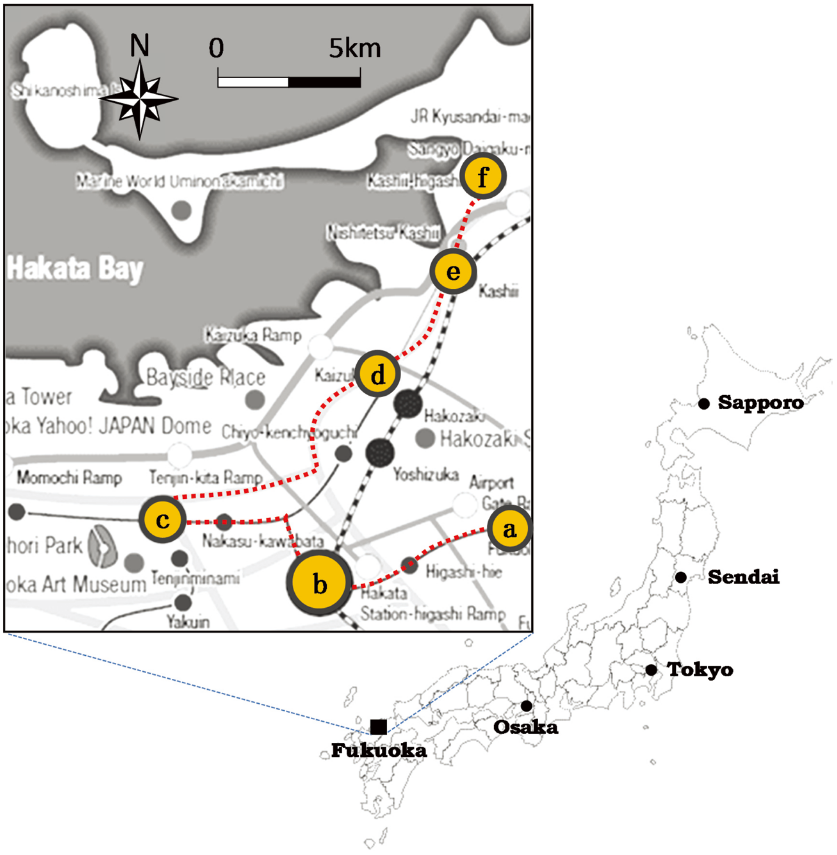

Fig. 1. The designed commuting route on the highlighted Fukuoka City in Japan.

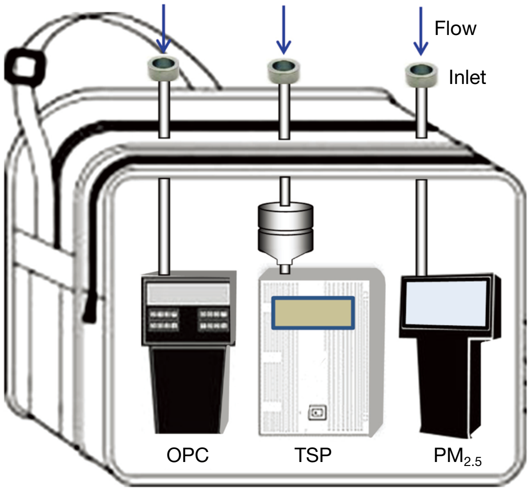

Fig. 2. The bag loading measuring and sampling instruments.

1) (See Fig. 1).

2. 3 Mobile and Fixed Field Measurements

For a given route and survey day, an investigator (i.e., a trip-maker) carried a lightweight portable bag (see Fig. 2) loaded the real-time measurement devices which take simultaneous measurement for size-fractioned particle number concentration and $PM_{2.5}$ mass concentration while traveling on foot, subway, and bus. A TSP collector was also loaded in a portable bag and it was operated during a fixed measurement.

The bag (see Fig. 2) was made to hold the measuring and sampling instruments (i.e., OPC, TSP sampler, and $PM_{2.5}$ monitor) securely as well as for noise abetment. In the running subway and bus, the inlet height was adjusted to being around the passenger's head height. The number-size distribution of aerosol particles was monitored by an optical particle counter (OPC) (HACH®, HPC3+, USA). In the field measurement, OPC was operated every 10 second in the dynamic range of >0.3 μm with three-step cutoff diameter of 0.3-0.5 μm, 0.5-1.0 μm, and >1 μm. In order to assess the highly time resolved.

$PM_{2.5}$ mass concentration, a Dust scan Scout (DustScan®, 3020, USA) was operated. This $PM_{2.5}$ monitoring system makes use of a near-forward light scattering to assess the mass concentration of PM. The scattered light caused by the presence of particles is received by a sensor, forming the basis of the monitor's computations. Mass concentration data are reported in micrograms per cubic meter.

A filter pack sampler with a mini-pump collected TSP on the 25 mm diameter Nuclepore® polycarbonate filter with $10\,L\,min^{-1}$ flow rate.

The PM exposure assessments along each commuting mode were carried out two times during morning rush hours.

2. 4 Elemental Analysis of TSP Samples

The TSP samples collected inside subway and bus were the target of elemental analysis using a Particle Induced X-ray Emission (PIXE) installed at the Cyclotron Research Center of Iwate Medical University. This PIXE analytical system has the great advantages such as an excellent sensitivity, a nondestructive technique for multielement with a wide range of elements ($Z>10$), and a short measuring time The more detailed analytical procedures and experimental set-up used for PIXE analytical system were described elsewhere (Sera *et al*., 1999).

3. RESULTS AND DISCUSSION

3. 1 PM Exposure along Different Commuting Routes

Fig. 3 shows the comparison of number concentration of size-resolved PMs among several different points on the commuting route-1. As shown in Fig. 2, the commuter's exposure to PM displays significant difference among the points of commuting route. As one of peculiar points of PM exposure, the number concentration of $PM_{0.5\text{-}0.3}$ was significantly higher than those of other size fractions regardless of the location of monitoring. A comparison of PM number concentration on two different surface streets (i.e., downtown and outskirts of a city) indicates that the PM exposure was more elevated on the heavily populated and congested downtown street than that of the outskirts of a city. The PM exposure at underground town was slightly higher than the level of outdoor downtown street. A similar result, i.e., more polluted air in the semi-closed underground town compared to that of outdoor in Seoul was reported (The Segye Times, 2014). Meanwhile, PM exposure levels on subway platform and inside subway train were overwhelmingly higher than those of other points on commuting route. Of the two high PM exposure points (i.e., on platform and inside train), the former was still higher than the latter. However, Park and Ha (2008) reported that the PM_{10} and $PM_{2.5}$ inside trains were significantly higher than those measured on platforms in Seoul subway system. They assumed that it was due to subway trains in Seoul not having mechanical ventilation systems to supply fresh air inside the train.

There are many factors that could influence PM exposure in the subway system, e.g., running train number, passenger density, outdoor traffic amount, ventilation

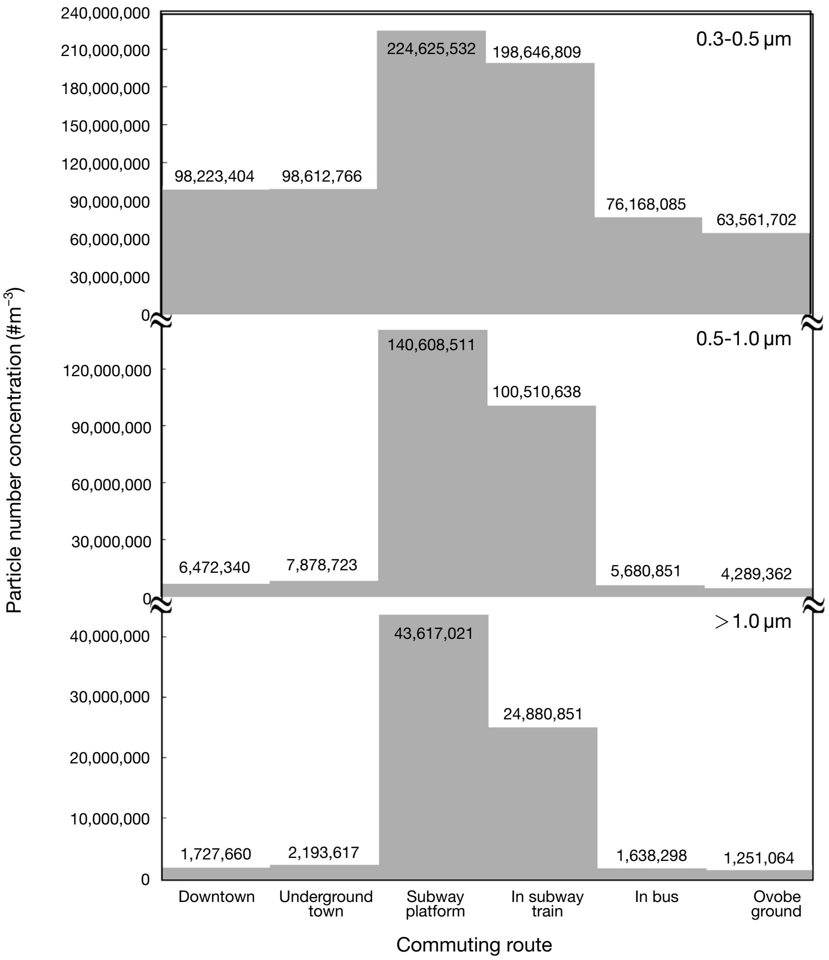

Fig. 3. Average number concentration of size-classified particles at different points during commuting (Route-1).

system, screen door, shopping mall at underground space, etc. Several previous field studies reported that railway systems are a great generator of PM (Abbasi *et al.*, 2011; Lorenzo *et al.*, 2006). In any case, there is terrible concern to the commuter's PM exposure from the daily using of underground subway system.

Average PM exposure in bus, which is being used as one of major public transportation systems in Fukuoka, were 38.3%, 5.7%, and 6.6% of those in subway train in the PM size fraction of 0.3 μm-0.5 μm, 0.5 μm-1.0 μm, and > 1.0 μm, respectively. The level of PM exposure inside bus was even lower than that of downtown because the bus was driving from the urban hubs to suburbs.

Fig. 4 shows the variation in PM number concentration across the 6-point of travel through commuting route-2. For three kinds of PM size also showed the considerable inter - course variability on commuting route. The fluctuation pattern of PM exposure is nearly similar to that of route-1 (Fig. 3). However, the amount PM exposure through whole location of monitoring was absolutely higher than that of route-1 regardless of PM size. This could be because the PM exposure on the route of commuting is seriously affected from the daily air quality of outdoor. Outdoor pollutants including PM are easily flowed into the semi-closed microenvironment (e.g., underground town, subway train, and bus) through entrances, gaps, and windows. The pollutant materials and then locally transport in indoor reservoir space through the mechanisms as infiltration, exfiltration, deposition, and resuspension. As an unprecedented phenomenon, there is no great difference between the PM exposures in train running on above ground and that on above ground (i.e., outdoor). It can therefore be said that the commuting on the above ground-rail may have potential health benefits when compared to traveling on underground subway.

The $PM_{2.5}$ levels on subway platform and in running bus for several different cities in the world are summarized in Table 1. Although, it is not reasonable to com-

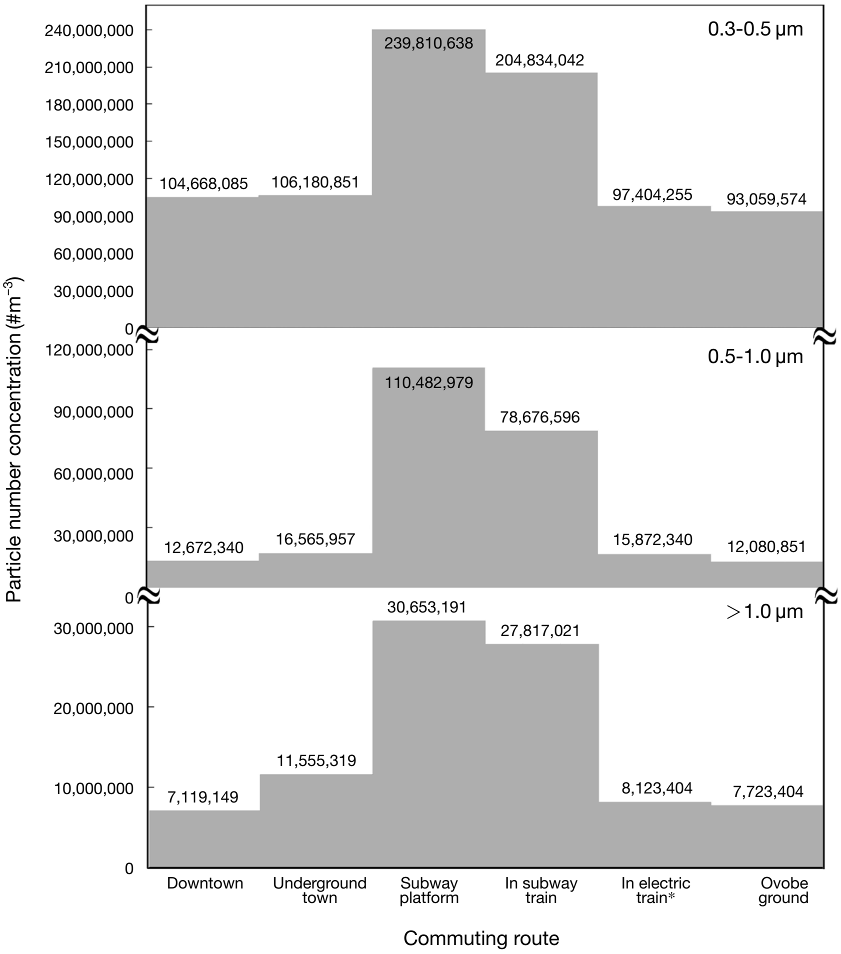

Fig. 4. Average number concentration of size-classified particles at different points during commuting (Route-2). Electric train (*) runs on above ground.

Table 1. A comparative $PM_{2.5}$ mass concentrations ($\mu g\, m^{-3}$) in subway and bus in Fukuoka and other cities in the world

City	Subway	Bus	Subway/Bus	Reference
Fukuoka	74	38	1.95	Current study
Guanzhou	44	123	0.36	Chan *et al.* (2002b)
Helsinki	21	35	0.60	Aarnio *et al.* (2005)
Hong Kong	33	71	0.46	Chan *et al.* (2002a)
London	202	39	5.18	Adams *et al.* (2001)
Mexico	70	61	1.15	Gómez-Perales *et al.* (2004)
Taipei	35	39	0.90	Tsai *et al.* (2008)

pare without detailed information, the level of PM pollution in London subway was far higher than on subway platform in other cities. The $PM_{2.5}$ measured on subway platform in current study was 2.7 times lower than that measured at London subway. The ratios of $PM_{2.5}$ on subway platform-to-in bus described the 4th column in Table 1 were highly disperse with a range of 0.36-5.18. The highest ratio was shown in London (5.18), the oldest rail system in the world, followed by Fukuoka (1.95), and Mexico (1.15). Guanzhou in China shows the lowest ratio (0.36) and one of the reasons might be that the underground railway systems in this city have the centralized air-conditioning systems with filtered ambient air supply and the trains used air-conditioning system with air exchange mode.

In spite of the growing concern of health effects

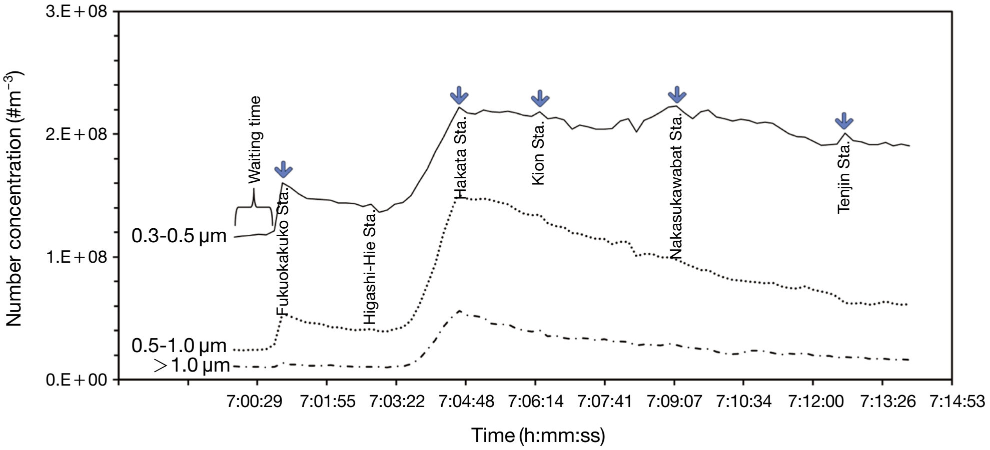

Fig. 5. Exposure profile of size-selected PM while a subway train was running from section (a) (Fukuoka Airport Sta.) to (c) (Tenjin Sta.) in Fig. 1.

associated with $PM_{2.5}$ exposure at subway, the relevant regulation law is still inadequate in many countries. In Japan, indoor air quality (IAQ) guideline does not prescribe for the PM in the underground, such as subway station and underground commercial quarter. The subway IAQ is therefore subject to the act on maintenance of sanitation in buildings providing not $PM_{2.5}$ but SPM (suspended PM smaller than 10 μm) ($\leq 150\ \mu g\ m^{-3}$). Meanwhile, the ministry of environment, Korea established the recommended standards for the IAQ of public transportation in 2007. The Korean PM_{10} air quality standard at the subway area is $\leq 150\ \mu g\ m^{-3}$.

In Fig. 5, arrows show each subway station on the subway commuting route from Fukuoka Airport Sta. (departure station) to Tenjjn Sta. (transfer station). After waiting time, PM number concentrations in a whole size-range were considerably fluctuated according to each station. The particle number concentration increased sharply when a train started from Hakata Sta. after door closing. Hakata Sta. is the largest and busiest station in Kyushu, and is a gateway to other cities in Kyushu for travelers from Honshu. PM exposure monitored during train running was significantly higher than that while train was waiting at departure station (i.e., Fukuoka Airport Sta.). This result suggests that the passengers using the largest and busiest station are exposed to far higher levels of PM.

3.2 Theoretically Reconstructed PM Mass Concentration

Although fine PM, especially ultrafine PM, presents in the indoor air of underground subway in high numbers, it contributes little to mass concentration. However, its small mass concentration and adverse health outcomes are closely linked (Wichmann *et al.*, 2000).

It is also necessary to understand the origin of fine PM in subway microenvironment for the assessment of its health risk as well as its reduction measures establishment. In this study, the mass concentration of $PM_{2.0\text{-}0.3}$ measured at a fixed site (i.e., Hakata Sta.) was theoretically reconstructed by number concentrations of size-resolved PM, the result of elemental analysis, and referential data.

Both fine PM number concentration and $PM_{2.5}$ mass concentration were intensively monitored on the platform of underground Hakata Sta. which is one of most congested and polluted stations (see Fig. 5). This intensive monitoring was performed between rush hours and non-rush hours (i.e., from 8:40AM to 2:00PM). The number concentrations of three size-fractionated fine PMs (0.3-0.5 μm (channel-1), 0.5-1.0 μm (channel-2), and 1.0-2.0 μm (channel-3)) and $PM_{2.5}$ were simultaneously monitored by an OPC (RION, KC-01D) and a Dust scan Scout (Rupprecht & Patashnick Co. Model 3020), respectively.

The theoretical mass of each particle fraction ($m(d_{pi})$) was calculated based on particle's size, its number, and the density of its respective chemical compositions. The $m(d_{pi})$ and the integrated mass concentration of $PM_{2\text{-}0.3}$ were computed as follows:

$$m(d_{pi}) = \frac{\pi}{6} d_{pi}^{3} \rho(d_{pi}) n(d_{pi})$$

$$PM_{2\text{-}0.3} = \sum_{i=1}^{3} m(d_{pi}) f(d_{pi})$$

where i is the channel number of optical particle counter; d_{pi} is the arithmetic mean diameter of the upper and lower boundaries for channel i; $m(d_{pi})$ is the mass concentration in channel i; $\rho(d_{pi})$ is the density of par-

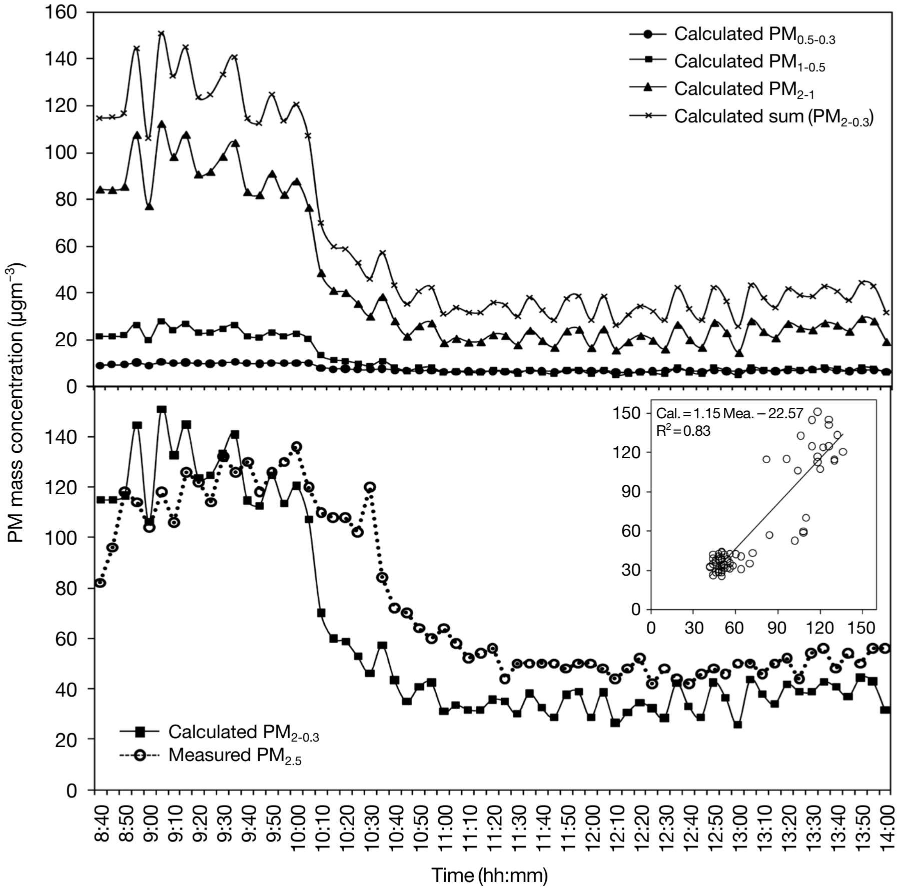

Fig. 6. Time- and size-resolved theoretically calculated mass concentration of PM (upper) and the plotting of calculated $PM_{2\text{-}0.3}$ with measured $PM_{2.5}$ (bottom) on the platform of Hakata Sta.

ticle in channel *i*; and $n(d_{pi})$ is the number concentration in channel *i*.

In this study, $\rho(d_{pi})$ was determined by multiplying the occupation ratios assigned specifically in each particle channel to the density of each representative component in channel. Cheng *et al.* (2008) reported that the fine PM levels at the subway station in Taipei were significantly influenced by the air quality in outdoor ambient. Hence, in the current study, the densities of submicron size PMs, i.e., channels of 0.3-0.5 μm and 0.5-1.0 μm, were calculated by literature outdoor data.

Ito *et al.* (2003) estimated the chemical compositions of size-resolved particle collected at urban outdoor. According to their report, as the major compositions of PM, ammonium sulfate ($\rho_{(NH4)2SO4}$:1.77), soil (ρ_{CaCO3}: 2.70), and elemental carbon ($\rho_{\text{General non-crystal C}}$:1.9) accounted for 68.5%, 18.0%, and 13.5% of PM with 0.29-0.47 μm and 57.0%, 28.6%, and 14.4% of PM with 0.47-0.67 μm, respectively.

In a previous study performed by Lorenzo *et al.* (2006), the size-resolved mass contributions of the particle classes for the sampling sites at 10 m distance from the railway lines showed the maximum peak between 0.7 μm and 3 μm for each identified PM class (i.e., Fe class, Si class, and Ca class). The density of the PM sized 1-2 μm was therefore approximately calculated from these major chemical compositions determined by PIXE analysis of the $PM_{2.5}$ collected at the platform of underground Hakata Sta. in current study.

Fig. 6 shows the time dependent variation of the theoretically calculated mass concentration of size-resolved PM (i.e., 0.3-0.5 μm, 0.5-1.0 μm, and 1.0-2.0 μm) with measured $PM_{2.5}$. The plotting of computed $PM_{2\text{-}0.3}$ versus measured $PM_{2.5}$ is also displayed at inner of Fig. 6. The time serial calculated PM mass concentration is also severely fluctuated throughout the whole measurement period. As might be expected, the rush-hour levels of $PM_{2.5}$ were found to be higher than during non-rush hour periods. As a matter of course, this time series fluctuation of PM mass concentration was associated with the variation of train's number, passenger's number, and outdoor air quality. The calculated mass

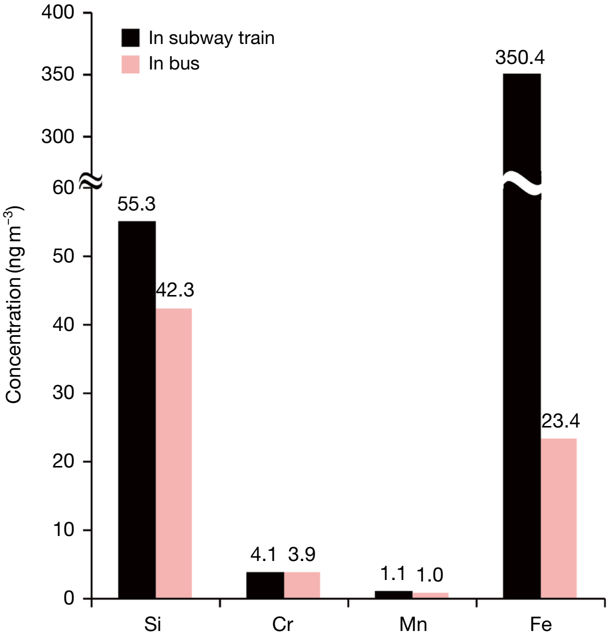

Fig. 7. Intercomparision of four elements in TSPs collected inside subway train and bus.

concentration of PM_{2-1} shows a remarkable level compared to other small PM size fractions and ranks a highly elevated level during rush hour. This result thus indirectly indicates that the 1-2 μm size PM predominately contributes to the mass of fine PM in subway environment. The enrichment of mass concentrations in this particle size range is in a good agreement with the result of individual PM measurement carried out by Lorenzo *et al.* (2006).

Although the overestimating and underestimating of calculated $PM_{2-0.3}$ were shown from AM 8:40 to AM 9:30 and after AM 9:30, respectively, the reconstructed $PM_{2-0.3}$ mass concentration accounted for 83.3% of the actually monitored $PM_{2.5}$. There was also a close resemblance (0.83 R^2 level) between the computed $PM_{2-0.3}$ and the measured $PM_{2.5}$ as displayed in Fig. 6. This result suggests that the portion of $PM_{2.5}$ on the subway platform of Hakata Sta. was largely occupied by $PM_{2-0.3}$ and the PM in underground subway will be associated with PMs both generated in subway system and originated from outdoor environment. Moreover, it can be reasonably said that $PM_{2.0-0.3}$ in the microenvironment of underground subway was mostly composed by the chemical components employed on PM mass reconstruction in our study.

3.3 Intercomparision of Elements in TSPs Collected Inside Subway Train and Bus

In order to estimate the difference of elements exposure between two different public transportations, the TSP samples collected from the inside of subway train and bus were analyzed by PIXE which is one of most advanced analytical techniques for elemental analysis. The concentrations of all four elements (i.e., iron and silica as major elements, and chromium manganese as minor elements) in TSP of train-inside were more enriched than those of bus. Among them, iron shows a great dissimilarity between subway and bus. With relatively low levels of elemental concentration, the bus commuting may be good for user's health compared to the commuting by underground subway.

4. CONCLUSIONS

Transportation planner often do not account for air pollution-related health effects when evaluating alternative transportation infrastructures. This study was aimed to thoroughly estimate the personal exposure of commuters in public transport to PM. The PM exposure measurements designed in different days were significantly affected by the variation of transport modes. Our survey clearly provided an actual situation that the extremely high PM exposure was experienced by the underground subway using commuters. It can be said that we may be able to cut down on our chance of PM exposure by switching our commute route which has potential for health benefits. The results of the present study pointed out that in order to attract individuals to use public transportations, the improvement of their air quality, especially subway, is critical. A more comprehensive assessment is being planned to identify how exactly journey time is related to the negative health of public transport users through a long-term periodic evaluation.

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