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Influences of Commuting Mode, Air Conditioning Mode and Meteorological Parameters on Fine Particle ($PM_{2.5}$) Exposure Levels in Traffic Microenvironments

Da-Lei Wu[1], Mang Lin[1], Chuen-Yu Chan[1,2*], Wei-Zhong Li[3], Jun Tao[4], You-Ping Li[1,5], Xue-Fang Sang[1], Chun-Wei Bu[1]

[1] *School of Environmental Science and Engineering, Sun Yat-sen University, Guangzhou 510275, China*
[2] *Faculty of Science and Engineering, University of Nottingham Ningbo, Ningbo 315100, China*
[3] *Institute of Environmental Science, Nanhai District, Foshan 528299, China*
[4] *South China Institute of Environmental Sciences, Guangzhou 510655, China*
[5] *College of Chemistry and Chemical Engineering, China West Normal University, Nanchong 637009, China*

ABSTRACT

With the aim of determining the impacts of various factors on commuter exposure to fine particulate matter ($PM_{2.5}$), a series of field studies were carried out to measure commuter exposure to $PM_{2.5}$ on six major commuting modes (in-cabin mode: bus, taxi and metro; on-roadway mode: walking, bicycle and motorcycle) in a highly industrialized city in the Pearl River Delta, China. The results showed that the exposure level was greatly influenced by the commuter mode, with the on-roadway mode showing a higher $PM_{2.5}$ concentration (76 μg/m^3). An experiment with the taxi mode suggested that the use of air-conditioning can effectively reduce exposure levels in most cases (by at least 83%). Apart from traffic-related emissions, ambient $PM_{2.5}$ concentration also had important impacts on exposure levels in most commuting modes, which was further ascertained by the seasonal variations in exposure levels and their significant correlations ($p < 0.05$) with meteorological parameters (temperature, relative humidity, wind speed and direction). The results of a General Linear Model analysis show that temperature, traffic mode and wind speed were significant factors that explained 27.3% of variability for the in-cabin mode, while relative humidity and wind speed were the significant determinants for the on-roadway mode, which contributed 14.1% of variability. In addition, wind direction was also an important determinant for both in-cabin and on-roadway modes. This study has some valuable implications that can help commuters to adopt appropriate travel behavior to reduce their personal exposure to such pollutants.

Keywords**:** Commuter; Exposure; Traffic modes; $PM_{2.5}$.

INTRODUCTION

The adverse health effects of fine particulate matter ($PM_{2.5}$) have been identified by recent epidemiological studies. Short- and long-term exposure to $PM_{2.5}$ is directly associated with various health effects, including respiratory and cardiovascular diseases (Pope III *et al.*, 2004; Dominici *et al.*, 2006). Health studies also suggest that exposure to $PM_{2.5}$ is indirectly related to various diseases, especially cancer (Pope III *et al.*, 2002; Vinzents *et al.*, 2005). Additionally, exposure to $PM_{2.5}$ has been linked to induction of oxidative DNA damage in toxicological studies (Risom *et al.*, 2005). The implication is that it has become important to precisely understand the $PM_{2.5}$ exposure levels in various microenvironments. Traffic microenvironment has received particular attention because $PM_{2.5}$ concentration is often substantially higher than ambient levels on which air quality standard is assessed (Adams *et al.*, 2001; Kam *et al.*, 2011; Cheng *et al.*, 2012a). The importance is also highlighted by the fact that people can spend a long time in this microenvironment (including commuting in motor vehicles and on bicycle, walking along and waiting on busy street).

Exposure level in traffic microenvironment is influenced by transportation mode (Briggs *et al.*, 2008; Kaur and Nieuwenhuijsen, 2009; Kingham *et al.*, 2011), air conditioning (A/C) mode (Chan *et al.*, 2002; Chan and Chung, 2003; Esber and El-Fadel, 2008; Geiss *et al.*, 2010; Knibbs *et al.*, 2010) and meteorological parameters (Adams *et al.*, 2001; Kaur and Nieuwenhuijsen, 2009; Cheng and

[*] Corresponding author. Tel.: +86 (0) 574 8818 3049;
Fax: +86 (0) 574 8818 0175
E-mail address: John.Chan@nottingham.edu.cn

Li, 2010; Buonanno *et al.*, 2011). However, it is currently difficult to precisely quantify the differences in air pollution exposure among different modes of transport. The influences of A/C mode and meteorological parameters on commuter exposure were also incompletely understood. Furthermore, although numerous experimental studies were conducted in developed countries in the past 20 years (e.g., Bevan *et al.*, 1991; Adams *et al.*, 2001; Kaur *et al.*, 2005; Fondelli *et al.*, 2008; Boogaard *et al.*, 2009; Geiss *et al.*, 2010; Strak *et al.*, 2010; Buonanno *et al.*, 2011; Kim *et al.*, 2011; Dons *et al.*, 2012), corresponding researches were limited in developing countries (Gómez-Perales *et al.*, 2004, 2007; Murruni *et al.*, 2009; Apte *et al.*, 2011; Mugica-Álvarez *et al.*, 2011; Huang *et al.*, 2012). Developing countries are facing serious air pollution problems from both industrialization and urbanization processes (Economopoulou and Economopoulos, 2002; Afroz *et al.*, 2003; Wang *et al.*, 2003; Han and Naeher, 2006; Colbeck *et al.*, 2011; Cao *et al.*, 2012), and thus the traffic microenvironment may be more complicated.

To better address these questions, a wider range of experiments, which covered six major commuting modes and two different seasons, were conducted in an industrial city (Foshan) located at the Pearl River Delta (PRD), which is one of the most important industrial regions in China. Foshan city was greatly affected by both industrial and vehicle emissions (Wan *et al.*, 2011). The primary aim of this work was to present the commuter $PM_{2.5}$ exposure level in this highly polluted city. Systematic comparison on exposure levels among different modes of transport was performed. Influence factors would be also determined and quantified. Results from this study provided important implication for commuters on how to choose appropriate travel behavior to reduce their personal exposure.

METHODOLOGY

Field Study Design

Commuter exposures to $PM_{2.5}$ in six major traffic modes (bus, taxi, metro, walking, bicycle and motorcycle) in this study area were measured. We identified bus, taxi and metro as in-cabin mode, and walking, bicycle and motorcycle as on-roadway mode according to the different features of transportation modes and possible mode-specific influencing variables (Knibbs *et al.*, 2011). The study was conducted in the urban area of Foshan city in spring (5–10 March and 28 March–3 April) and summer (5–11 July) of 2011. In total, in-cabin mode was sampled for 20 days, and on-roadway mode for 14 days (data during 5–10 March was not available). Two portable real-time PM monitors (MicroDust pro, Casella CEL, Bedford, UK) were carried on the back of experimenters, who behaved as the same as common passengers. The $PM_{2.5}$ adaptors were put at the level of breathing zone. Detailed sampling method will be illustrated in next section. Experimenters took taxi randomly and ran on a fixed line with the length of 12.2 km for two cycles. Windows were opened without A/C (non-A/C mode) at the first cycle, while A/C was turned on with windows closed at the second cycle (A/C mode). Three different bus lines with the average length of 13.4 km were selected for bus mode. For metro, the only metro line (16.6 km) was chosen. As the ventilation mode for bus and metro were not under the control of experimenters, study of switching A/C mode was not applicable in these two in-cabin modes. Regarding the on-roadway mode, studies were conducted on two main roads with a total of 5.0 km. The detailed features of above-mentioned routes were shown in Fig. 1. All of the field samplings were carried out in the morning (0700–1200) and afternoon (1400–1900) in weekday. The elapsed time of one sample (i.e., one trip) ranged from 20–40 minutes and 30–60 minutes for on-roadway and in-cabin mode, respectively. Bus, taxi and motorcycle were powered by diesel, compressed natural gas, and regular unleaded gasoline, respectively. Smoking inside the public transportation modes was strictly prohibited in this region and we did not find any violation during the sampling period.

With an aim to better interpret our data, hourly ambient $PM_{2.5}$ concentration data during sampling period were obtained from two ambient air monitoring stations (AMS), which were operated by local Environmental Protection Bureau (Fig. 1). These two stations were both placed on the rooftop of building, which are ~7 m above the ground level and more than 30 m away from main traffic roads. Concentration of $PM_{2.5}$ was monitored by the Tapered Element Oscillating Microbalance (TEOM) method. More detailed description can be found in the work of Wan *et al.* (2011). The data from these two stations were averaged to represent the air quality over the study area. Hourly meteorological data (including temperature, relative humidity, wind speed and direction) during the sampling period were also obtained from the nearest weather station operated by local Meteorology Bureau (Fig. 1).

Sampling Method and Quality Assurance

The $PM_{2.5}$ concentration was measured by MicroDust pro via a near forward angle light scattering technique. Detection limit of MicroDust pro was 1 $\mu g/m^3$. A small personal sampling pump (D705-22, HARGRAVES, USA) was used to ensure a continuous airflow (3.5 L/min, stabilized by a flowmeter [Mini-Master, Dwyer Instrumens, Inc., USA]) through a photo detector. More detailed description of MicroDust pro can be found in Mohammadyan *et al.* (2010). As a quality control measurement, zero and span calibration of the monitor was performed before each survey trip. Briefly, purge bellows was used to inject clean air into the chamber for setting zero. An optical calibration filter (i.e., fixed reference) was used to confirm the factory calibration point for the instrument. Detailed procedure can be found in CASELLA CEL (2005). The monitor was turned on to stabilize for several minutes before start of sampling. Although this monitor was calibrated according to a known reference dust standard in factory, it was necessary to calibrate the response of the instrument because different dust types caused a different response from this instrument due to variation in particle size, refractive indices and color. MicroDust pro was calibrated against a mini-vol (5 L/min) air sampler, MINIVOL-TAS (AirMetrics Co., Oregon, USA) with sampling filters (Pure Quartz Filter, 47 mm, Whatman Inc., USA). These two samplers (MicroDust pro and

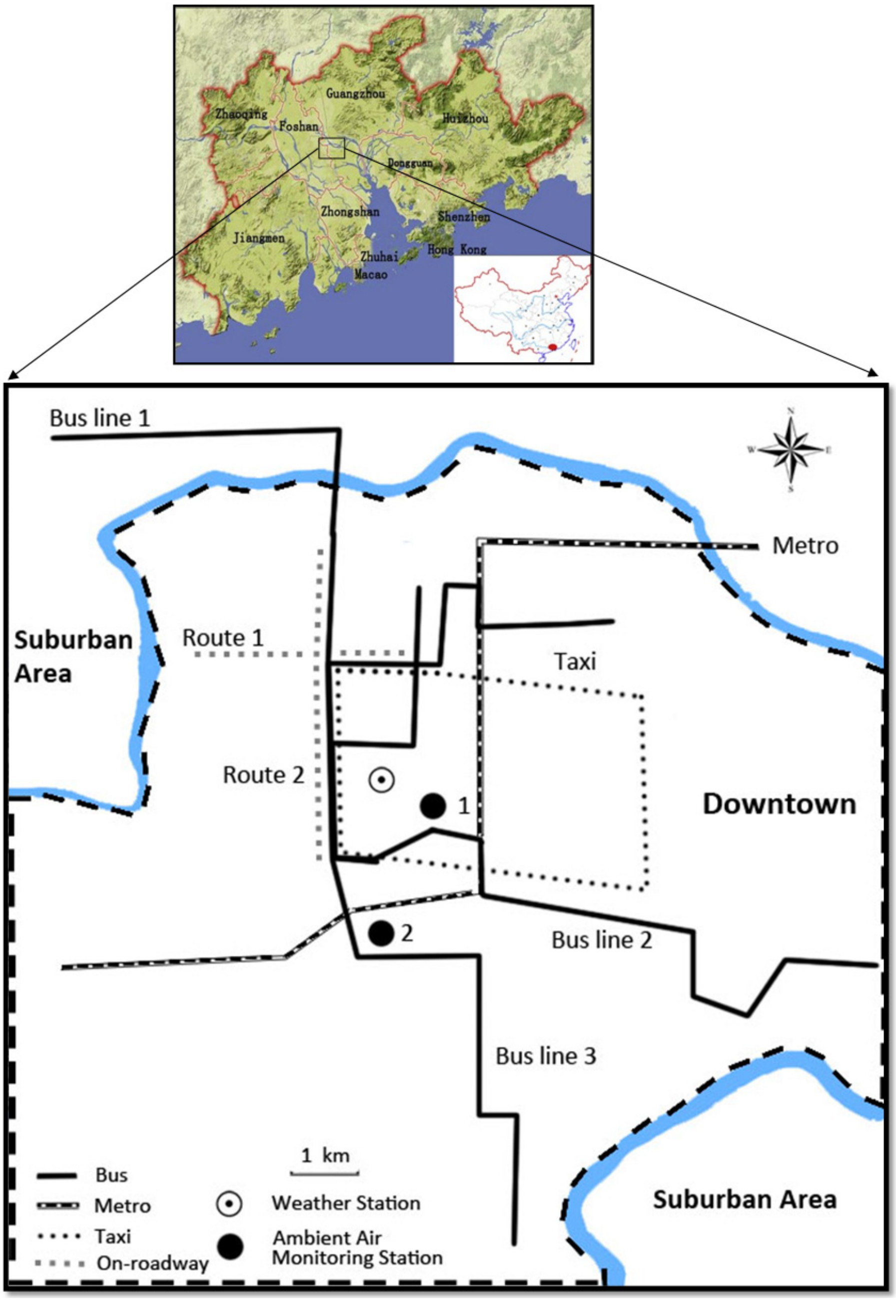

Fig. 1. Map showing the locations of Foshan city and study routes.

MINIVOL-TAS) were both placed at the same location and run for 24 hours simultaneously. A linear regression equation ($\text{Concentration}_{\text{MicroDust pro}} = 1.5 \times \text{Concentration}_{\text{MINIVOL-TAS}}$, $r = 0.92$, $p < 0.001$) can be derived from these 24-h average concentration data (14 pairs of samples). The slope (1.5) of this regression equation was used as an adjustment factor to correct for the proportional bias of MicroDust pro measurements.

Data Analysis

Statistical analysis (including independent t-test, Pearson correlation and linear regression) was performed using the software package SPSS (v18.0). Moreover, a General Linear Model (GLM) univariate procedure was used to determine the impacts of influence factors on personal exposure in transport microenvironments. The GLM univariate procedure (analysis of covariance (ANCOVA)) incorporates both regression analysis and analysis of variance and allows the input of categorical and continuous variables. A log transformation was applied to the exposure levels to make data normality. The statistical assumptions underlying the ANCOVA (including homogeneity of variance, correlations among covariates, normality, linearity, and regression slopes) were checked carefully prior to performing the procedure. Detailed statistical background of the GLM could be found in literatures (Adams *et al.*, 2001; Kaur and Nieuwenhuijsen, 2009). In this study, personal exposure concentrations were selected as the dependent variables, while transport mode and wind direction were regarded as the fixed factors. In the taxi mode analysis, A/C mode was selected as the fixed factor. Meteorological parameters were chosen as covariate variables. Note particularly that multiple inter-correlation variables would be indentified, among which only the variable most correlated with exposure levels was selected. Detailed selection procedure could be found in Adams *et al.* (2001). For in-cabin mode, temperature, wind speed and direction were selected based on this selection procedure, while relative humidity, wind speed and direction were chosen in on-roadway mode.

RESULTS AND DISCUSSION

Inter-Comparison of Commuting Modes

Substantial differences of $PM_{2.5}$ exposure levels existed among six commuting modes in this study (Table 1). During the whole sampling period, the $PM_{2.5}$ levels among three on-roadway modes (walking, bicycle and motorcycle) were more or less similar. The high exposure levels of these on-roadway modes (with an average of 76.0 μg/m^3) might be due to the direct impact of vehicle emission on road. On the other hand, the exposure levels of in-cabin modes were lower (with an average of 53.5 μg/m^3) but varied a lot, which ranged from the lowest in metro of 27.9 μg/m^3 to the highest in bus of 75.9 μg/m^3. More specifically, the exposure level of bus in springtime (93.1 μg/m^3) was profoundly higher than that in any other commuting mode. This phenomenon could be attributed to a host of reasons. Firstly, bus window was always opened in spring, leading to the significant ingress of particles. Secondly, bus door would be opened at each bus stop, which further facilitated the infiltration of $PM_{2.5}$ from the outside environment into the bus. Thirdly, bus was required to queue up when approaching the bus stop, and had to wait for a few seconds for the passengers to get on and off, which would make it much closer to emission sources (i.e., exhaust pipes) (Huang *et al.*, 2012). However, it is worthwhile to note that exposure level of bus in summertime was notably lower, and this phenomenon was because bus usually closed windows and turned on A/C in this season, which helped to prevent the ingress of particles. Regarding the lowest $PM_{2.5}$ concentration levels in underground metro system, it was owing to the zero emission of electric trains, more fluid traffic (with correspondingly less congestion) on the surface (Querol *et al.*, 2012), and more efficient ventilation using (Furuya *et al.*, 2001; Nieuwenhuijsen *et al.*, 2007; Cheng *et al.*, 2012b). Overall, such differences emphasized that being away from vehicle emission on road can effectively minimize the exposure level of commuting mode.

In early years, it was widely reported that the ratios of PM exposure in on-roadway mode to that in in-cabin mode (O/I ratio) were lower than 1, because in-cabin modes was closer to emission sources (Gee and Raper, 1999; Adams *et al.*, 2001; Rank *et al.*, 2001). The lower O/I ratio was also due to less advanced automobile manufacturing, ventilation technology and filtration system (Xu and Zhu, 2009; Knibbs *et al.*, 2010). However, most of the ratios in this study were found to be higher than 1, which was similar to the results from studies after 2005 (Table 2). Although differences existed among these studies (e.g., different research period, vehicle types and location), this result highlighted the improvement of automobile manufacturing, ventilation technology and filtration efficiency in recent years, which helped to prevent ingress of particles (Briggs *et al.*, 2008). It was worthwhile to note that the O/I ratio of bus in spring (mostly with non-A/C) and taxi with non-A/C mode were both lower than 1 in this study, suggesting that A/C mode might play an important role in reducing the exposure level of in-cabin mode.

Influence of A/C Mode

Statistically significant difference ($p < 0.01$) between exposure levels of taxi with and without A/C mode was found in this study (Fig. 2). More specifically, taxi commuters can reduce their $PM_{2.5}$ exposure via using A/C mode by 51.5% and 52.2% in spring and summer compared with the non-A/C mode, respectively. This was because closed windows could help to prevent ingress of particles. Besides, turning on the air conditioning system could further improve cabin ventilation rate and filtration efficiency (Briggs *et al.*, 2008; Knibbs *et al.*, 2011), which had vital impacts on

Table 1. Summary of meteorological parameters, $PM_{2.5}$ concentrations of ambient air monitoring stations (AMS) and various commute modes.

		n^a	Whole		Spring		Summer	
			Mean	S.D.^{b}	Mean	S.D.	Mean	S.D.
Meteorological parameters	Temperature (°C)	240	24.6	7.1	20.3	4.6	32.5	2.6
	Relative humidity (%)	240	55.3	17.9	52.8	19.9	60.0	12.2
	Wind speed (m/s)	240	2.0	1.0	1.9	1.0	2.2	1.0
$PM_{2.5}$ concentration (μg/m^3)	AMS	240	45.1	25.9	56.2	23.4	24.5	15.5
	Bus	101	75.9	56.6	93.1	54.3	22.1	14.0
	Taxi	53	56.8	37.9	69.1	38.0	28.2	15.6
	Metro	33	27.9	13.1	30.3	14.5	25.1	11.4
	Walking	54	74.1	50.0	71.7	34.4	79.7	76.2
	Bicycle	35	76.8	53.0	81.4	49.9	65.9	61.1
	Motorcycle	34	77.1	42.6	84.1	40.1	59.6	45.9

[a] Number of samples.

[b] Standard Deviation.

Table 2. Ratio of on-roadway to in-cabin mode (O/I) for PM exposure in previous studies.

Year	City	Season	PM size	Mode	Concentration ($\mu g/m^3$)	O/I ratio	A/C mode	Reference
1998	Copenhagen, Denmark	June	Total dust	bicycle/car	68/104	0.65	non-A/C	Rank *et al.,* 2001
		August	Total dust	bicycle/car	21/47	0.45	non-A/C	
1999	London, UK	July	$PM_{2.5}$	bicycle/car	30.7/35	0.88		Adams *et al.,* 2001
			$PM_{2.5}$	bicycle/bus	30.7/34	0.90		
2000		February	$PM_{2.5}$	bicycle/bus	20.1/30.9	0.65		
			$PM_{2.5}$	bicycle/car	20.1/23.7	0.85		
2003	London, UK	April and May	$PM_{2.5}$	walking/bus	27.5/34.5	0.80		Kaur *et al.*, 2005
			$PM_{2.5}$	walking/car	27.5/38	0.72		
			$PM_{2.5}$	walking/taxi	27.5/41.5	0.66		
			$PM_{2.5}$	bicycle/bus	33.5/34.5	0.97		
			$PM_{2.5}$	bicycle/car	33.5/38	0.88		
			$PM_{2.5}$	bicycle/taxi	33.5/41.5	0.81		
2005	London, UK	May and June	Coarse	walking/car	27.56/5.87	4.7	Moderate A/C	Briggs *et al.,* 2008
			$PM_{2.5}$	walking/car	6.59/3.01	2.19	Moderate A/C	
			Very fine	walking/car	3.37/1.82	1.85	Moderate A/C	
2005	Taipei, China		PM_{10}	motorcycle/car	112.8/41.9	2.69		Tsai *et al.,* 2008
			PM_{10}	motorcycle/bus	112.8/70	1.61		
			PM_{10}	motorcycle/metro	112.8/64.9	1.74		
			$PM_{2.5}$	motorcycle/car	67.5/22.1	3.05		
			$PM_{2.5}$	motorcycle/bus	67.5/38.5	1.75		
			$PM_{2.5}$	motorcycle/metro	67.5/35	1.93		
			PM_1	motorcycle/car	48.4/16.2	2.99		
			PM_1	motorcycle/bus	48.4/31.3	1.55		
			PM_1	motorcycle/metro	48.4/26.5	1.83		
2010–2011	Beijing, China	December and February	$PM_{2.5}$	bicycle/taxi	49.10/31.64	1.55	A/C	Huang *et al.*, 2012
				bicycle/bus	49.10/42.40	1.16	Mostly A/C	
2011	Foshan, China	June	$PM_{2.5}$	on-roadway mode/bus	68.4/22.1	3.10	Mostly A/C	This study
			$PM_{2.5}$	on-roadway mode/taxi	68.4/18.2	3.76	A/C	
			$PM_{2.5}$	on-roadway mode/taxi	68.4/38.1	1.80	non-A/C	
			$PM_{2.5}$	on-roadway mode/metro	68.4/25.1	2.73	A/C	
		March and April	$PM_{2.5}$	on-roadway mode/bus	79.1/93.1	0.85	Mostly non-A/C	
			$PM_{2.5}$	on-roadway mode/taxi	79.1/42.4	1.87	A/C	
			$PM_{2.5}$	on-roadway mode/taxi	79.1/87.4	0.91	non-A/C	
			$PM_{2.5}$	on-roadway mode/metro	79.1/30.3	2.61	A/C	

$PM_{2.5}$ exposure level as mentioned above. The cumulative probability distributions of taxi $PM_{2.5}$ exposure (Fig. 2) showed that turning points were observed at the ~90% (79 $\mu g/m^3$) and ~83% (27 $\mu g/m^3$) of $PM_{2.5}$ concentrations in A/C mode for spring and summer, respectively. The variations of $PM_{2.5}$ exposure levels above the turning points were notably larger (spanning from ~79 to ~150 $\mu g/m^3$ in spring and from ~27 to ~47 $\mu g/m^3$ in summer). If we defined these concentrations (79 $\mu g/m^3$ in spring and 27 $\mu g/m^3$ in summer) as the thresholds of pollution episodes, we can find that in non-A/C mode, approximately 70% cases were pollution episodes in both spring and summer. This suggested that usage of A/C mode was an effective approach to reduce exposure levels, under which at least 83% cases were non-episode cases.

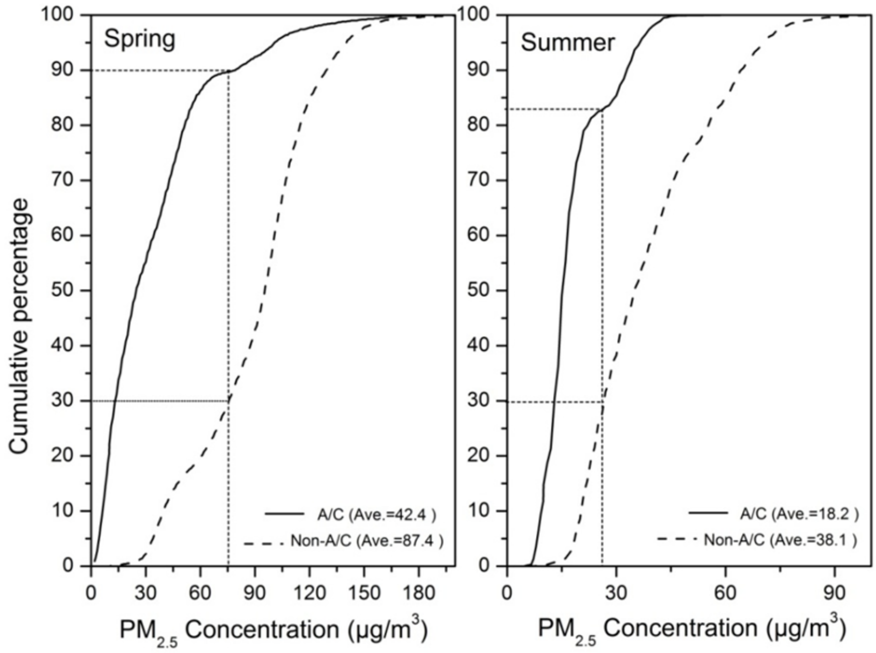

Fig. 2. The cumulative probability distributions of taxi exposure concentrations (one-minute averages) for A/C mode and non-A/C mode.

Relationship with $PM_{2.5}$ Concentration from AMS

As shown in Table 1, lower $PM_{2.5}$ concentration in summer can be found in AMS and six commute modes, highlighting the relationship between background pollution level and commuter exposure levels. In fact, measurements from AMS have been commonly used as surrogates for personal exposure levels to represent community exposure to pollutants such as $PM_{2.5}$ and CO in epidemiological and risk assessments. A large number of studies have revealed a good relationship between AMS and commuting exposure to $PM_{2.5}$ (Dennekamp *et al.*, 2002; Knibbs *et al.*, 2010; Wang and Oliver Gao, 2011), indicating that $PM_{2.5}$ concentration of urban background could be a good predictor of community exposure. In this section, their relationships would be simply quantified by linear regression method.

As expected, significant correlations between AMS concentration and exposure levels were found for most commute modes, suggesting the regression equations were able to predict the dependent variable (i.e., exposure level) by the independent variable (i.e., AMS $PM_{2.5}$ concentration) (Table 3). The small regression slopes of taxi (A/C) and metro suggested that usage of A/C can prevent the impacts from outside environment, and thus reduce in-cabin exposure level. On the other hand, the large regression intercepts in the regression equations for three on-roadway modes (ranging from 31.2 to 40.8 μg/m^3) implied that these three commuting modes were more influenced by their own microenvironment, which may be due to the direct exposure to traffic emission source and lack of mitigation measures (such as closing windows and turning on A/C in in-cabin mode). Although the metro system was assumed to be more independent, the correlation (R^2 = 0.52) between its exposure level and $PM_{2.5}$ concentration in urban background was found, which was probably because of the influences of ventilation system, passenger movement, station escalator tunnels and corridors (Braniš, 2006; Cheng *et al.*, 2008; Cheng and Lin, 2010; Kam *et al.*, 2011).

Overall, these results indicated that, although commuters moved around on the road surface, personal exposure was still affected by urban ambient pollutions besides traffic-related emission. Considering ambient $PM_{2.5}$ level was affected by meteorological condition, it is worthwhile to assess how meteorological parameters influence on exposure level.

Role of Meteorological Parameters

As mentioned previously, significant reductions of ambient $PM_{2.5}$ concentration and commuter exposure levels were observed in summer (Table 1). In this region, northerly continental monsoon and southerly maritime monsoon dominate in spring and summer respectively (not shown), which leads to significant differences in the meteorological parameters between these two seasons. Apart from the cleaner air mass from marine, the lower $PM_{2.5}$ level in summer was attributed to high temperature and wind speed in summer, which indicated a meteorological condition favorable for the dispersion and scavenging of airborne particulate matter. Detailed causes and influences of this seasonal pattern have been investigated by Wan *et al.* (2011). Previous studies have also found that there was a significant relationship between commuter exposure and wind speed (Kingham *et al.*, 1998; Alm *et al.*, 1999) and temperature (Zagury *et al.*, 2000; Kaur *et al.*, 2006). A detailed analysis on time-series (Fig. 3) showed that higher $PM_{2.5}$ exposure levels were always concurrent with lower wind speed and temperature. This further emphasized the role of meteorological parameters on both $PM_{2.5}$ concentrations from AMS and commuter exposure levels.

Table 3. Summary of regression models between $PM_{2.5}$ exposure in different modes and $PM_{2.5}$ concentration from the ambient air monitoring stations (AMS).

	AMS				
	Slope (μg/m^3 per μg/m^3)	Intercept (μg/m^3)	R^2	*p*	*n*
Bus	1.59	3.02	0.64	0.001	101
Taxi (non-A/C)	1.09	26.14	0.56	0.010	30
Taxi (A/C)	0.48	14.70	0.45	0.030	23
Metro	0.23	18.26	0.52	0.020	33
Walking	0.68	40.79	0.37	0.060	54
Bicycle	0.94	31.24	0.47	0.005	34
Motorcycle	0.91	34.22	0.53	0.001	35

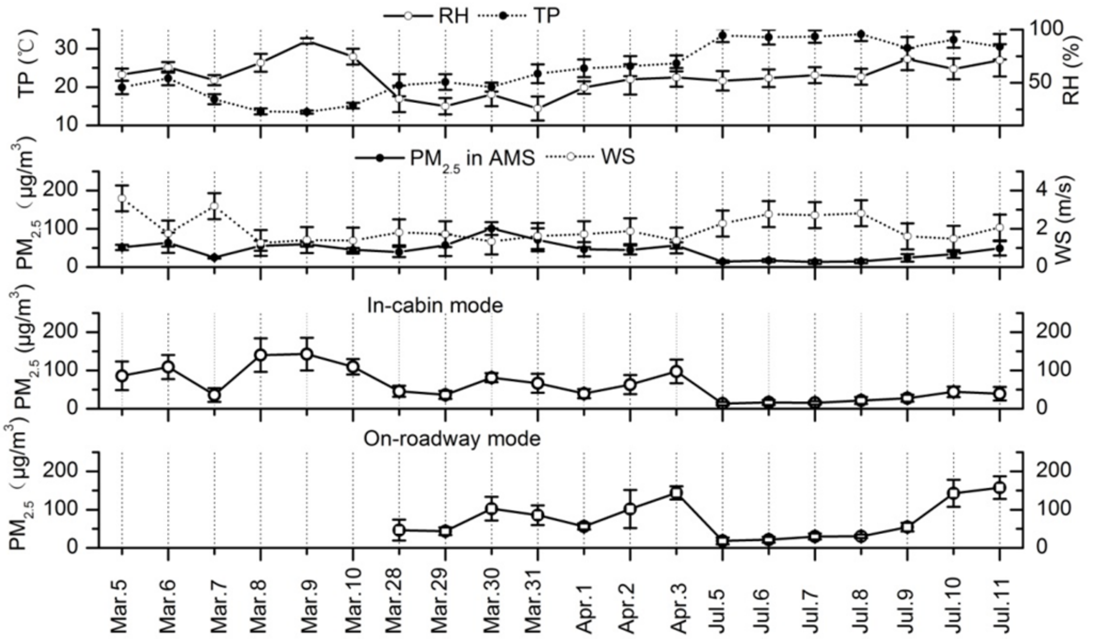

Fig. 3. Time-series of daily average $PM_{2.5}$ concentrations in ambient air monitoring stations (AMS), in-cabin mode and on-roadway mode, as well as wind speed (WS), relative humidity (RH) and temperature (TP) throughout the sampling period.

Pearson correlation coefficients between meteorological parameters and commuter exposure were calculated and shown in Table 4. Exposure levels of six commute modes (with the exception of taxi with non-A/C mode, r = –0.14, p = 0.48) were negatively correlated with wind speed ($p < 0.05$). In contrast, only exposure levels of bus and taxi were negatively correlated with temperature ($p < 0.05$). These results emphasized the role of high wind speed and temperature on reducing $PM_{2.5}$ level by enhancing dispersive capability of the atmosphere (via mechanical and thermal turbulence respectively). Given that on-roadway modes were more influenced by very local traffic emission (as suggested in previous section), the absence of correlation between exposure levels of on-roadway modes and temperature however implied that thermal turbulence might be unable to reduce the concentration of street $PM_{2.5}$ emitted by traffic sources. Relative humidity was found to be positive correlated with exposure levels of bus, taxi (non-A/C mode) and walking ($p < 0.05$), which can be also observed in the time series (Fig. 3). Similar results were also reported in other personal exposure (Adams *et al.*, 2001) and ambient air pollution study (Barman *et al.*, 2008). The positive correlations were probably due to that high relative humidity would accelerate the formation of secondary species such as sulfate and nitrate from their precursors (SO_2 and NO_x) (Sun *et al.*, 2006).

It is also worthwhile to point out that wind direction is one of the most important variables to determine the air pollution level. Although limited studies were focused on the influence of wind directions on commuter exposure, distinct pattern of exposure levels in different wind direction sectors was found in this study (Fig. 4). Higher $PM_{2.5}$ exposure levels in both in-cabin and on-roadway mode were found in northwesterly and southeasterly wind sectors. In this region, pollution episodes were always found when northwesterly wind was prevailing, because it was marked by weak regional flow with calm condition or with weak prevailing winds (Fig. 4) and directly affected by emission source in the northwest PRD (more specifically, agricultural activities in rural region). However, such cases were very rare (Fig. 4), and typically only occur when this region was influenced by tropical cyclones (Chan and Chan, 2000; Zhang *et al.*, 2010; Lin *et al.*, 2012). On the other hand, the

Table 4. Correlations between meteorological parameters and $PM_{2.5}$ exposure level in traffic modes.

	Bus *n = 101*	Taxi (non-A/C) *n = 30*	Taxi (A/C) *n = 23*	Metro *n = 33*	Walking *n = 54*	Bicycle *n = 34*	Motorcycle *n = 35*
Temperature	**–0.73****	**–0.59****	**–0.52***	–0.10	–0.07	–0.16	–0.29
Relative humidity	**0.46****	**0.54****	0.31	0.24	**0.54****	0.35	0.35
Wind speed	**–0.29****	–0.14	**–0.45***	**–0.38****	**–0.32****	**–0.49****	**–0.39****

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

elevated $PM_{2.5}$ concentrations observed in southeasterly wind sectors were likely due to large $PM_{2.5}$ emission in its upwind region (i.e., Dongguan, Zhongshan and Shenzhen) (Fig. 4 in Zheng *et al.*, 2009).

Determination of Influence Factors on Commuter Exposure

In the GLM analysis, common logarithmic concentration of personal exposure was regarded as dependent variable, commuting modes and wind directions were regarded as fixed factor variables. Regarding the covariate variable, wind speed and temperature were selected for in-cabin mode, while relative humidity and wind speed were chosen for on-roadway mode. With an aim to quantify the impact of A/C mode, taxi mode was specifically selected as dependent variable to perform another GLM analysis, in which A/C mode was selected as the fixed factors. Because AMS concentration was highly affected by meteorological parameters, it was not included in this study to prevent any possible duplication. The R^2 values presented in Table 5 indicated the proportion of the total variability in the exposure levels that was accounted for the variation in the independent and covariate variables.

Temperature was the most important significant factor for in-cabin mode explaining 20.9% of the variation. Contributions of commuting mode and wind speed were also significant, which accounted 3.9% and 2.5% of the total variation, respectively. In contrast, wind speed and relative humidity contributed 6.8% and 7.3% of the variation for on-roadway mode. For taxi mode, A/C mode and temperature explained 14.1% and 11.0% of the variation, respectively, which once again brought out the importance of A/C mode on the exposure levels in taxi as pointed out earlier. Wind direction also contributed high variation for both in-cabin and on-roadway modes, although it failed to reach 0.05 significance level, which was probably attributed to the high degrees of freedom (Table 5). Note particularly that if only 8 dominant wind directions (with percentage approximately 73%) were selected, the contributions of wind direction for both in-cabin and on-roadway mode would be significant at 0.10 significance level (not shown).

Although the contribution of temperature to $PM_{2.5}$ exposure level was scarcely quantified by previous studies, Kaur *et al.* (2006) and Kaur and Nieuwenhuijsen (2009) did find a large portion of temperature (22% and 12%, respectively) in variability of personal exposure of ultrafine particle counts. Contribution to the variation of commuter exposure from wind speed found here was much smaller than those in other studies. For instance, Adams *et al.* (2001) found that wind speed explained approximately 18% of the variance in $PM_{2.5}$ exposure in on-roadway mode. Zagury *et al.* (2000) reported that wind speed explained 39% of the variability of the black smoke concentrations inside the vehicles. Mode of transport was also a significant factor, explaining 6% of the variance in $PM_{2.5}$ exposure, in Adams *et al.* (2001), which was more or less similar to this study. Although few studies focused on the contributions from relative humidity and wind direction, our results implied that these factors might be important determinants in exposure levels.

In summary, the difference of influence factors on in-cabin and on-roadway modes might be due to the different features of transportation modes. For instance, commuters were directly exposed to the atmosphere for on-roadway transportations, while in-cabin mode users can close windows and turn on A/C to prevent this direct exposure. In particular, commuting mode was a significantly determining factor for in-cabin mode, but not for on-roadway mode, indicating in-cabin mode users can reduce their $PM_{2.5}$ exposure levels by selecting different modes. Although the meteorological parameters exert significant effects on the personal exposure levels for both in-cabin and on-roadway modes, commuters can do little to change these factors. In any case, they may refer to the meteorological data released by government to choose the appropriate travel time. City designers could also try to allow more airflow through the city for reducing pollution levels.

CONCLUSIONS

A series of field studies were carried out to measure commuter exposure to $PM_{2.5}$ on six major commuting modes in an industrial city in the PRD, China. Significant differences of $PM_{2.5}$ levels were found between in-cabin and on-roadway modes. Due to the isolation between in-cabin mode and vehicle emission on the road, exposure levels in in-cabin mode were notably lower. This result was different from those in earlier studies, highlighting the improvement of automobile manufacturing, ventilation technology and filtration efficiency in recent years. Actually, the $PM_{2.5}$ exposure level for in-cabin mode was significantly lower in A/C mode, suggesting that commuters can reduce their exposure via choosing in-cabin mode with turning on the A/C and closing windows. Significant seasonal differences were found between spring and summer, which highlighted the impacts of meteorological parameters. The results from Pearson correlation and GLM analysis implied that the impacts of meteorological parameters on different commuter modes were different.

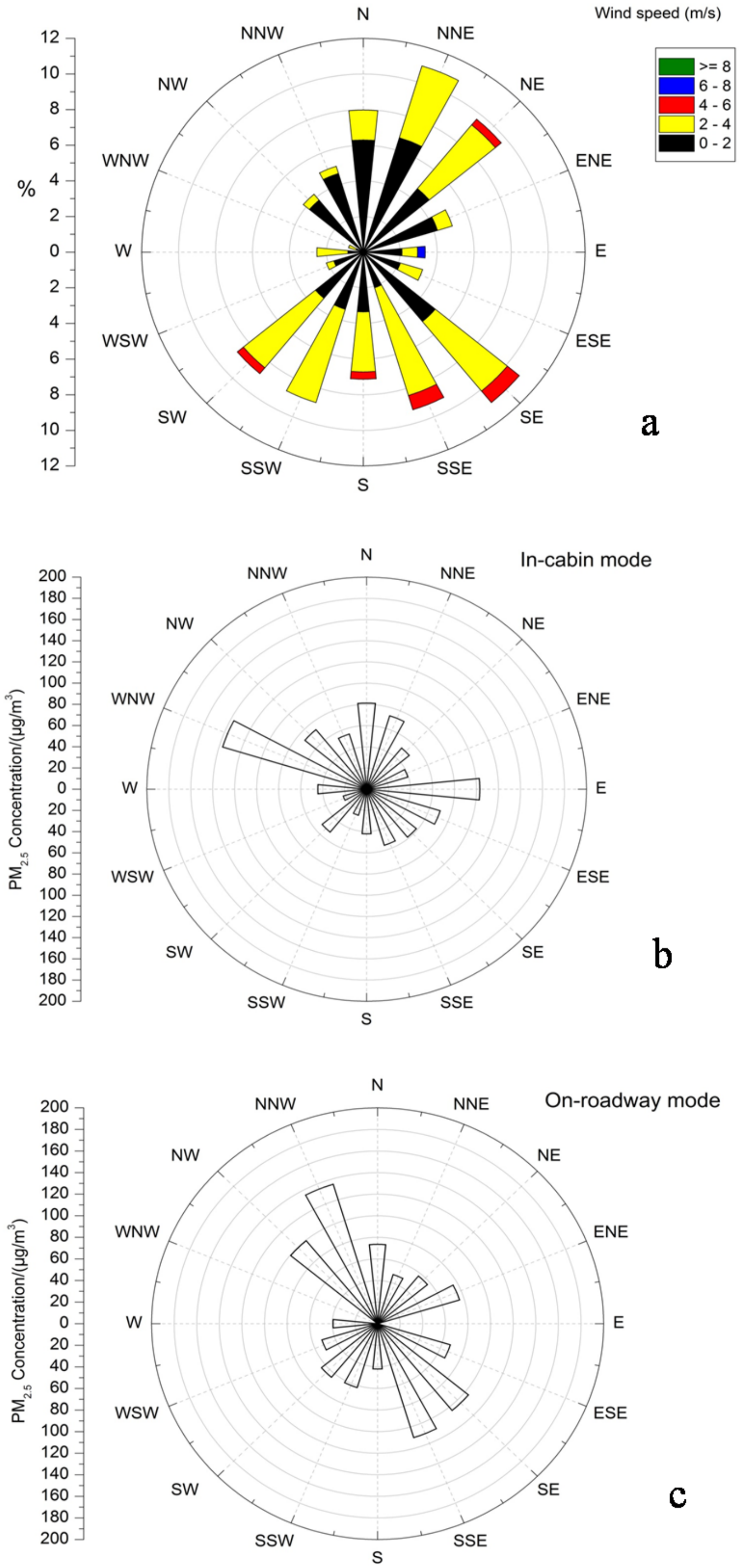

Fig. 4. (a) Wind roses, $PM_{2.5}$ concentrations of (b) in-cabin mode and (c) on-roadway mode vs. wind direction sectors during the sampling period.

Table 5. Summary of the General Linear Model (GLM) results.

	df[a]	MS[b]	*F* value	*p*	R^2
In-cabin mode, n = 187, R^2 = 0.54					
Mode	2	0.48	7.95	0.001	0.039
Wind direction	15	0.09	1.50	0.112	0.056
Temperature	1	5.06	84.76	< 0.001	0.209
Wind speed	1	0.61	10.28	0.002	0.025
On-roadway mode, n = 121, R^2 = 0.22					
Mode	2	0.001	0.03	0.974	< 0.001
Wind direction	13	0.083	1.46	0.153	0.124
Relative humidity	1	0.64	11.13	0.001	0.073
Wind speed	1	0.59	10.39	0.002	0.068
Taxi mode, n = 53, R^2 = 0.45					
A/C mode	1	0.714	13.44	0.001	0.141
Wind direction	12	0.048	0.90	0.56	0.113
Temperature	1	0.558	10.50	0.003	0.110
Wind speed	1	0.085	1.60	0.216	0.017

[a] *df*: Degrees of freedom.
[b] MS: Mean squares.

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