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Characterization of Ultrafine Particles  
and Other Traffic Related Pollutants  
Near Roadways in Beijing

A thesis submitted in partial satisfaction  
of the requirements for the degree Master of Science  
in Environmental Health Sciences

by

Xiaosen Xie

2012



## ABSTRACT OF THE THESIS

### Characterization of Ultrafine Particles and Other Traffic Related Pollutants Near Roadways in Beijing

by

Xiaosen Xie

Master of Science in Environmental Health Sciences

University of California, Los Angeles, 2012

Professor Yifang Zhu, Chair

The mass concentrations of PM<sub>2.5</sub> (particles with aerodynamic diameter < 2.5 μm), number concentration of ultrafine particles (UFP, particles with aerodynamic diameter < 100 nm), concentrations of carbon dioxide (CO<sub>2</sub>), as well as mass concentrations of black carbon (BC, results from incomplete combustion of fossil fuels and biomass, usually consists of several linked carbon atoms, commonly referred to as “soot”) were measured near the Peking University (PKU) campus in Beijing from December 10<sup>th</sup> to December 23<sup>rd</sup>, 2011. Correlation between UFP number concentrations and PM<sub>2.5</sub> mass concentrations, as well as PM<sub>2.5</sub> mass concentrations and BC mass concentrations were determined while taking into consideration the local meteorological conditions and traffic densities determined from recorded video footage. Traffic emissions were calculated using ultrafine particle number concentration (PNC) and CO<sub>2</sub>

concentrations. The PM<sub>2.5</sub> mass concentration, PNC, BC mass concentration as well as calculated traffic emission data were compared with existing data for the Los Angeles metropolitan region. The differences and similarities between the two data sets were compared and discussed.

No correlation was found between PNC and PM<sub>2.5</sub> mass concentrations. However, a high correlation between BC and PM<sub>2.5</sub> mass concentrations was found. Also, correlations were identified between local meteorological conditions such as wind direction and PNC, PM<sub>2.5</sub>, and BC mass concentrations near roadways, especially when the site was downwind of local traffic. No correlation was found between wind speed and PNC, although strong correlations were found between wind speed and PM<sub>2.5</sub>, as well as BC mass concentrations. Days where both PM<sub>2.5</sub> mass concentrations and PNC were higher at the control site were observed to be wind direction dependent, indicating the detection of regional emission sources. A strong correlation between PM<sub>2.5</sub> mass concentrations and local visibility was also demonstrated. In terms of traffic, total traffic had almost no correlation with PNC. However, total diesel traffic was found to have some correlation to PNC, with higher diesel vehicle volume correlating to higher PNC. Finally, from the comparison between Los Angeles and Beijing data sets, Beijing tends to have higher emission factors, as well as near roadway PNC and PM<sub>2.5</sub> mass concentrations, after controlling for wind direction.

Data generated from this study could be used to model near roadway exposures to PM<sub>2.5</sub> as well as UFP, especially from an occupational exposure standpoint for roadside workers such as food stand workers, traffic directing personnel, among others.

The Thesis of Xiaosen Xie is approved.

Shane S. Que Hee

Nola Kennedy

Yifang Zhu, Committee Chair

University of California, Los Angeles

2012

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The Los Angeles dataset was from a study conducted by Quiros et al in July 2011. The coauthors were David C. Quiros, Qunfang Zhang, Wonsik Choi, Meilu He, Suzanne E. Paulson, Arthur W. Winer, Rui Wang, and Yifang Zhu. The manuscript from the study has been submitted to Environmental Science and Technology for review and is pending publication as of the submittal of this thesis. The above coauthors were responsible for all data gathering and analysis during the study period, and Yifang Zhu was the Principle Investigator (PI). Raw data from the July 2011 Los Angeles study was obtained from David C. Quiros with permission for analysis and comparison in the current study.

## CHAPTER 1: INTRODUCTION

Previous studies have demonstrated a link between vehicle traffic density and PM<sub>2.5</sub>, UFP, and BC concentration levels (Harrison et al, 1997, Shi et al, 1999, Querol et al, 2001, Cyrus et al, 2003, Zhu et al, 2002 & 2006), as well as meteorological conditions and their influence on local and regional air quality parameters in both Los Angeles (Lu & Turco, 1994, Pakbin et al, 2010) and Beijing (Streets et al, 2006). Particulate pollution has also been linked to adverse health outcomes, particularly respiratory and cardiovascular diseases (Xu & Wang, 1993, Dockery & Pope, 1995, Schwatz & Neas, 1999, Schulz et al, 2005). These diseases are prevalent in developing countries such as China (Gu et al, 2005, Liu et al, 2007), where air pollution levels are often orders of magnitude higher than those in developed countries such as the United States and European nations (Chan & Yao, 2007). Recent studies on UFP have shown that they may be particularly damaging to human health due to their ability to penetrate deeper into the lung and induce oxidative stress in deep lung tissue (Oberdorster, 2000, Donaldson et al, 2002, Li et al, 2003, Renwick et al, 2004). To date, regulations in both developing and developed countries still focus on PM<sub>2.5</sub> and PM<sub>10</sub> mass based standards which are inadequate for protection against adverse health outcomes associated with exposures to traffic emissions (Wichmann & Peters, 2000), particularly because from a number based standpoint, the majority of traffic emitted particulates are in the ultrafine range.

PM<sub>2.5</sub> particles could be generated in the atmosphere from secondary aerosol formation, however, both PM<sub>2.5</sub> and UFPs are also emitted by various types of vehicles and other combustion sources, but diesel trucks and buses have higher emission profiles for PM<sub>2.5</sub> and UFPs, as well as BC (Gertler, 2004, Ban-Weiss et al, 2007). BC is generated from any type of combustion of fuels such as from biomass burning and vehicle exhaust. It is also a marker for

diesel exhaust from an exposure assessment standpoint (Fruin et al, 2004). PM<sub>2.5</sub> sources in the Los Angeles region are dominated primarily by secondary nitrate, secondary sulfate, vehicular gasoline, and diesel emissions, low percentages of airborne soil and sea salt are also present (Kim & Hopke, 2007, Kim et al, 2010). In terms of UFPs, particular attention has been paid to traffic generated UFP levels in Los Angeles. Various studies have shown higher PM<sub>2.5</sub>, BC and UFP generated from diesel engines compared to gasoline engines (Geller et al, 2006, Toner et al, 2007, Wang et al, 2007), as well as an association between heavy diesel truck volume and higher UFP concentrations on or near roadways (Kittelson et al, 2003, Westerdahl et al, 2005, Zhu et al, 2008). Also, due to the topography around Los Angeles, as well as the fact that Los Angeles is in a coastal environment with mountainous regions nearby, the local traffic generated pollutants tend to stay in the region and thus affecting local air quality (Lu & Turco, 1994, Pakbin et al, 2010); this suggests that much of the pollution of the Los Angeles basin area is locally generated. In Beijing, however, due to its geographic location near a desert region and the prevailing winds, silica dust is the highest contributor to PM<sub>2.5</sub> sources, followed by secondary nitrate, sulfate, and vehicular exhaust from both gasoline and diesel sources, coal burning sources, biomass burning sources, with cigarette smoke as the lowest contributor (Zheng et al, 2005). The carbonaceous portion (both organic and inorganic) of PM<sub>2.5</sub> in Beijing was found to have wide seasonal differences between winter and summer months; with coal combustion being a major contributor during the winter, and biomass burning, traffic as well as industry emissions being the major contributors during the summer months (Dan et al, 2004). PM<sub>2.5</sub> has also been linked to decreased visibility during haze and fog episodes in Beijing, as well as being heavily affected by meteorological conditions (Feng et al, 2005, Sun et al, 2006).

The air quality in Beijing can change dramatically from day to day, depending on meteorological conditions, as the air quality in Beijing is significantly affected by regional as well as local sources. It is estimated that on average 34% of PM<sub>2.5</sub> particulates originate from regional sources in neighboring provinces, as well as 35 – 60% of ozone (Streets et al, 2006). In terms of BC sources in Beijing, gasoline & diesel exhaust are both high contributors (Wang et al, 2009). There is also evidence that soil sample BC levels are higher from rural sites than from the inner city in Beijing (Liu et al, 2011), indicating higher BC pollution levels in the inner city. In terms of UFPs, studies conducted during the 2008 Beijing Olympics has shown that government action in reducing and restricting the number of vehicles in the city during the games, especially heavy polluting diesel trucks, significantly decreased UFP concentrations compared to data gathered in the previous year (Wang et al, 2009).

It is important to note that in terms of occupational exposures in Beijing, there are several vulnerable populations that may suffer disproportionately larger exposure compared to the average population to near road pollutants such as ultrafine and PM<sub>2.5</sub> particulates. It was observed that many low income roadside food stand workers operate their businesses during both morning and afternoon rush hours, with some operating into late night. These food stand workers are also exposed to cooking emissions on top of traffic and ambient air pollutant emissions. Other observed vulnerable populations are traffic regulating personnel at busy intersections, other civil servants such as road sweepers/cleaners, and private security guards for universities such as PKU and other institutions, whose duties include standing guard near school gates for extended periods of time.

Transportation behavior also differs greatly between residents of Beijing and Los Angeles. In Los Angeles, the most prevalent transportation mode is by personal vehicles. However, in

Beijing, despite the fact that car ownership has sky-rocketed over the last decade, public transportation, including taxis, buses and the subway system remain widely used. Other popular intra-city transportation tools include bicycles and electric mopeds. However, this wide use of various types of transportation methods would increase exposures to both UFP and PM2.5 for the average Beijing citizen compared to residents of developed countries, as Beijing residents are on average more exposed to traffic emissions as well as ambient pollution. Figure 1 below illustrates a crowded bus stop at nearly 9 PM on a weekday night, which demonstrates high public transit usage at transit hubs.



**Figure 1:** Bus transit hub in Beijing

From December 10<sup>th</sup> to December 23<sup>rd</sup> of 2011, a total of 14 days of ambient stationary sampling was conducted in Beijing. In this study, vehicle densities as well as meteorological conditions were seen to influence PM2.5, UFP and BC concentrations. A comparison between PM2.5 mass, PNC, as well as traffic emission data between Beijing and Los Angeles were also conducted in this study.

## CHAPTER 2: STUDY OBJECTIVES

A short term ambient monitoring campaign was conducted on the PKU campus located in Beijing, China. The objective was to determine the correlation between UFP number concentration, PM<sub>2.5</sub> and BC mass concentrations; to assess meteorological effects such as wind speed and direction as well as effects of changing traffic densities on UFP, PM<sub>2.5</sub>, and BC concentrations, and finally, compare available data from a study conducted by Quiros et al. (2012) of roadside UFP number concentrations and PM<sub>2.5</sub> mass concentrations in Los Angeles to that of Beijing, and assess the differences and similarities between the two data sets.

The specific research aims were: 1.) To analyze temporal and spatial variations of UFP number concentrations, PM<sub>2.5</sub> mass concentrations, as well as BC concentrations. 2.) Assess and attempt to explain the correlation or lack of correlation between PNC and PM<sub>2.5</sub> mass concentration as well as between BC and PM<sub>2.5</sub> mass concentration. 3.) Assess the effects of meteorological effects such as wind speed and wind direction on PNC as well as PM<sub>2.5</sub> mass concentrations. 4.) Analyze the effects of varying traffic densities of both total traffic densities and diesel bus densities on PNC. 5.) Compare PNC, PM<sub>2.5</sub> mass concentration, and vehicle emission factors between the Beijing study and similar data gathered in Los Angeles in July of 2011. 6.) Discuss the possibility of using the data generated from this study to model near roadway occupational exposures.



## CHAPTER 3: EXPERIMENTAL METHODS

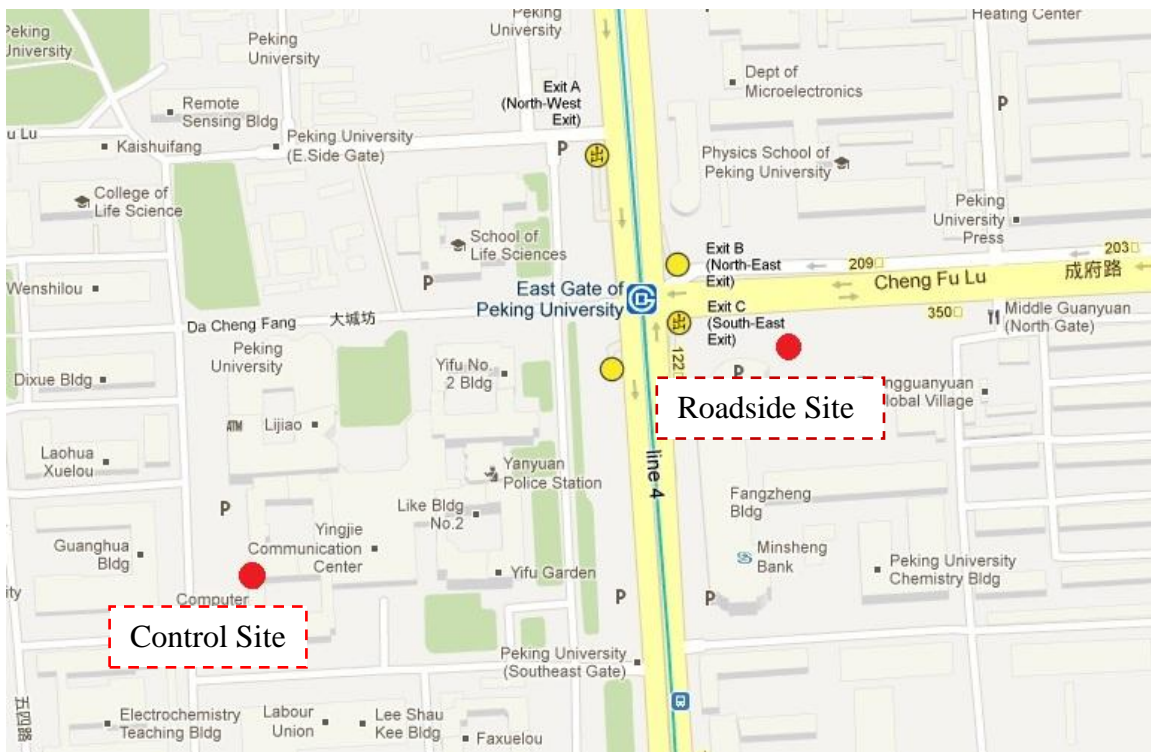
The stationary sampling in Beijing was conducted for fourteen days from December 10<sup>th</sup> to December 23<sup>rd</sup>, 2011 at two different sites located on the PKU campus; the control site was located on the roof of the six story computation center, a building located on the main campus, while the roadside site was located at a gate guard station located at the entrance to the PKU School of Chemistry. The roadside site is approximately 25 meters from the center of an intersection with heavy daily vehicle traffic, including light duty gasoline vehicles as well as heavy diesel trucks and buses. Beijing is a city of approximately 19.6 million residents with a total area of 6487 square miles (Xinhua News, 2010).

**Table 1:** Instruments used during study

<b>Instrument</b>	<b>Make &amp; Model</b>	<b>Target Constituent</b>
<b>CPC</b>	TSI Inc. 3775, 3785 & 3786	Particulate (>7nm diameter) Number Concentration
<b>Dust-trak</b>	TSI Inc. 8520	Particulate (w/ PM 2.5 adaptor) Mass Concentration
<b>Q-trak</b>	TSI Inc. 8552 Plus	Temperature, Relative Humidity, CO, & CO <sub>2</sub>
<b>Aethalometer</b>	Magee Scientific, AE-42	Black Carbon Mass Concentration

The same set of instruments listed in Table 1 above was set up at both stationary sampling sites (two red dots in Figure 2 below). The control site is located on the main PKU campus, while the roadside/downwind site is located near the T intersection where Chengfu Road terminates into Zhongguancun Road, as shown in Figure 2 below. The PKU School of Chemistry gate guard station is where the roadside site is located. The Dust-trak, Q-trak and Aethalometer were placed outdoors during sampling hours of 8 AM to 9 PM. The water-based CPC is placed within the guard station due to its temperature sensitive nature, and a length of TSI conductive tubing (to prevent particle loss in the tubing due to electrostatic charge) was used to connect the

sampling inlet on the instrument through a window to the outside environment (See Figure 3 & 4 below).



**Figure 2: Sampling map**



**Figure 3: Roadside/Downwind site CPC indoor setup**



**Figure 4:** Roadside/Downwind Site CPC Sampling Tube

The control site is located on the six-storey roof of the Peking University Computer Center Building, in an enclosed room with roof access. The Dust-trak and Q-trak were placed on the roof during the 8AM to 9PM continuous sampling period, and the CPC were located within the room with similar TSI conductive tubing connected to the sample inlet and extended to the outside ambient environment.

Half-hourly meteorological data such as wind speed and wind direction were gathered from a weather station located at/near the Beijing School for the Blind (AWS ID 545110, Latitude: +39.933, Longitude +116.283) and recorded in the database managed by the National Climatic Data Center (NCDC) of the US National Oceanic and Atmospheric Administration's (NOAA) Satellite and Information Services. This weather station is the closest to the study site and is located approximately 9 kilometers Southwest of PKU, and data generated there is assumed to be representative for the local meteorological pattern over the sampling period.

The TSI Dust-trak 8520 unit measures PM<sub>2.5</sub> mass concentrations averaged per minute of sampling time. The TSI Q-Trak 8552 Plus measures relative humidity in terms of percent, CO and CO<sub>2</sub> concentrations in parts per million (ppm), and temperature in Celsius (C) or Fahrenheit (F). The TSI Water-based CPC 3785 & 3786 are similar models that measure UFP number concentrations in number of particles per cubic centimeter of air. The Magee Scientific Aethalometer AE-42 measures BC mass concentrations averaged per minute of sampling time in nanograms (ng) per cubic meter of air. All instruments are within the manufacturer annual calibration. Data were downloaded each day immediately after the sampling period has ended.

For traffic density data at the roadside site, video recordings were made using commercial cameras set up with a tripod and stationed indoors at the guard station with the camera pointing towards the T intersection of Zhongguancun Road and Chenfu Road. Recordings were made for 5 minutes for every 15 minutes of continuous air sampling. Thus, for an hour of air sampling, a total of 20 minutes of recordings were made. The number of vehicles was then counted per minute from the recordings.

All the instruments were collocated to make sure there are no significant differences between the sets of instruments in terms of real time readings. This was done both prior to shipping the instruments from Los Angeles, as well as prior to the start of sampling on December 9<sup>th</sup> in Beijing at the control site.

## CHAPTER 4: RESULTS AND DISCUSSION

The basic descriptive statistics for PNC (from data recorded per second), PM2.5 mass concentration (from data recorded per minute), and for BC mass concentrations (from data recorded per minute) are shown in Table 2, below.

**Table 2:** Basic Descriptive Statistics of PNC, PM2.5, and BC

<b>Dustrak Data (PM2.5)</b>	<b>Control Site</b>	<b>Roadside Site</b>
<b>Mean (ug/m<sup>3</sup>)</b>	93.1	80.3
<b>Standard Deviation</b>	91.7	87.0
<b>Geo. Mean (ug/m<sup>3</sup>)</b>	55.5	49.0
<b>Geometric Std. Dev.</b>	2.87	2.66
<b>Minimum (ug/m<sup>3</sup>)</b>	3.00	9.00
<b>Maximum (ug/m<sup>3</sup>)</b>	585	1,170

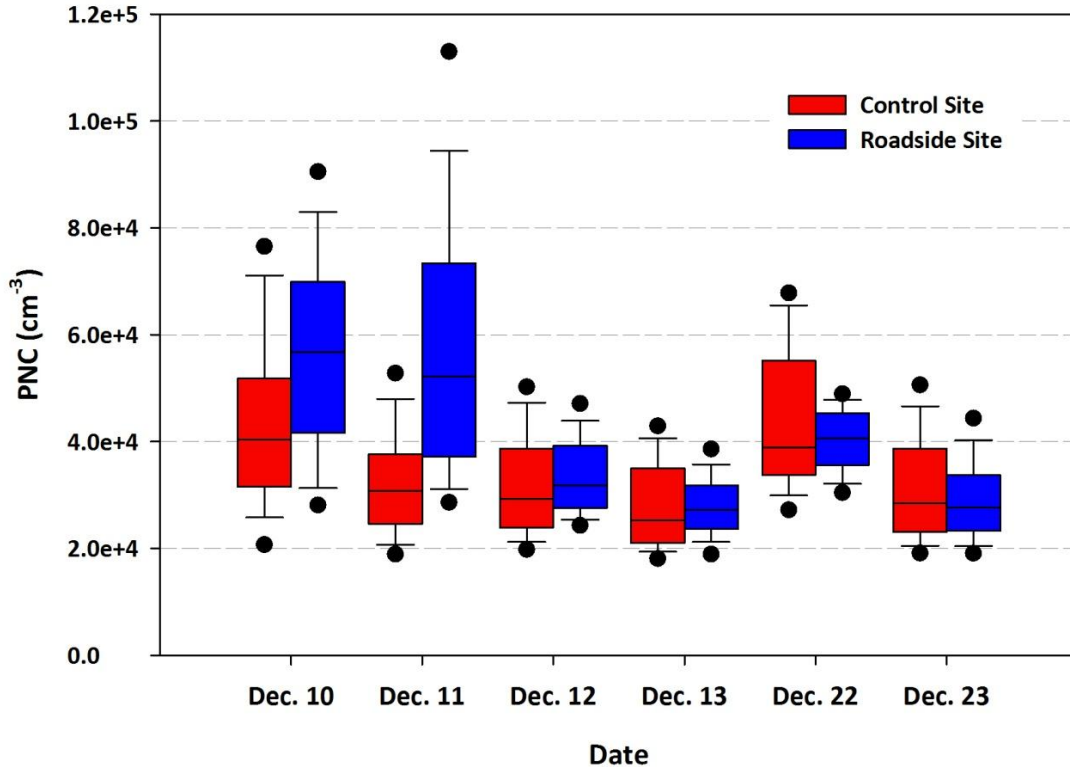
  

<b>CPC Data (PNC)</b>	<b>Control Site</b>	<b>Roadside Site</b>
<b>Mean (particle cm<sup>-3</sup>)</b>	36,200	36,100
<b>Standard Deviation</b>	12,000	19,300
<b>Geo. Mean (particle cm<sup>-3</sup>)</b>	34,300	32,300
<b>Geometric Std. Dev.</b>	1.38	1.59
<b>Minimum (particle cm<sup>-3</sup>)</b>	1,000	5,400
<b>Maximum (particle cm<sup>-3</sup>)</b>	113,000	220,000

<b>Aethalometer Data (BC)</b>	<b>Roadside Site Only</b>
<b>Mean (ug/m<sup>3</sup>)</b>	4.7
<b>Standard Deviation</b>	5.4
<b>Geo. Mean (ug/m<sup>3</sup>)</b>	3.0
<b>Geometric Std. Dev.</b>	2.6
<b>Minimum (ug/m<sup>3</sup>)</b>	0.1
<b>Maximum (ug/m<sup>3</sup>)</b>	190

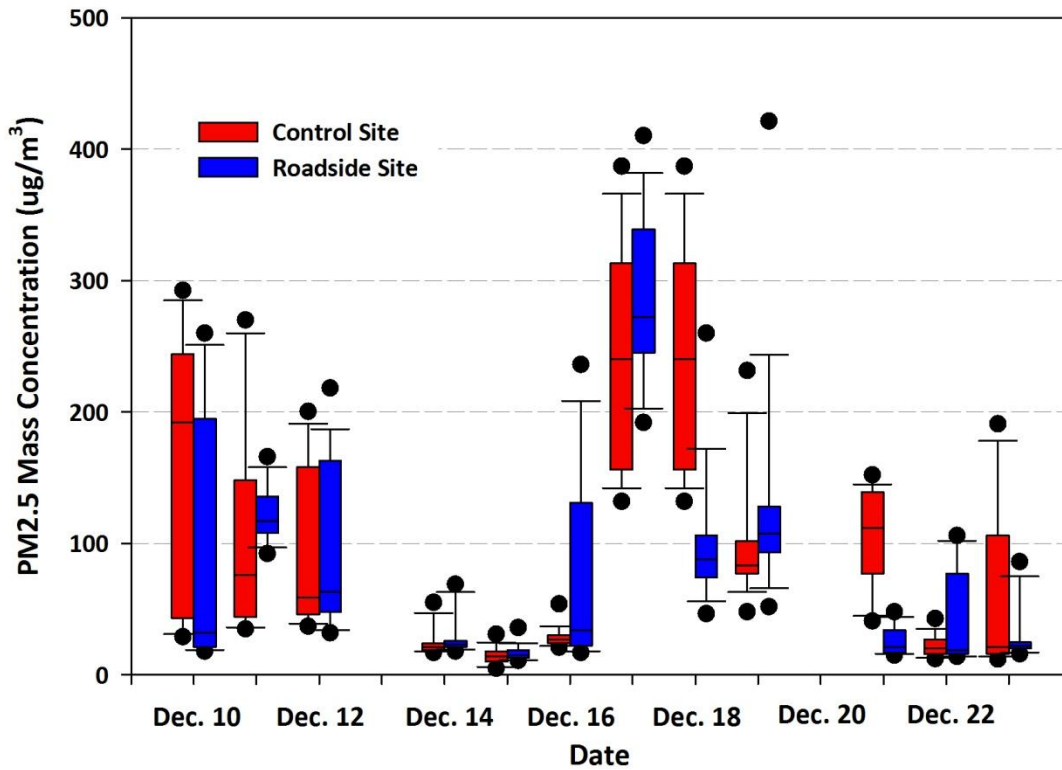
The daily PNC, PM<sub>2.5</sub> mass concentration, as well as BC mass concentrations are shown in Figures 5, 6, and 7, respectively, below.



**Figure 5:** Daily Particle Number Concentration (PNC) ranges of both the control and roadside sites

Figure 5, or the daily PNC for the control and roadside sites, demonstrates the high variability in ultrafine particle concentrations, especially at the roadside site. Interestingly, on December 10<sup>th</sup> and December 11<sup>th</sup> the PNC range is much higher at the roadside site compared to the control site; on December 12<sup>th</sup>, December 13<sup>th</sup>, December 22<sup>nd</sup>, and December 23<sup>rd</sup>, the concentration ranges are generally lower at the roadside site. During December 14<sup>th</sup> through December 21<sup>st</sup>, the roadside site CPC Model 3785 instrument suffered technical issues and was sent to the local Beijing TSI office for analysis, repair, and recalibration. The data gathered on December 22<sup>nd</sup> and 23<sup>rd</sup> were done using a TSI Model 3775 CPC loaned from the Beijing TSI

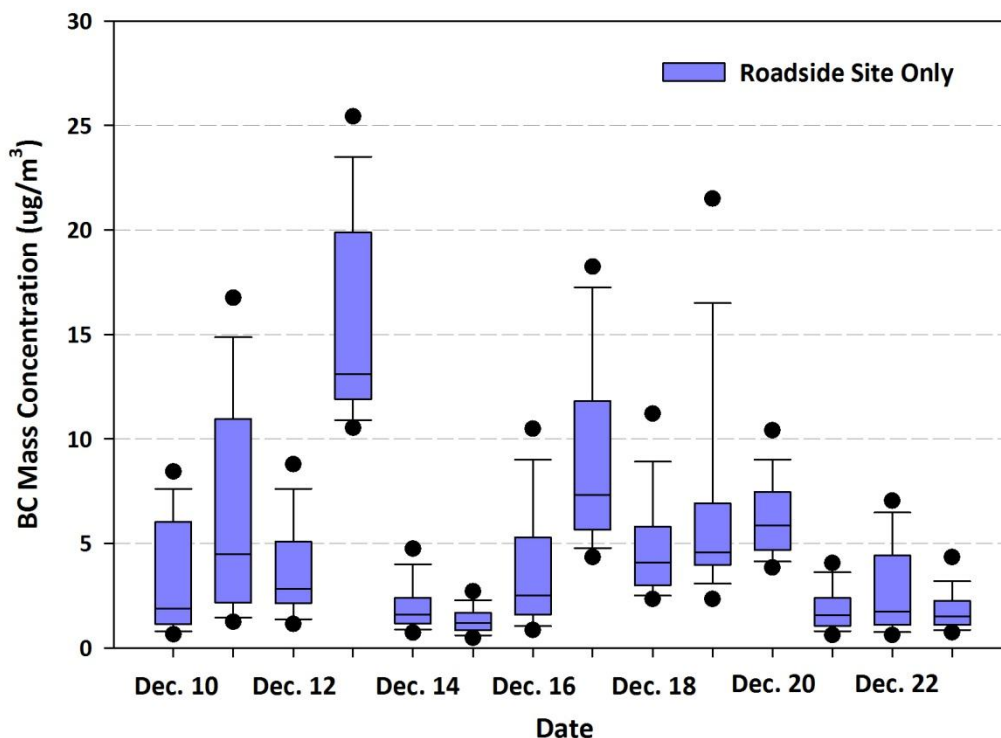
office. It is assumed that instrument variation between the Model 3775 CPC and the Model 3785 CPC are minimal, as the internal components are nearly identical. From the variations of the different sampling days, it can be inferred that the influence of other factors such as local and regional meteorological conditions as well as traffic densities could greatly influence PNC as well as PM<sub>2.5</sub> and BC mass concentrations, as shown in Figure 6 and 7 below, respectively.



**Figure 6:** Daily PM<sub>2.5</sub> mass concentration ranges of both the control and roadside sites

There is high variability during the sampling period for the PM<sub>2.5</sub> mass concentrations as well as BC concentrations. BC mass concentrations should be of particular concern in Beijing due to the high densities of diesel buses used for public transportation. It should be noted that BC mass concentrations in Figure 7 somewhat resembles those of PM<sub>2.5</sub> roadside mass

concentrations in Figure 6, perhaps indicating regional emission influences on BC mass concentrations due to meteorology.



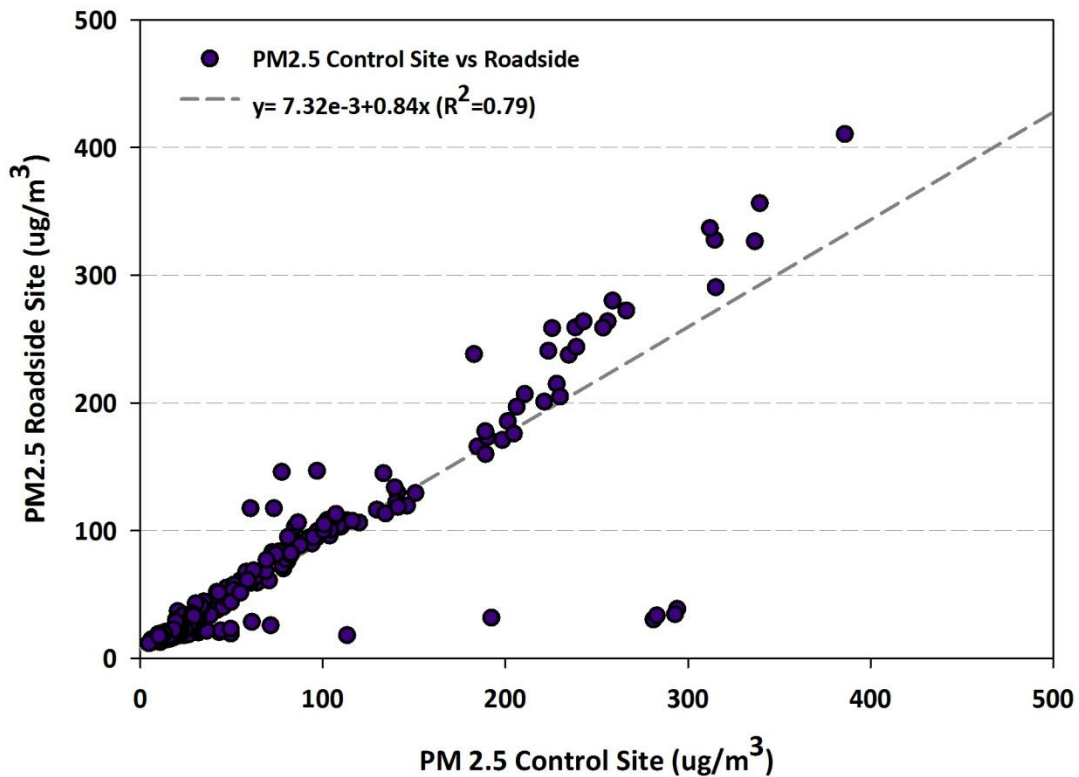
**Figure 7:** Daily BC concentration ranges of the roadside site

The relationship between PNC and PM<sub>2.5</sub> mass concentrations on days when the Model 3875 CPC at the roadside site was functioning normally, namely, December 10<sup>th</sup> through 13<sup>th</sup>, and December 22<sup>nd</sup> and 23<sup>rd</sup> were assessed for both the roadside site and the control site. Both the PNC and the PM<sub>2.5</sub> mass concentrations were averaged at 30 minute intervals for this analysis. However, no statistically significant results were found between PNC and PM<sub>2.5</sub> at both the control and roadside sites, even after controlling for the effects of wind direction ( $R^2=0.02$  and  $0.03$ , respectively). This indicates that PNC and PM<sub>2.5</sub> have no relationship. This result is not surprising considering that PNC is a number based air quality metric while PM<sub>2.5</sub> is



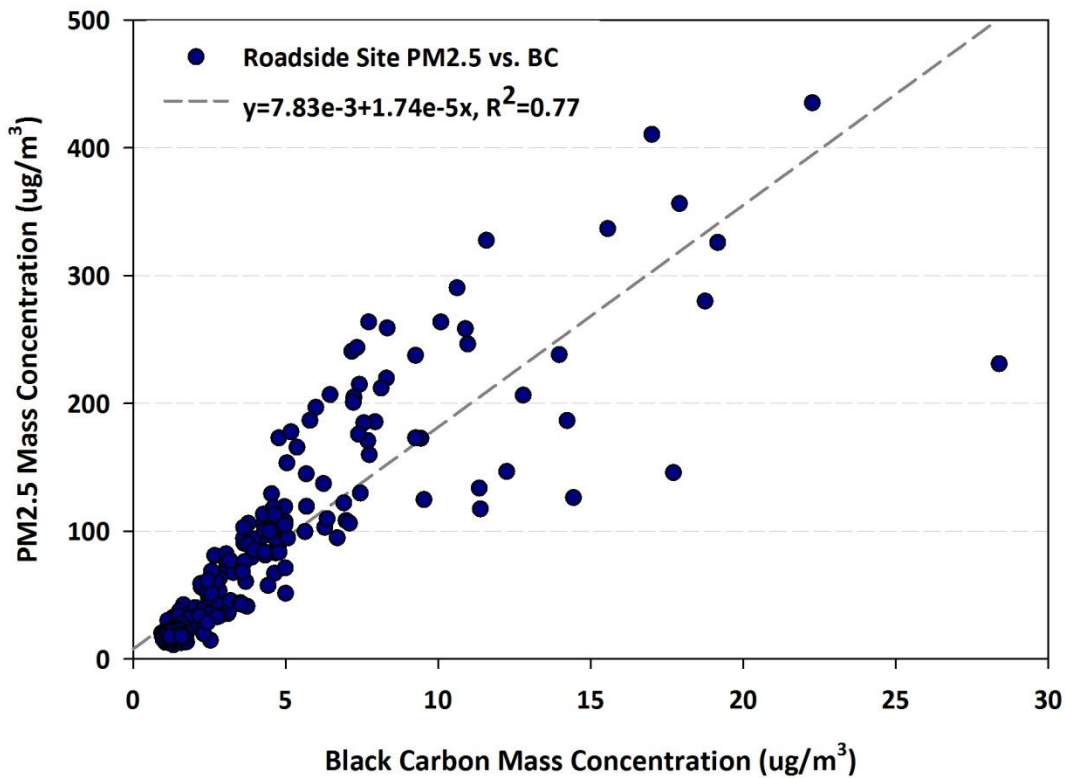
a mass based metric. Also, PM<sub>2.5</sub> has both local and regional source influences and is partially formed via secondary aerosol formation, while PNC measures the number concentration of UFP, which is heavily influenced by traffic.

PM<sub>2.5</sub> mass concentrations at the control site and the roadside site were also analyzed for association and were found to closely correlate with each other as shown in Figure 8 ( $R^2=0.79$ ). Interestingly, there are a several outliers indicating that the control site sometimes had significantly higher PM<sub>2.5</sub> mass concentrations compared to the roadside site, during these periods, the wind direction is predominantly from the west or northwest direction (270 – 360 degrees, see Figure 10), possibly indicating meteorology dependent regional influences from those wind directions on PM<sub>2.5</sub> mass concentrations.



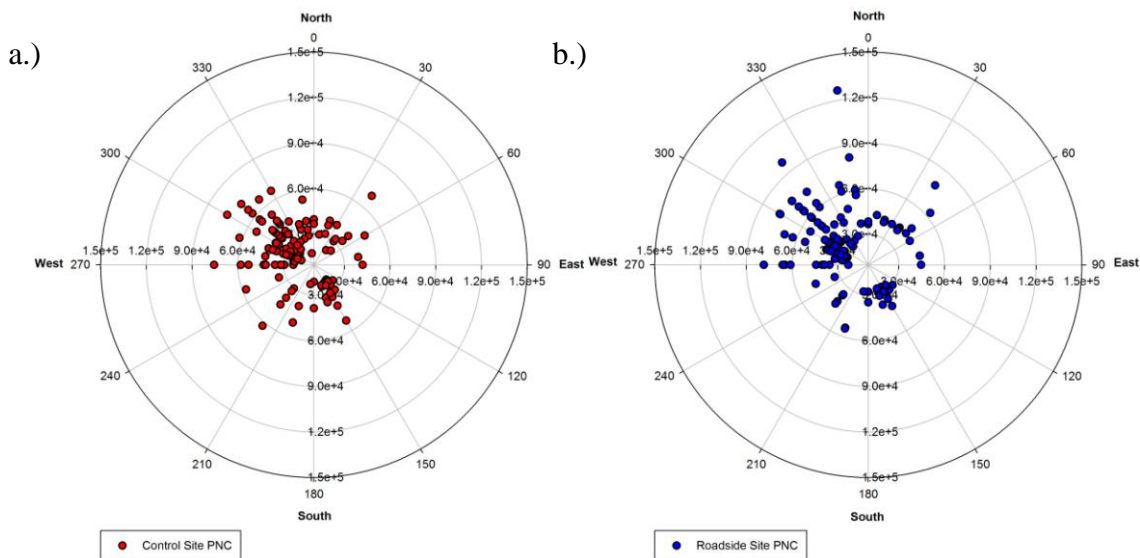
**Figure 8:** Correlation of PM<sub>2.5</sub> between control site and roadside site

The association between BC and PM2.5 mass concentrations at the roadside site was also assessed, as shown in Figure 9. Previous studies have shown strong correlations between PM2.5 and BC mass concentrations (Voiidanoja et al, 2002, Chaloulakou et al, 2003), and the present study has also shown a similarly high correlation between BC and PM2.5 mass concentrations. This result is not surprising based on previous studies in Beijing that showed higher regional influences on PM2.5 and BC from coal and other forms of fuel burning, especially in the winter months (Dan et al, 2004). Also, some of the BC associated with PM2.5 was due to traffic emissions. Both the BC and PM2.5 mass concentration data were averaged in half hour increments for both Figure 8 and Figure 9.



**Figure 9:** Correlation between PM2.5 and BC at the roadside site

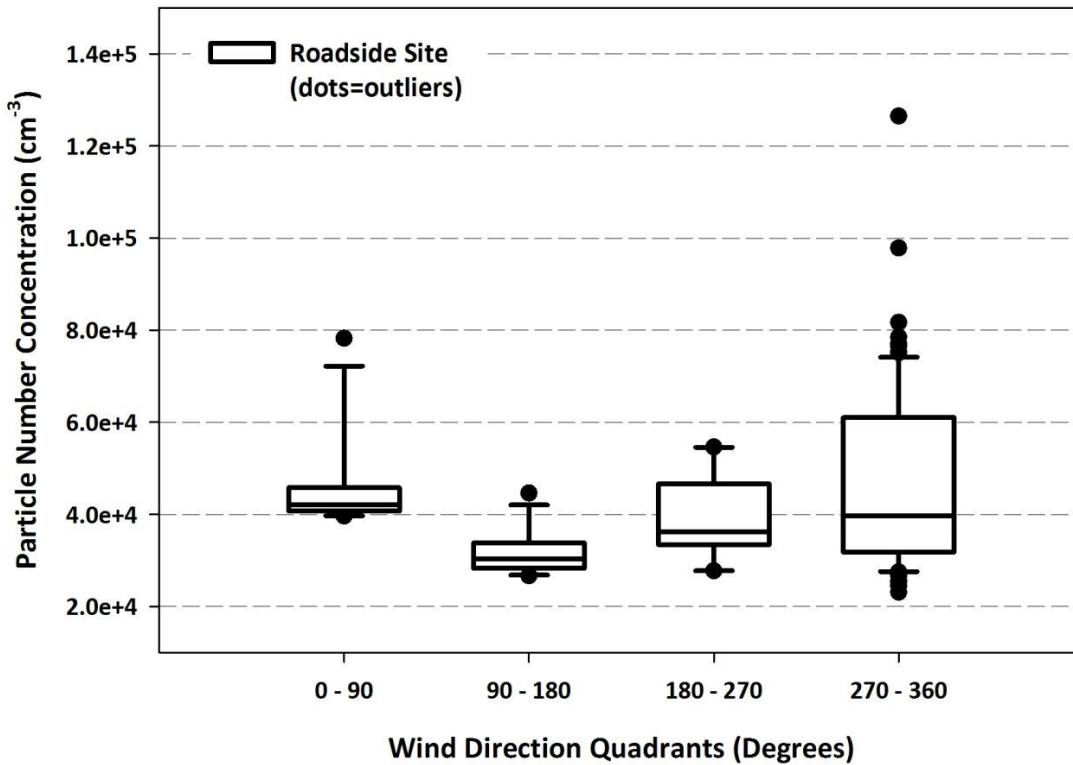
Previous studies have shown strong effects of local meteorology on PNC (Zhu et al, 2002, Wang et al, 2009). To assess the effects of meteorological conditions on PNC, as well as PM<sub>2.5</sub> and BC mass concentrations, wind direction and wind speed were analyzed in relation to studied air pollutants. Wind direction was assessed against PNC in Figure 10 a. and b. for both the control site and the roadside site, respectively. The PNC was averaged every half hour to match the wind direction and speed measurements taken at similar half hour intervals by the weather station. As shown in Figure 10 b. for the roadside site, PNC tended to be higher when the wind direction was predominantly from the Northwest. This is not as apparent for the control site as shown by Figure 10 a.



**Figure 10:** a.) Wind direction effects on PNC at the control site, b.) Wind direction effects on PNC at the roadside site

Because the roadside site is on the southeast corner of the T intersection of Chengfu Road and Zhongguancun Road, when the wind was from the northwest (270 – 360 degrees) direction, the roadside site is thus downwind of all traffic emissions from both of the roads. When the wind is blowing from the southwest direction (180 – 270 degrees), the roadside site is downwind of Zhongguancun Road only. If the wind is blowing from the northeast (0 – 90 degrees), the

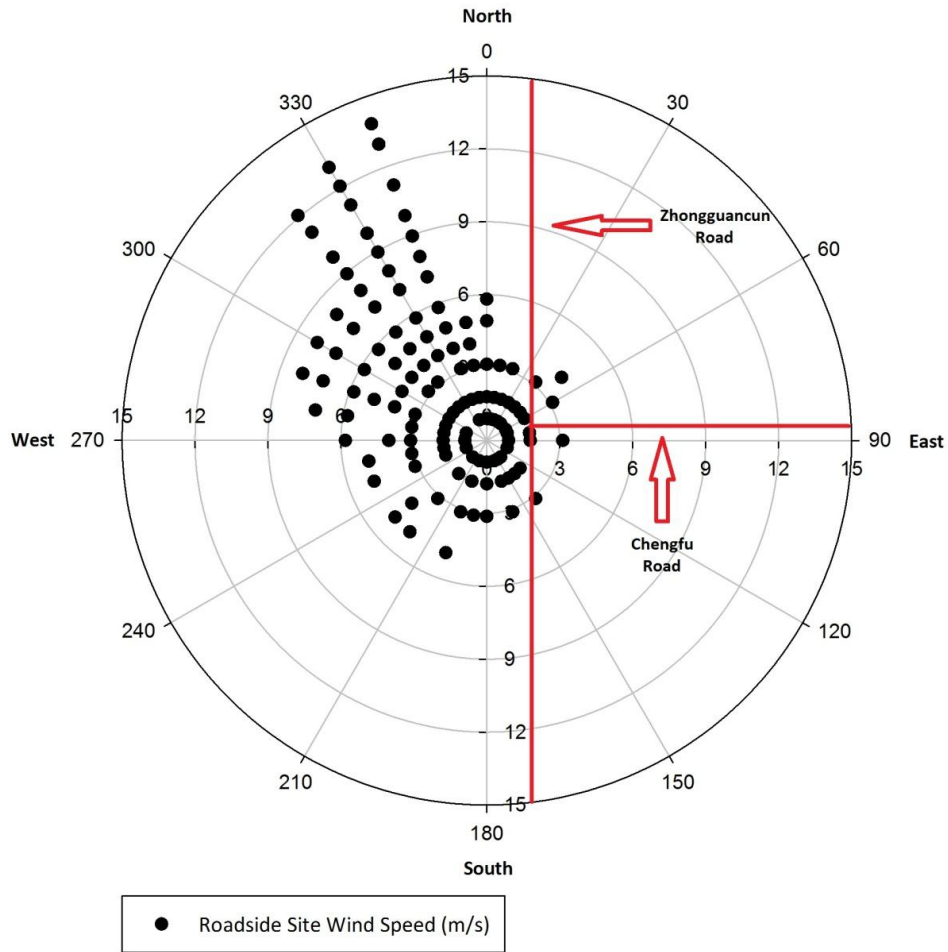
roadside site is downwind of Chengfu Road only. Finally, when the wind is blowing from the southeast (90 – 180 degrees), the roadside site is upwind of both roads. Thus, theoretically, if the wind direction quadrants in Figure 10 b. were to be analyzed separately, the lowest concentration of PNC for the Southeast quadrant should be observed. This is indeed the case as demonstrated in Figure 11, below.



**Figure 11:** Wind direction effects on PNC by quadrant

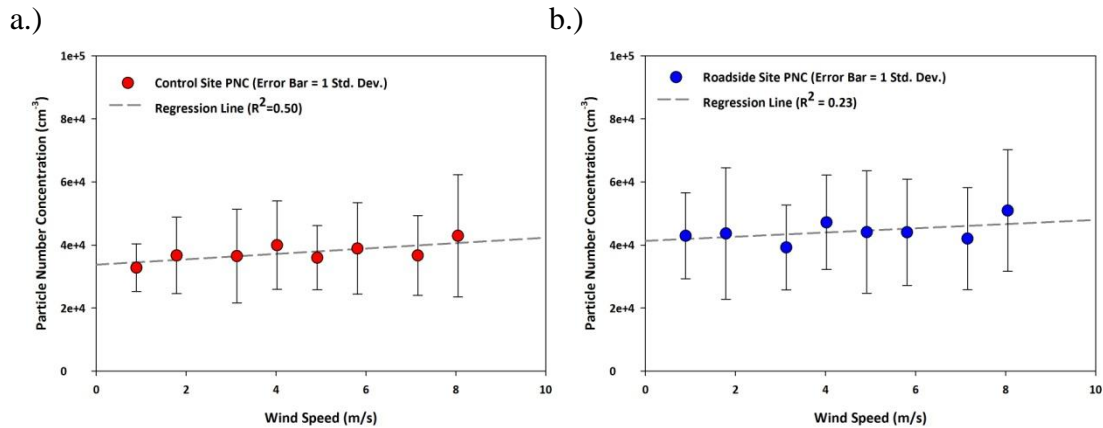
Figures 10 a. and b. confirm that wind direction can greatly influence near roadway PNC. Where from an exposure standpoint, staying upwind of both the roadways presents the lowest exposure to ultrafine particles resulting from traffic emissions; while staying downwind of any of the roadways would cause higher levels of human exposure to traffic emitted ultrafine particles.

The association between wind speed and wind direction at the roadside site is demonstrated in Figure 12, where it clearly shows that during the sampling days, stronger winds (up to 13.5 m/s) were primarily from the northwest. The T intersection sampled by the roadside site is shown on the figure for reference.



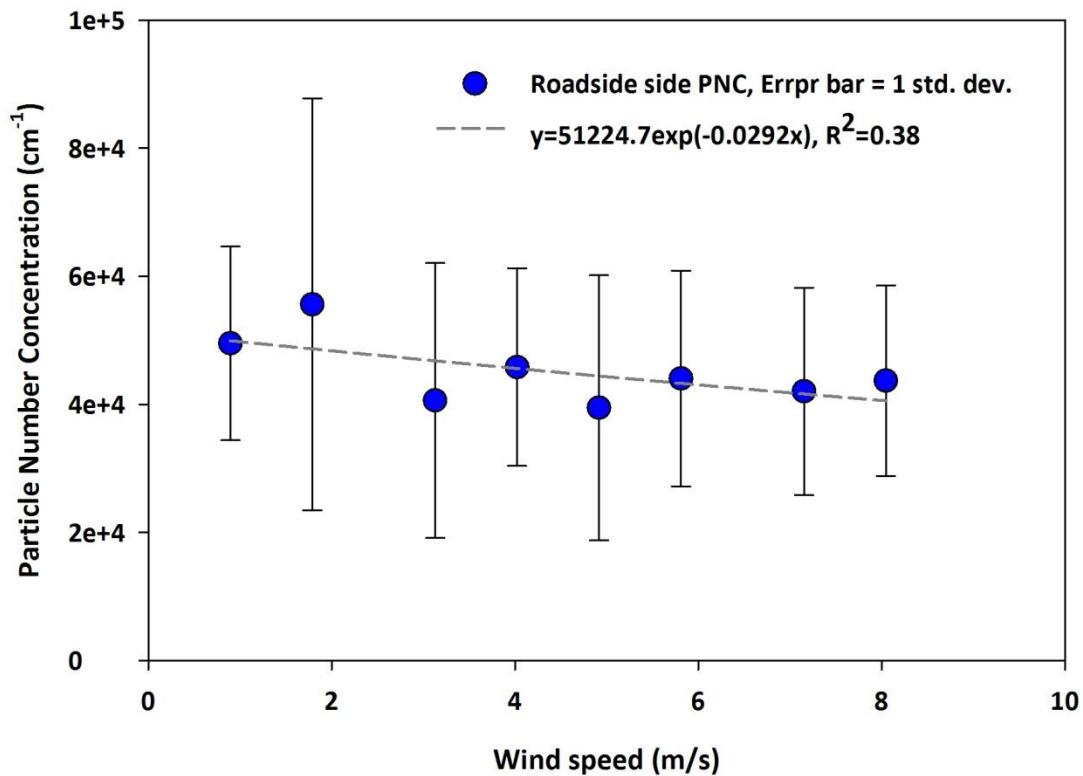
**Figure 12:** Relationship between wind speed and wind direction at the roadside site

The associations between wind speed and PNC, as well as PM<sub>2.5</sub> mass concentrations were then analyzed. Figure 13 shows the influence of wind speed on near roadway PNC.



**Figure 13:** Wind speed effects on a.) control site and b.) roadside site PNC

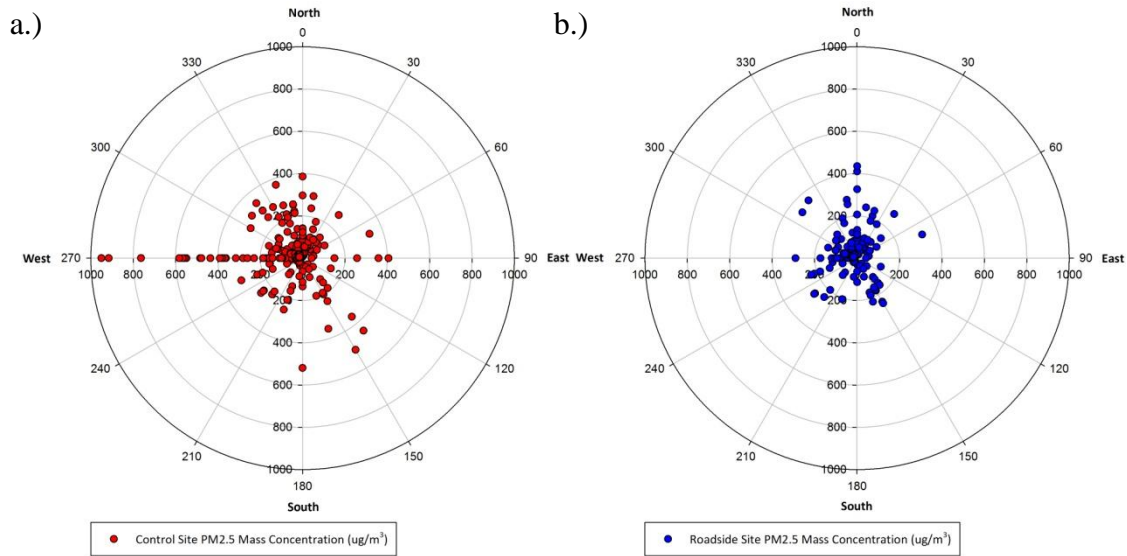
Figure 13 suggests that higher wind speeds are associated with higher PNC, with  $R^2$  values of 0.50 for the control site and 0.23 for the roadside site. This is possibly misleading and is in contrast to studies conducted in the US (Zhu et al, 2002, Wang et al, 2008), where increasing wind speeds were shown to be statistically associated with a decrease in PNC. A possible explanation is that the local meteorological conditions are more complex with wind speed and direction changing with relative higher frequency in this study. To assess the effects of wind direction on the association between wind speed and PNC, only upwind PNC and wind speed data were used for the control site (180 – 360 degrees only), and only downwind PNC and wind speed data were used for the roadside site (90 – 180 degrees removed). The resulting plot for the control site showed almost no association between wind speed and PNC, with a  $R^2$  value of 0.04. However, the roadside site data, with downwind data only, demonstrated a negative correlation between wind speed and PNC ( $R^2=0.38$ ), shown in Figure 14 below.



**Figure 14:** Wind speed effects on roadside Site PNC\*  
 \*(with upwind data removed)

Other influences such as high variation in traffic densities as well as different proportions of light versus heavily polluting vehicles may also play a role in affecting the relationship between wind speed and PNC. It is also important to note that all the  $R^2$  values are low indicating low statistical association between wind speed and PNC concentrations.

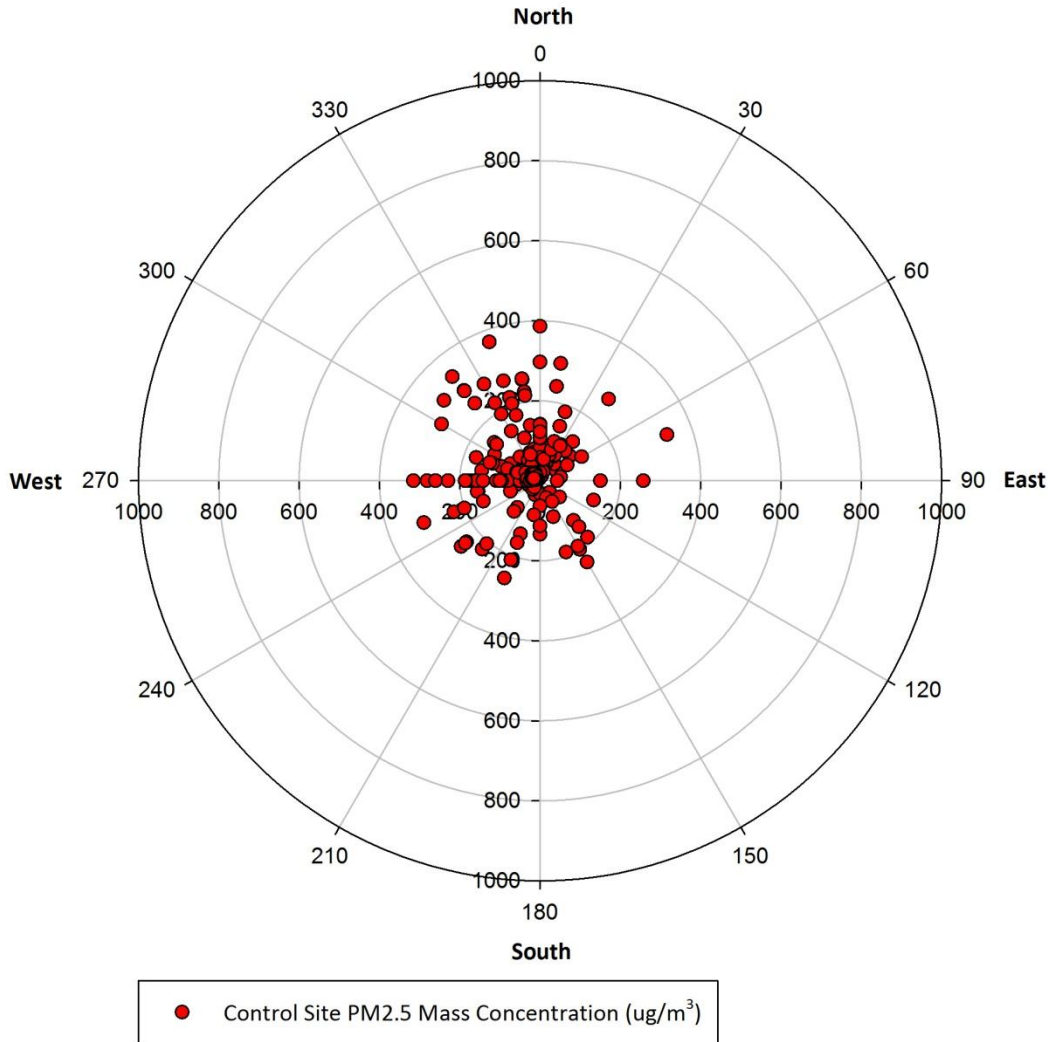
Effects of wind direction were also assessed for PM<sub>2.5</sub> mass concentrations, and these were plotted for both the control and roadside sites in Figures 15 a. and b. below, respectively.



**Figure 15:** Wind direction effects on a.) control site and b.) roadside site PM2.5 mass concentrations

For the control site, there is a strong spike in PM2.5 mass concentrations when the wind is coming from the West. The majority of these data points are from December 13<sup>th</sup>, when the dominant wind direction is from the west. December 13<sup>th</sup> was a high haze day, with visibility recorded by the weather station at an average of 1.56 miles during the sampling period of 8AM to 9 PM. High levels of PM2.5 is closely associated with regional haze which negatively affect visibility (Sisler & Malm, 2000, Sun et al, 2006). However, if the December 13<sup>th</sup> data were removed from the plot, the association between wind direction and PM2.5 mass concentrations at the control site is less clear; this is demonstrated in Figure 16 below.



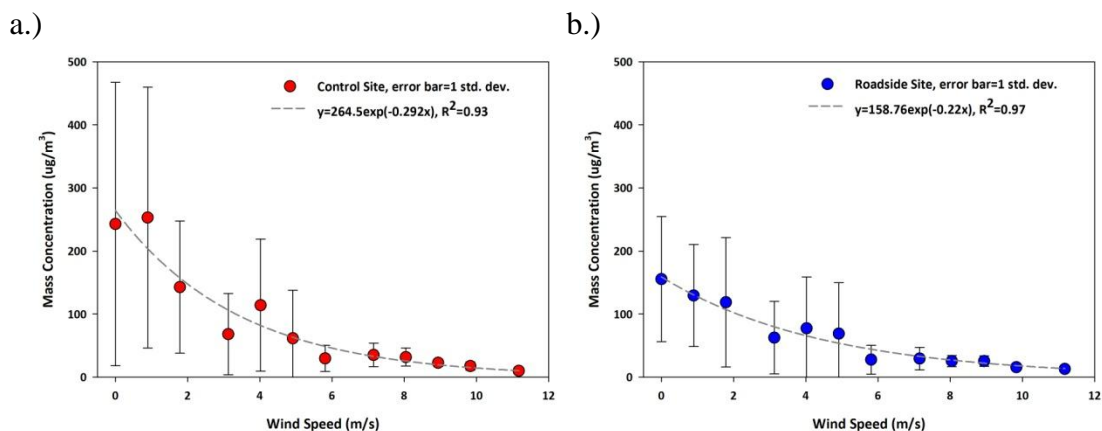


**Figure 16:** Wind direction effects on control site PM2.5 mass concentrations\*  
 (\*December 13<sup>th</sup> data removed)

On Figure 15 b. for the roadside site, where the December 13<sup>th</sup> data were missing due to a Dust-trak malfunction which lost the recorded data for the day. An overall trend where wind from the northwest (270 – 360 degrees) and northeast (0 – 90 degrees) was somewhat associated with higher PM2.5 mass concentrations could be observed; this relatively light trend is also seen on Figure 16 above for the control site when December 13<sup>th</sup> data were removed. This is possibly due to the fact that the Gobi desert is approximately 560 kilometers in the northwest direction in relation to Beijing, indicating signs of regional dust influence. As supporting evidence, previous

studies have demonstrated a clear association between strong dust uplift fluxes over the Gobi Desert and associated subsequent heavy dust events in Beijing, and as far as Seoul, South Korea, and Tsukuba, Japan (Jimin et al, 2000, Yumimoto et al, 2008).

PM2.5 is also strongly associated with wind speed in a log decay relationship; with lower wind speeds associated with lower PM2.5 mass concentrations, which are demonstrated in Figure 17, below.

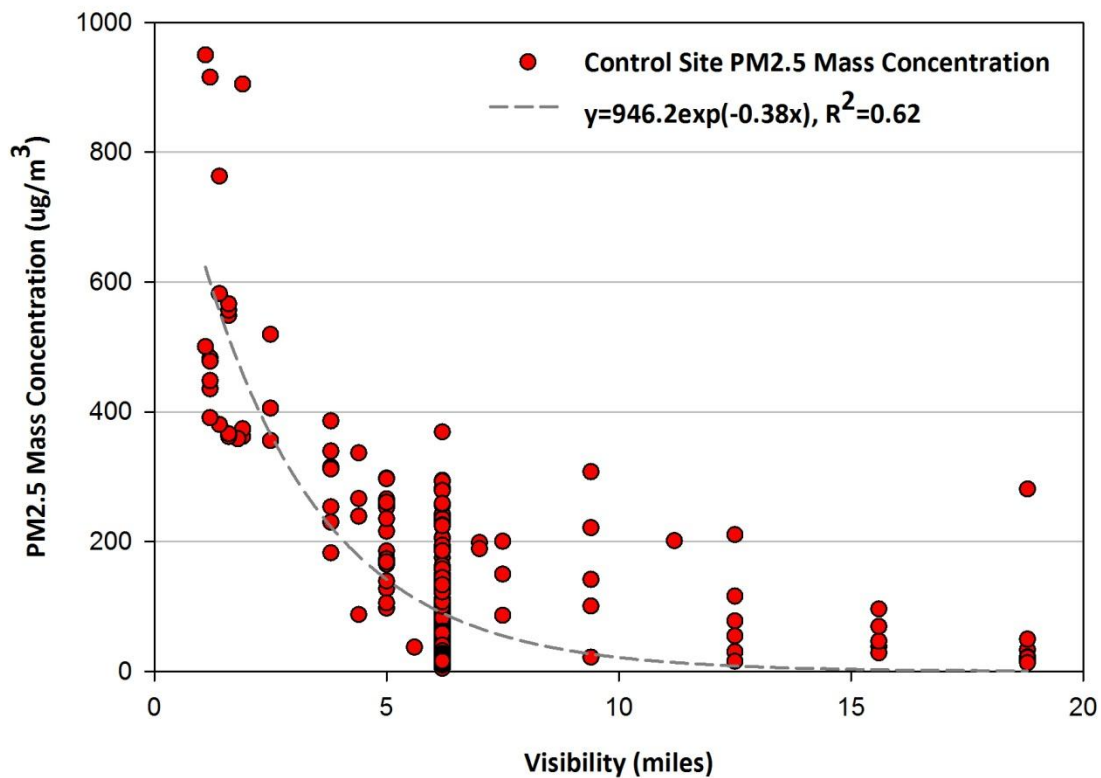


**Figure 17:** Wind speed effects on a.) control site and b.) roadside site PM2.5 mass

Figure 17 shows the effects of wind speed on PM2.5 mass concentrations at both the control site and the roadside site. This is in sharp contrast to the low statistical association between wind speed and PNC shown in Figure 13 a. & b. and Figure 14. There is a clear statistically significant association between wind speed and PM2.5 mass concentrations ( $R^2$  value of 0.93 and 0.97 for the control and roadside sites, respectively). Higher wind speeds are associated with a relative drop in average PM2.5 mass concentrations. This result is not surprising considering that larger particles are more affected by wind speed due to their larger surface areas. Also, PM2.5 mass concentrations are more indicative of regional ambient pollution levels compared to UFP number concentrations, which are more indicative of local traffic emissions. PNC tends to drop sharply

as distance from a roadway is increased due to both particle coagulation as well as atmospheric dispersion (Zhu et al, 2002).

The association between control site PM<sub>2.5</sub> mass concentrations and visibility data were then analyzed and plotted in Figure 18. The visibility data were gathered from the same weather station described in the Experimental Methods section; PM<sub>2.5</sub> mass concentrations are averaged every 30 minutes to match the sampling period of the meteorology data.



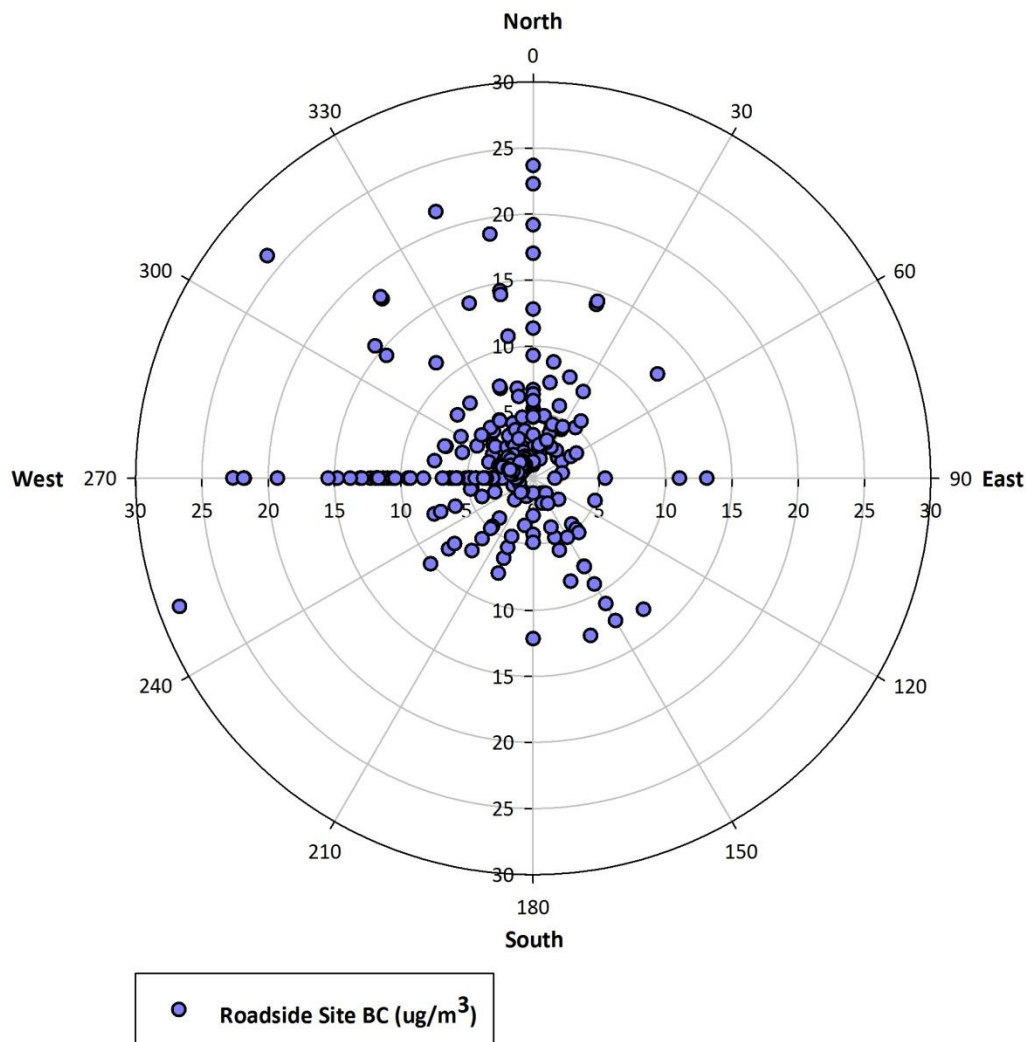
**Figure 18:** Control site PM<sub>2.5</sub> mass concentrations and visibility

There is a relatively high association between poor visibility and higher PM<sub>2.5</sub> mass concentrations with a  $R^2$  value of 0.62. This indicates that PM<sub>2.5</sub> is associated with regional pollutant sources that increase haze and negatively affect overall visibility in Beijing. This

association is logarithmic, with higher PM<sub>2.5</sub> levels greatly influencing visibility compared to lower PM<sub>2.5</sub> levels.

The association between higher roadside site PM<sub>2.5</sub> mass concentrations and lower visibility is not as apparent as that of the control site with an R<sup>2</sup> value of 0.26. However, this is partially due to missing Dust-trak data from December 13<sup>th</sup>, a day of extremely low visibility (average 1.56 miles during sampling period), and high PM<sub>2.5</sub> mass concentrations (average 0.522 mg/m<sup>3</sup> during sampling period). Although the association is weak, a log decay negative association is still somewhat apparent.

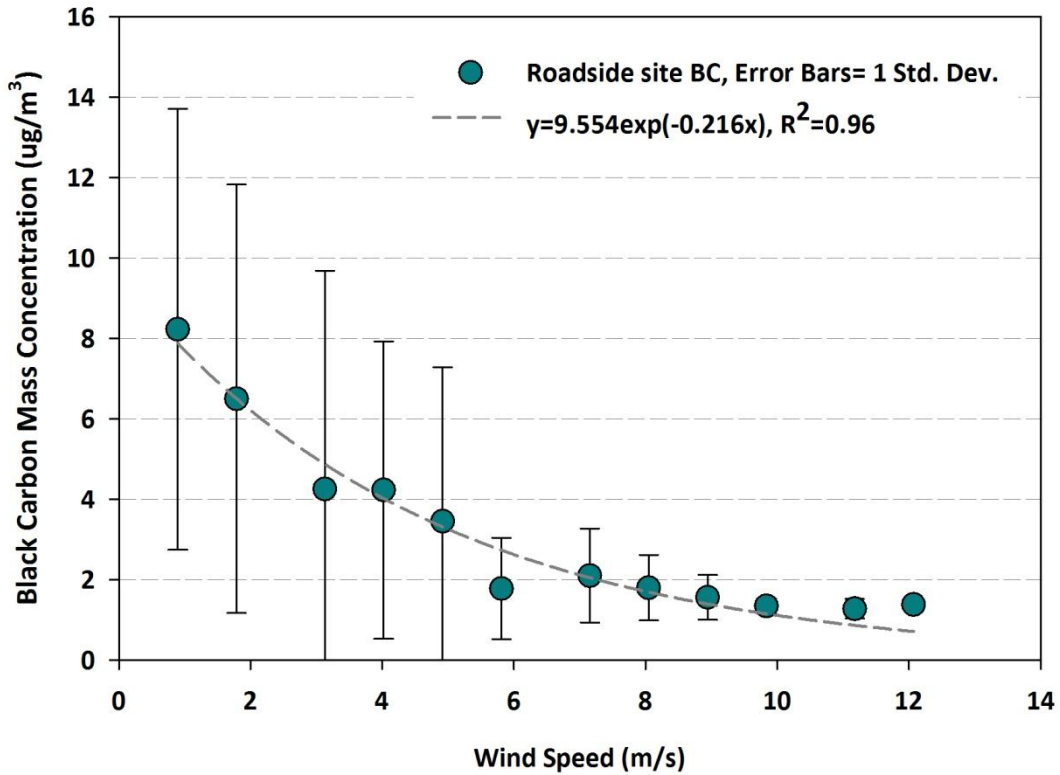
In terms of meteorological effects on BC mass concentrations, their association with wind direction is shown in Figure 19 below. The BC mass concentrations are averaged in half hour increments to match data from the weather station like that for the PNC and PM<sub>2.5</sub> mass concentration above.



**Figure 19:** Wind direction effects on roadside site BC mass concentration

The effects of wind direction on BC seems to indicate, like that for the PNC, a strong association between being downwind of Chenfu Rd. and Zhongguancun Rd. and higher mass concentrations. This outcome is expected as BC has been found to be associated with traffic and especially diesel emissions (Wang et al., 2009). It is important to note, however, that the strong response of BC from the west (270 degrees) reflects a similar strong response for PM<sub>2.5</sub> shown in Figure 15 a. This indicates that there may be other BC sources strongly associated with PM<sub>2.5</sub> that perhaps do not originate from traffic emissions. There may be regional biomass burning or some other anthropogenic source that has been detected by the instruments.

The effects of wind speed on BC mass concentrations was also assessed and shown in Figure 20 below.



**Figure 20:** Wind speed effects on roadside site BC mass concentrations

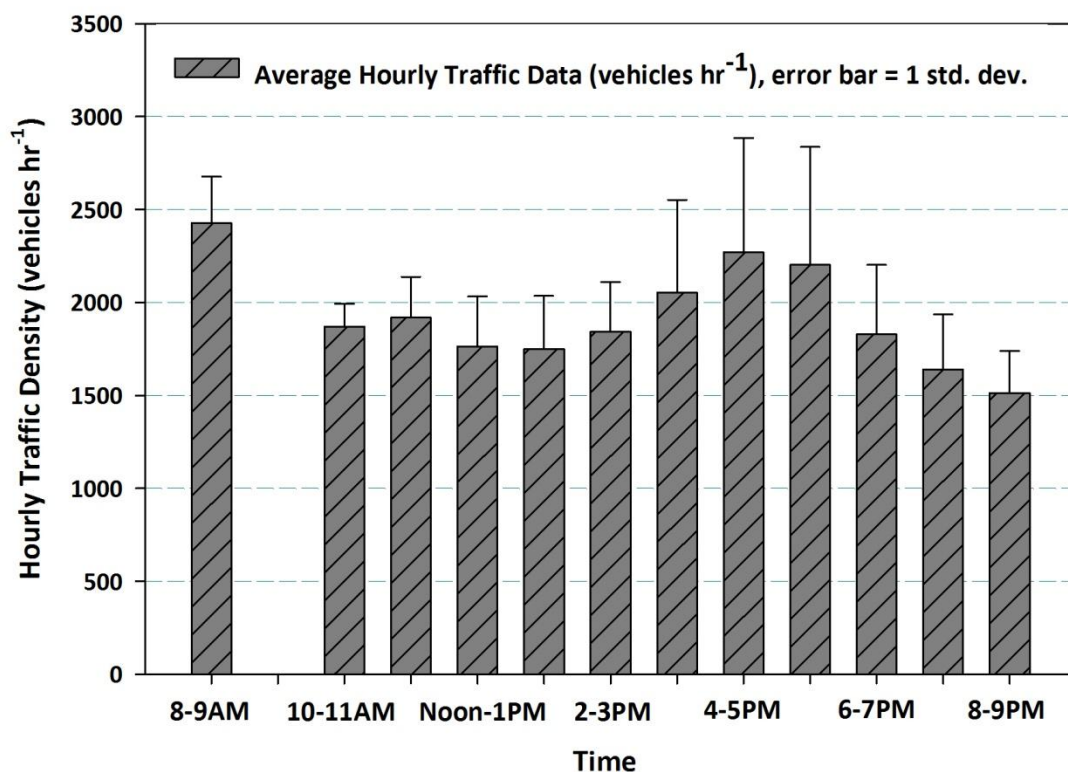
There is a strong association ( $R^2=0.96$ ) between wind speed and BC mass concentrations, with a profile similar to that between wind speed and PM2.5 mass concentrations. This result is not surprising considering previous studies have shown BC to generally reside in the PM2.5 size range (Hitzenberger & Tohno, 2001, Viidanoja et al, 2002).

Traffic density is another important factor that may influence roadside PNC, especially combined with local meteorological conditions. The overall traffic density data are compiled in the following table.

**Table 3:** Overall traffic density data over the sampling period

	<b>Total Traffic (hr<sup>-1</sup>)</b>	<b>Light Duty Vehicle Density (hr<sup>-1</sup>)</b>	<b>Heavy Duty Vehicle Density (hr<sup>-1</sup>)</b>	<b>HDV / LDV Ratio (%)</b>
<b>Average</b>	1889	1666	222	15
<b>Std. Dev.</b>	779	733	137	13

The above traffic density data shows a high hourly variation, and that overall, heavy duty vehicles (HDV), including buses and transport trucks, comprises approximately 15% the traffic density of light duty vehicles (LDV) such as passenger cars and light duty trucks. The per hour average diurnal traffic pattern of all days where traffic counting was conducted is shown in Figure 21.



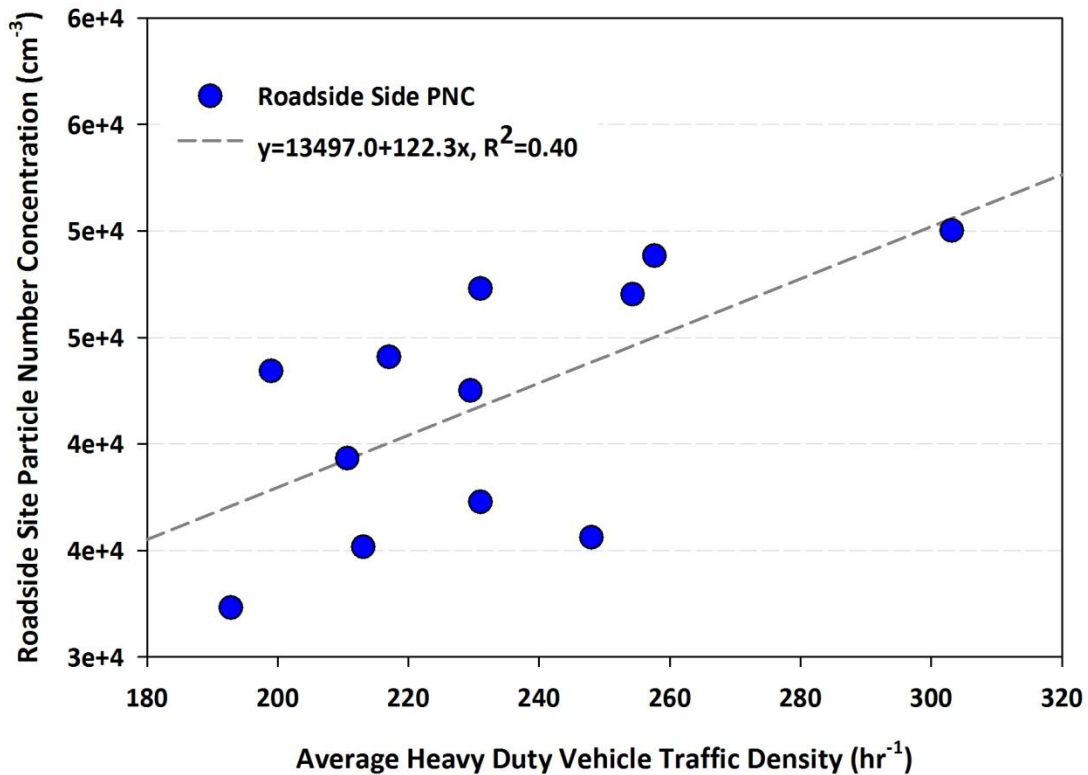
**Figure 21:** Overall hourly traffic pattern

The traffic pattern on Chengfu Rd. shows that hourly traffic densities may become quite high during the morning and afternoon rush hours (8AM – 9AM, 4PM -7PM, respectively), and is capable of reaching an average of over 2500 vehicles per hour.

The overall hourly traffic densities were then analyzed and compared with the corresponding hourly roadside site PNC. The analysis excluded data from periods when the roadside site is upwind of both Chengfu Rd. or Zhongguancun Rd, or when the wind direction is primarily from the Southeast. Also, hourly PNC data were excluded from periods where a vehicle was seen on video footage to idle directly in front of the instrumentation for more than 5 minutes, as the PNC were found to be heavily affected, reaching average concentrations of over 80,000 cm<sup>-3</sup>, which heavily skewed the plots. After the above analysis, average hourly PNC was found to have



nearly no correlation with hourly total traffic densities ( $R^2=0.05$ ). However, there was a comparatively much higher correlation between hourly PNC and HDV densities. This is shown in Figure 22 ( $R^2=0.40$ ).



**Figure 22:** Effects of hourly heavy duty vehicle traffic density on PNC

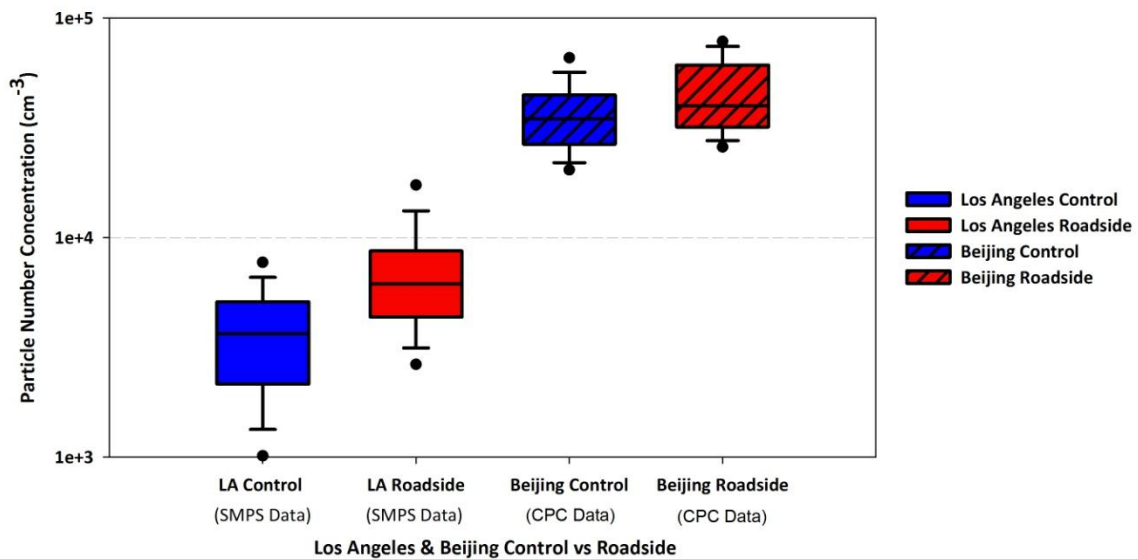
There are several possible explanations as to why the correlation between HDV density and PNC ( $R^2=0.40$ ) is much higher than the correlation between total traffic density and PNC ( $R^2=0.05$ ). One is that vehicle speeds may have a strong effect on PNC, especially since traffic speeds on local streets such as Chenfu Rd. and Zhongguancun Rd. is dependent upon the traffic light at the T intersection, and previous studies have found higher emissions of UFP when vehicles are travelling at higher speeds (Kittelson et al, 2004). Another explanation is that HDVs such as diesel trucks were found in previous studies to emit much higher concentrations of UFP

compared to LDVs (Fraser et al, 2003, Kittelson et al, 2004), and due to the high density of diesel vehicles seen on recorded video footage, their UFP emission rate may be much higher than those from LDVs such as passenger cars, despite the much higher density of LDVs.

A comparison between the Beijing dataset and a Los Angeles near road ambient air quality study dataset were conducted to assess the major differences and similarities between the two cities in terms of PM<sub>2.5</sub> and ultrafine particulates. The Los Angeles study was conducted by the Quiros et al of the Zhu Lab located at the UCLA Department of Environmental Health Sciences during the month of July in 2011. The study consisted of a control site and a roadside site near the 405 Freeway located in Santa Monica.

The first major difference between Beijing and Los Angeles is local meteorology. Los Angeles experiences a general diurnal pattern in terms of wind direction. During daytime, the wind direction is from the west, while at night, the wind direction is predominantly from inland, or the east. However, if a marine layer is present, the wind may also be from the west near the coast at night time. Los Angeles also does not experience high variation in terms of wind speed. In Beijing, the local meteorology is often highly variable, which has already been shown to affect local ambient air quality in this study as well as others (Feng et al, 2004, Streets et al, 2008). Other differences are sources that impact air quality. For example, although both cities experience high pollutant contributions from vehicular exhaust, Los Angeles generally does not experience a heavy regional influence compared to Beijing in terms of desert dust, biomass burning, coal burning, and other regional sources. The exception is that during episodes of strong Santa Ana winds during autumn or early spring, Los Angeles may experience some regional influence as well, especially during wild fire episodes.

The following figures show general differences in PNC as well as PM<sub>2.5</sub> mass concentrations between the two studies described above. The Beijing roadside PNC data is of downwind data only, or when the wind direction is primarily from the Northwest and Northeast, where the roadside site is experiencing downwind of both Chengfu Rd. and/or Zhongguancun Rd. This allows a comparable set of data to that of the downwind data from the roadside site of the Quiros et al. study, where the roadside site remained completely downwind of the 405 Freeway and never upwind.

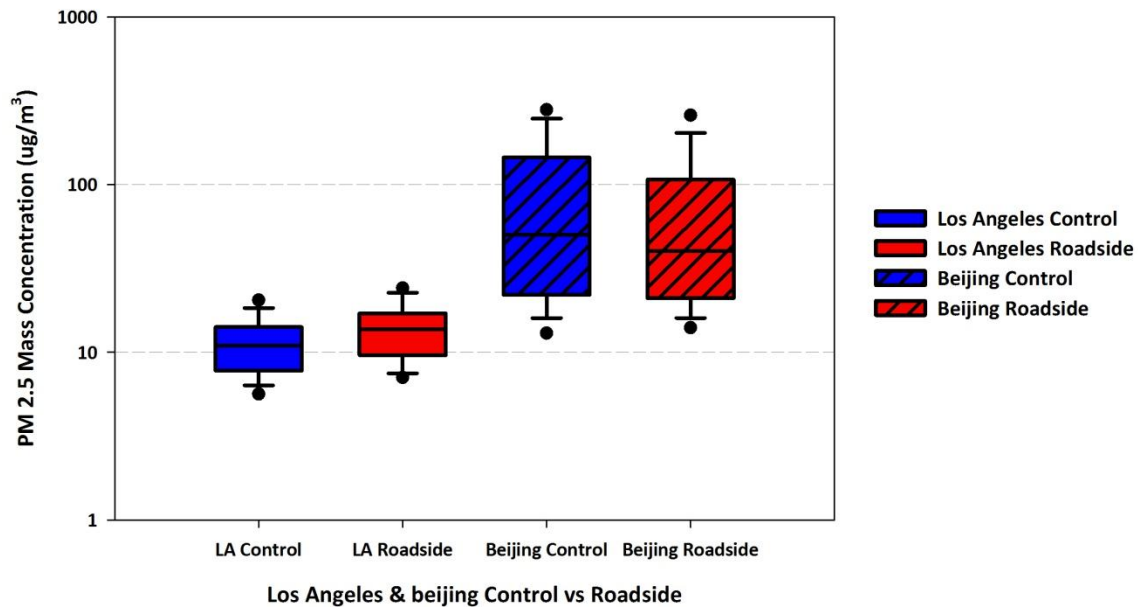


**Figure 23:** Los Angeles and Beijing PNC comparison

It is important to note that the Los Angeles dataset of PNC is gathered using a TSI Scanning Mobility Particle Size (SMPS) while the Beijing PNC dataset is gathered using a TSI WCPC. There are instrument differences in terms of data gathering; the main difference between the SMPS and the WCPC is that the SMPS is capable of measuring particle size distributions as well as measure overall particle number concentrations. However, for a general number concentration comparison, the data of the SMPS was not adjusted. Another important note is that the Y axis of PNC is in log scale compared to previous figures which all utilized the linear scale. From the

comparison, it can be observed that in Beijing, the PNC at the control site is nearly an order of magnitude higher than that of the Los Angeles roadside site. This major difference between the two datasets suggests that in terms of UFP, vehicular emissions are much higher in Beijing.

In terms of PM<sub>2.5</sub> mass concentrations, a comparison is also conducted which is shown in Figure 24 below.



**Figure 24:** Los Angeles and Beijing PM<sub>2.5</sub> mass concentration comparison

In terms of PM<sub>2.5</sub> mass, the concentrations in Beijing are approximately an order of magnitude higher than in Los Angeles at both the control and roadside sites. The range is also much more variable in the Beijing study compared to the Los Angeles study. It is also interesting to note that in Beijing, PM<sub>2.5</sub> mass concentrations are higher at the control site compared to the roadside site. Considering that the control site in Beijing is located at nearly 6 stories above ground, it could be inferred that this is evidence that regional influences on PM<sub>2.5</sub> mass plays a stronger role in Beijing compared to that of Los Angeles, where PM<sub>2.5</sub> mass concentrations are higher at the roadside site compared to that of the control site.

Another parameter compared is emission factors in terms of numbers of particles emitted per kilogram of fuel burned. The equation used for this analysis was adapted from previous studies, where similar equations were independently deduced (Herndon et al, 2008, Ning et al, 2008, Wang et al, 2008). This equation assumes that carbon mass in the vehicle's exhaust are all in the form of CO & CO<sub>2</sub>.

$$EF_{UFP} = \frac{10^{12}}{0.5357} \left( \frac{\Delta UFP}{\Delta CO_2 + 10^2 \Delta CO} \right) w_c$$

EF<sub>UFP</sub> is the emission factor for ultrafine particles in terms of number of particles per kg of fuel consumed. The ΔUFP is the increases in the number concentrations of UFP above background levels (or the difference in UFP between the downwind/roadside site and the control site). The ΔCO<sub>2</sub> and ΔCO are the increase in concentration of CO<sub>2</sub> and CO above background levels in parts per million (ppm). The weight fraction of carbon in the fuel considered is 0.87 for diesel and 0.85 for gasoline (Wang et al, 2008). In the analysis of the Beijing and Los Angeles datasets, 0.85 for gasoline was used.

Our analysis showed an overall average emission factor of 4.812 E+14 kg<sup>-1</sup> with a standard deviation of 4.179 E+14 kg<sup>-1</sup> for the Beijing dataset. For Los Angeles study, the overall average emission factor was 4.50 E+14 kg<sup>-1</sup> with a standard deviation of 3.60 E+14 kg<sup>-1</sup>. For the Beijing dataset, only data when the roadside site is downwind of the two roads were used, as much of the PNC data for when the roadside site is upwind, i.e. when the wind direction was primarily from the Southeast, was lower than that for the control site.

The comparison of the two sets of emission factors show that vehicles in Beijing generally have a higher emission factor compared to that of Los Angeles. There is also a higher variation in the emission factors in Beijing, indicating the presence of both low as well as very high emitting vehicles. What is interesting is that although the concentrations for UFP are much

higher in Beijing, the traffic emission factors are not significantly different. One explanation is that CO<sub>2</sub> concentrations were generally higher in Beijing compared to Los Angeles; in Beijing, the CO<sub>2</sub> was on average 420 ppm at the control site and 470 ppm at the roadside site, respectively. While in Los Angeles, the average was 400 ppm at the control site and 420 ppm at the roadside site, respectively. If the assumption is that the concentration of CO<sub>2</sub> is an indicator for fuel consumption, then it shows that in Beijing, more fuel is being consumed on average compared to Los Angeles. This could be caused mainly by lower efficiency vehicles operating on Beijing streets. It would also explain the why the emission factor is similar yet the PNC is much higher in Beijing compared to Los Angeles.

It should also be noted that the emission factor equation was developed with data from other U.S. studies, and fuel efficiencies may be lower in China, rendering the calculated emission factor from this study a rather conservative estimate. Another issue is that there are high densities of diesel buses that operate on local Beijing city streets, and although diesel trucks also operate on Los Angeles highways, they do not contribute as high a percentage to the emissions on the 405 Freeway, as the majority of diesel traffic through Los Angeles is on the 710 Freeway. Lastly, the study conducted in Beijing was along city streets, while the study in Los Angeles was focused on Highway 405, which has a much higher traffic density.

Another study conducted in on local streets in Laredo of Texas in the U.S. resulted in average emission factors of  $2.30 \text{ E}+14 \text{ kg}^{-1}$  of fuel burned (Wang et al, 2008). This is nearly half of the emission factor calculated from the Beijing dataset.

The data gathered from this study could be used to generate a model for near roadway human exposures to both PM<sub>2.5</sub> and UFP. For example, the current study showed that despite wind speed having low correlation to PNC, exposures to UFP are higher when downwind of a

roadway than upwind. The same is true for PM<sub>2.5</sub>; however, PM<sub>2.5</sub> is heavily influenced by wind speed as well as wind direction. Thus, by obtaining quantitative near roadway meteorological data as well as PNC and PM<sub>2.5</sub> mass concentrations, human exposure to ultrafine and PM<sub>2.5</sub> particulates could be estimated, especially for those whose occupation limits them to be near roadways.

## CHAPTER 5: CONCLUSIONS

PNC, PM<sub>2.5</sub> and BC mass concentrations all showed strong daily variations in this study. Unexpected findings such as days where the PNC as well as PM<sub>2.5</sub> mass concentrations were higher at the control site were found to indicate strong local and regional meteorology influences, as well as local and regional emission source influences, such as from traffic, biomass burning, or possible long range dust transport from the Gobi desert.

This study also validated previous studies conducted in Chinese cities where PM<sub>2.5</sub> mass concentration was strongly associated with visibility, indicating that controlling PM<sub>2.5</sub> emissions with more stringent regulation should be effective in reducing the number of high haze days in cities such as Beijing.

Data comparison between Beijing and Los Angeles has shown that Beijing's air quality still lags behind those of developed nations, and that average traffic emission per vehicle is higher in vehicles operating on Beijing roads. There is also indication that vehicles in Beijing are on average less fuel efficient compared to vehicles in Los Angeles. The data analysis in this study also suggests that UFP exposures near roadways in Beijing could be much higher depending on local meteorology and HDV traffic density. The relatively higher correlation between HDV density and PNC indicates that perhaps by upgrading the fleet of public transit buses and other diesel vehicles with newer and less polluting diesel engines may go a long way in reducing near road exposures to UFPs in Beijing.

Further studies should be conducted during other seasons such as the summer months as a comparison to this study which was conducted during the winter, since previous studies in Beijing has shown strong seasonal variations in emission sources for PM<sub>2.5</sub> and other air pollutants.



More data obtained in future studies in the summer months, combined with data from the current study, could be used to quantitatively generate exposure models for near roadway human exposures. For example, calculation of intake fractions (a ratio between attributable population intake to total emissions) for PM<sub>2.5</sub> and UFP is possible both for the average resident in Beijing, as well as for workers who spend most of their work hours on or near roadways, such as operators of food stands, street cleaners, and traffic directing personnel, among others.

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