Taylor & Francis
Taylor & Francis Group

Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/uawm20

Roadside Measurements of Ultrafine Particles at a Busy Urban Intersection

Yungang Wang , Yifang Zhu , Robert Salinas , David Ramirez , Saritha Karnae & Kuruvilla John

To cite this article: Yungang Wang , Yifang Zhu , Robert Salinas , David Ramirez , Saritha Karnae & Kuruvilla John (2008) Roadside Measurements of Ultrafine Particles at a Busy Urban Intersection, Journal of the Air & Waste Management Association, 58:11, 1449-1457

To link to this article: http://dx.doi.org/10.3155/1047-3289.58.11.1449

Published online: 28 Mar 2012.

Submit your article to this journal

Article views: 201

View related articles

Citing articles: 23 View citing articles

Full Terms & Conditions of access and use can be found at
http://www.tandfonline.com/action/journalInformation?journalCode=uawm20

Download by: [University of North Texas] **Date:** 05 January 2017, At: 23:47

TECHNICAL PAPER

ISSN:1047-3289 *J. Air & Waste Manage. Assoc.* **58**:1449–1457
DOI:10.3155/1047-3289.58.11.1449
Copyright 2008 Air & Waste Management Association

Roadside Measurements of Ultrafine Particles at a Busy Urban Intersection

Yungang Wang, Yifang Zhu, Robert Salinas, David Ramirez, Saritha Karnae, and Kuruvilla John
Department of Environmental Engineering, Texas A&M University–Kingsville, Kingsville, TX

ABSTRACT

A field sampling campaign on ultrafine particles (UFPs, diameter <100 nm) was conducted at a busy traffic intersection from December 2006 to June 2007 in Corpus Christi, TX. This traffic intersection consisted of South Padre Island Drive (SPID, Highway 358) and Staples Street. Traffic densities on SPID were 9102/hr and 7880/hr for weekdays and weekends, respectively. Staples Street traffic densities were 2795/hr and 2572/hr, respectively. There were approximately 3.7% heavy-duty diesel vehicles (HDDVs) on both roadways. Peak traffic flows occurred early in the morning and late in the evening during weekdays and around noon on weekends. The average UFP total number concentration collected by a condensation particle counter (CPC 3785; TSI) was 66×10^3 cm^{-3}. A direct relationship between the UFP number concentration and traffic density was observed, but the HDDV traffic density was found to be a better estimator of the UFP number concentration than total traffic density. A scanning mobility particle sizer (SMPS 3936 with DMA 3081 and CPC 3785, TSI) measuring the particle size distribution from 7 to 290 nm was rotated among four corners of the intersection. The upwind and downwind size distributions were both bimodal in shape, exhibiting a nucleation mode at 10–30 nm and a secondary mode at 50–70 nm. The highest and lowest particle concentrations were observed on the downwind and upwind sides of both roadways, respectively, indicating the importance of wind direction. Wind speed also played an important role in overall particle concentrations; UFP concentrations were inversely proportional to wind speed. A negative correlation was observed between particle number concentrations and ambient temperature. The particle number concentration was 3.5 times greater when traffic was idling at a red light than moving at a green light.

IMPLICATIONS

Although many epidemiological and toxicological studies have demonstrated that UFPs are more toxic and more biologically active than larger particles on a unit mass basis, little is known about UFP number concentration and size distribution at urban intersections when a roadway network is present. The study presented here, conducted at a four-way traffic intersection, shows that within 20 m from both roadways, UFP concentrations were affected by wind direction, wind speed, ambient temperature, and traffic. HDDV density was found to estimate the UFP number concentration better than total traffic density.

INTRODUCTION

It has been recognized worldwide that adverse health effects due to particulate matter (PM) are significant.[1,2] A large number of epidemiological and toxicological studies have identified PM as an important risk factor for the development and exacerbations of cardiovascular disease (c.f., ref 3). Although it is unlikely that the physically and chemically diverse forms of inhalable ambient PM have similar toxicity, it is unclear how specific size ranges, chemical species, and/or sources of PM impact the observed adverse health effects. Ultrafine particles (UFPs, diameter <100 nm) can penetrate deeply into the human lungs and deposit within the alveoli to mediate lung injury.[4] Health effects appear to be more strongly, or as strongly, associated with UFP number concentration than with fine particulate matter ($PM_{2.5}$) mass concentration.[5] UFPs have been suggested to be more toxic and biologically active than larger inhalable particles.[6]

Vehicular emissions are the major contributors to UFPs in urban environments.[7] In Finland, Kerminen et al.[8] showed that traffic emissions may be a dominant source of UFPs under suitable meteorological conditions. In the Netherlands, Weijers et al.[9] found that the UFP number concentration increased with increasing traffic intensity. The highest concentrations were found on motorways, road crossings, and inside tunnels. In the United States, Zhu et al.[10] found that the wind speed was an important factor in determining the characteristic of UFP concentration near freeways; in particular, the stronger the wind, the lower the particle number concentrations. The UFP number concentration was shown to be directly related to traffic density and decreased significantly during a traffic slowdown on the I-405 freeway in Los Angeles.[11]

Data from recent measurements of UFP number concentration obtained at different locations worldwide are summarized in Table 1. Number concentrations of UFPs were the lowest in coastal and suburban surroundings. Higher number concentrations were found in residential areas near the beach and along

Table 1. Summary of the results from recent studies focused on UFP measurements at various locations worldwide.

Type of Measurement Site	Location	Traffic Density (hr^{-1})	Size Range (nm)	Concentration ($\times 10^3$ cm^{-3})	Reference
Rural background	Pennsylvania, United States	N/A	10–500	8.4	12
Rural freeway side	California, United States	6,330	6–237	3–72	13
Coastal and rural background	Noord-Holland, Netherlands	N/A	7–7,500	5	9
Suburban	Paris, France	800–10,500	7–3,000	4	14
Suburban road side	Gothenburg, Sweden	542–834	10–368	2	15
Beach residential	California, United States	N/A	7–1,000	26	16
Urban background	Copenhagen, Denmark	N/A	10–700	9	17
Urban background	Lahti, Finland	1,042–1,209	10–300	10	18
Urban background	California, United States	N/A	17–100	13	19
Urban background	Pennsylvania, United States	N/A	10–500	16.5	12
Urban background	Helsinki, Finland	N/A	10–500	18	20
Urban background	Alkmaar, Netherlands	N/A	10–500	20	20
Urban background	Erfurt, Germany	N/A	10–500	20	20
Street canyon	Brisbane, Australia	N/A	16–626	10–20	21
Street canyon	Tingalpa and Murrarie, Australia	2,130–3,400	15–697	20–80	22
Street canyon	Copenhagen, Denmark	N/A	10–700	21	17
Street canyon	Birmingham, United Kingdom	1,250–6,667	3–7 to 400	30–100	23
Street canyon	Lahti, Finland	1,042–1,209	6–300	40	18
Street canyon	Paris, France	800–10,500	7–3,000	220	14
Urban freeway side	Brisbane, Australia	4,000–5,917	16–700	5.9–8.8	24
Urban freeway side	Minnesota, United States	N/A	3–1,000	38	25
Urban road side	Helsinki, Finland	300–3,000	30–1,020	50–650	8
Urban freeway side	California, United States	12,180–13,900	6–220	130–350	10, 11
Urban freeway	California, United States	N/A	7–1,000	190	16
Motorway ring	Amsterdam, Netherlands	N/A	7–7,500	160	9
Traffic congestions	Nijmegen, Netherlands	N/A	7–7,500	600	9
Urban intersection	Brisbane, Australia	200–1,920	9–407	0.8–260	26
Urban intersection	Texas, United States	11,175	6–220	66	This study

Notes: N/A = not applicable.

rural freeways than at the corresponding background sites. At the urban background, the number concentrations of particles with diameters from 10 to 700 nm ranged from 9×10^3 cm^{-3} to 20×10^3 cm^{-3}.

For the urban atmosphere, it is important to emphasize the importance of particles in the lower size limits, because the number of particles is normally higher in the lower end of the particle size range.[15] Results from an urban street canyon located in Copenhagen, Denmark from May to November 2001, showed a mean UFP number concentration of 21×10^3 cm^{-3}.[17] The particle number concentration in the size range from 6 to 220 nm was found to be $(130–350) \times 10^3$ cm^{-3} in the vicinity of two major Los Angeles freeways.[10,11] Measurements conducted in winter at two distances near a major road in Helsinki, Finland, showed a particle number concentration of $(50–650) \times 10^3$ cm^{-3} in the size range from 30 to 1020 nm.[8] A study conducted at a busy central urban intersection in Australia showed that the average particle concentration ranged between 0.8×10^3 cm^{-3} and 260×10^3 cm^{-3} in the size range of 9–407 nm.[26]

Despite these near-roadway UFP studies, the relationships among traffic density, meteorological parameters, and UFP number concentration and size distribution at urban intersections are still not well understood. In addition, most of the earlier studies were conducted in metropolitan areas focusing on a single roadway. The interaction between roadways, with respect to UFP number concentration, in medium-size cities (population <1 million) has not been well investigated yet. The aim of this study is to characterize UFP number concentration and size distribution in relation to traffic density and meteorological parameters at a busy traffic intersection in a medium-size city in south Texas.

EXPERIMENTAL PROCEDURES

Description of the Sampling Sites

Measurements were conducted at a traffic intersection between South Padre Island Drive (SPID) and Staples Street in the city of Corpus Christi, TX, for a total of 7 days from December 12, 2006 to June 2, 2007. Corpus Christi is a coastal city in Texas with a total area of 1192 km^2 and a population of 277,454.[27]

SPID runs east and west close to the sampling site (20 m) and is parallel to the shoreline of Corpus Christi Bay (Figure 1). SPID has six lanes, three north bound and three south bound. Staples Street, running perpendicular to SPID, is a major local street with seven lanes, three west bound and four east bound. It is 5 m from the sampling site.

Sampling Procedures and Instrumentation

Meteorological data, including ambient temperature, relative humidity (RH), wind speed, and wind direction were measured at a nearby weather station (Holly

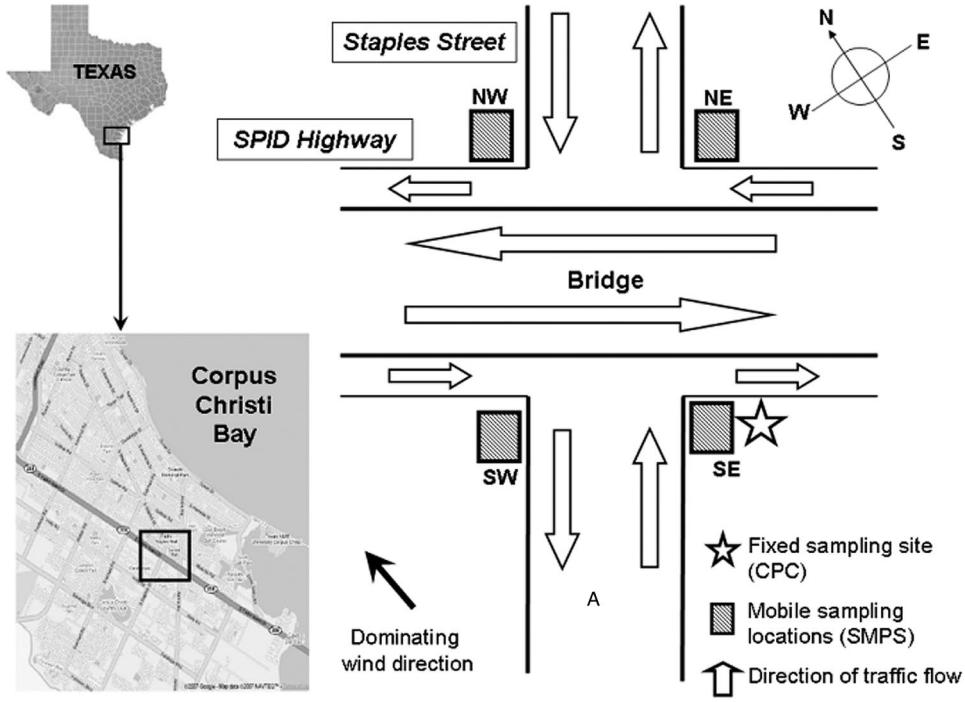

Figure 1. Sampling sites near SPID and Staples Street in Corpus Christi, TX.

Road C660, Corpus Christi, TX, U.S. Environmental Protection Agency [EPA] site no. 48-355-0660), 3 m above ground level and approximately 1.5 km southwest of the sampling traffic intersection. The traffic density on both SPID and Staples Street, defined as the number of passing vehicles per hour, was counted manually throughout the study. Traffic counting captured all of the lanes of SPID and Staples Street. Three-minute traffic count samples were randomly collected in each 15-min interval, and four samples in 1 hr were merged together and converted into hourly average data. Heavy-duty diesel vehicles (HDDVs) and light-duty gasoline vehicles (LDGVs) were counted separately.

Particle number concentration and size distribution in the size range from 6 to 220 nm were measured by one condensation particle counter (CPC 3785; TSI Inc.) and a scanning mobility particle sizer (SMPS 3936 with differential mobility analyzer [DMA] 3081 and CPC 3785, TSI Inc.), respectively. Data reduction and analysis of the SMPS output were done with the Aerosol Instrument Manager software (version 7.3.0, TSI Inc.). Measurements were taken at four corners of the traffic intersection (Figure 1). The CPC was located at the southeastern corner (fixed sampling site) throughout the measurements. The SMPS was moved around all corners of the intersection (mobile sampling locations) to measure UFP number size distribution. At each corner, not less than 10 size distributions were taken in sequence with the SMPS using a 100-sec upscan and 20-sec retrace. Before each measurement session, all instruments were time synchronized. Measurements taken during the 7 sampling days (Table 2, five weekdays and two weekends) ranged from 7:00 a.m. to 6:00 p.m., capturing the morning and afternoon rush hours.

Table 2. Summary of sampling dates, times, and hourly average meteorological parameters.

Parameters	Tuesday, December 12, 2006	Wednesday, January 10, 2007	Friday, January 12, 2007	Saturday, February 3, 2007	Tuesday, May 15, 2007	Wednesday, May 16, 2007	Saturday, June 2, 2007
Time	8:30 a.m. to 6:00 p.m.	8:30 a.m. to 5:30 p.m.	8:30 a.m. to 6:00 p.m.	7:00 a.m. to 6:00 p.m.	7:00 a.m. to 6:30 p.m.	7:00 a.m. to 6:30 p.m.	7:00 a.m. to 6:00 p.m.
Wind direction (degrees to the north)	289 (±10)	90 (±28)	130 (±8)	27 (±12)	137 (±31)	110 (±133)	115 (±11)
Wind speed (m/sec)	2.11 (± 0.93)	2.34 (±0.59)	3.55 (±0.76)	2.96 (±0.69)	2.64 (±0.65)	2.37 (±0.84)	2.52 (±0.32)
Temperature (°C)	22.7 (± 2.3)	19.0(±2.3)	23.0 (±0.9)	10.5 (±1.7)	28.0 (±1.4)	28.5 (±2.2)	29.1 (±0.9)
RH (%)	49	70	77	68	64	55	67

Notes: Numbers in the parentheses represent 1 SD.

RESULTS AND DISCUSSION

Effects of Meteorological Conditions on UFP Number Concentration and Size Distribution

Hourly average meteorological data on each sampling day, including ambient temperature, RH, wind direction, and wind speed are reported in Table 2. The particle number concentration and size distribution data were averaged at 1-hr intervals in synchronization with the meteorological data. An inversion layer often formed at night and became stronger in the morning. The wind speeds decreased from 5.8 m/sec during the day to 2.5 m/sec at night. Both result in air stagnation, which has been shown to weaken the dispersion of UFPs and cause high UFP number concentrations in the morning.[28] To reduce these meteorological influences, we only adopted the particle number concentration data from 9:00 a.m. to 6:00 p.m. in the following analysis. During this time period, the traffic density was fairly stable, ranging from 10,045 vehicles/hr to 14,885 vehicles/hr as discussed later in the traffic effect section (Figure 6).

Wind Direction Effect on UFP Number Concentration and Size Distribution

The wind direction played a major role on the particle number concentration.[29] The relationship between wind direction and particle number concentration (data from the control CPC) is shown in Figure 2. The average wind speed and ambient temperature, with 1 standard deviation (SD), are listed for each wind direction. The RH was stable during the measurements, which is also given in the figure. Under these similar weather conditions, we can minimize the variation of wind speed and ambient temperature to deduce a more accurate relationship between the UFP number concentration and wind direction.

Particle number concentration at the downwind side of both roadways was the highest (51,019 ± 10,988 cm^{-3}). The second highest particle number concentration (27,945 ± 22,004 cm^{-3}) was observed when the CPC was at the downwind side of one roadway and the upwind side of the other. It is not surprising that when the CPC was at the upwind side of both roadways, the lowest particle number concentration (15,681 ± 12,706 cm^{-3}) was observed. Particle number concentration at the downwind side of both roadways was 1.8 and 3.3 times as much as at the downwind side of just one roadway and at the upwind side of both roadways, respectively.

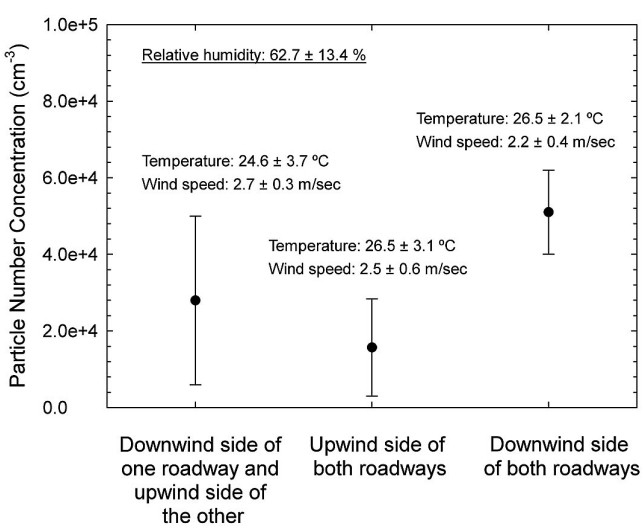

Figure 2. UFP number concentration at the fixed sampling site under different wind directions. Error bars represent 1 SD.

Figure 3 shows the average UFP size distribution data collected at four corners of the intersection; that is, the upwind side of both SPID and Staples Street, downwind side of both SPID and Staples Street, the downwind side of SPID and the upwind side of Staples Street, and the upwind side of Staples Street and the downwind side of SPID. The SMPS was located approximately 20 and 5 m away from SPID and Staples Street at each corner, respectively. Again, the concentration at the downwind side of both roadways was the highest among the four different locations. UFP number size distribution at the upwind side of both roadways was broader, smoother, and also the lowest among the four locations, although the mobile sampling site was very close to the roadside.

Overall, the particle size distribution showed a relatively stable mode for all four curves. The upwind and downwind distributions were both bimodal, exhibiting a nucleation mode at 10–30 nm and a secondary mode at 50–70 nm. The findings showed that the transport of vehicular-emitted UFPs to the sampling site strongly depended on wind direction, especially for nucleation mode particles. The result also clearly showed that SPID contributed more to the observed UFPs than Staples Street, even if the sampling site was closer to Staples Street (5 m) than SPID (20 m).

Wind Speed Effect on UFP Number Concentration

In this study, we found that the wind speed was important in determining the concentration of UFPs at the urban intersection. The same conclusion was drawn by Zhu et al.,[11] a study conducted near Freeway 405 in Los Angeles (13,900 vehicles/hr, 93% of the vehicles were gasoline-powered cars). In Figure 4, particle number concentrations measured by the control CPC are plotted as a function of wind speed. We selected the CPC data when at the downwind side of either SPID or Staples Street, and when the ambient temperature was in the range of 23.4 ± 6.1 °C (average ± 1 SD). An exponential decay line (solid line), equation, and coefficient of determination values are given in the figure. Data from Zhu et al.,[11] collected near Freeway 405 are also plotted (dashed line) for comparison.

The exponential decay pattern of particle number concentration as a function of wind speed is similar between the two studies. The difference between the absolute value of particle number concentration is due in part to the difference in the background concentration, traffic density, and vehicle types. Freeway 405 is a

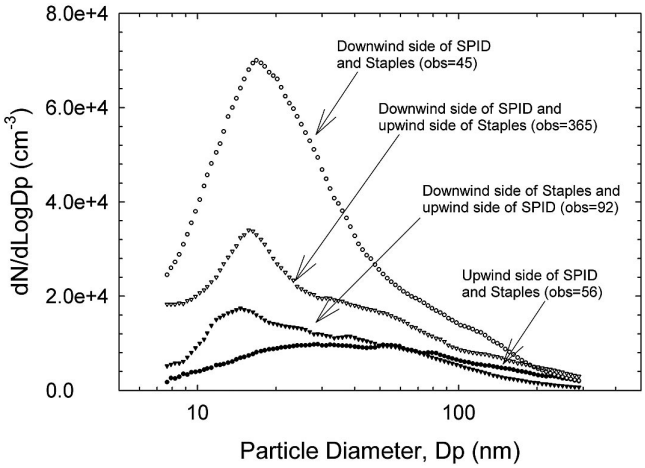

Figure 3. Average UFP size distributions at different locations. Ambient temperature: 23.2 ± 5.8 °C; wind speed: 2.6 ± 0.8 m/sec; RH: 61.7 ± 10.6%.

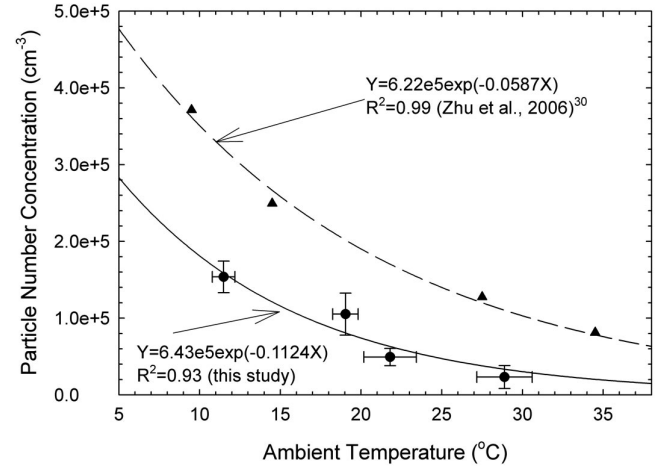

Figure 5. UFP number concentrations at the fixed sampling site as a function of ambient temperatures. Error bars represent 1 SD.

major route in Southern California, with a traffic density of 13,900 vehicles/hr and approximately 5% of the vehicles being HDDVs during the sampling period. The average UFP upwind background concentration (300 m upwind of the freeway) was 3.5×10^4 cm^{-3}.[11] In the study presented here, traffic density was approximately 12,000 vehicles/hr, with 3.7% HDDVs. The average UFP upwind background concentration was 1.6×10^4 cm^{-3} (Figure 3). More measurements with wind speed less than 1 m/sec are needed to understand the relationship between particle number concentration and wind speed under calm wind conditions.

Ambient Temperature Effect on UFP Number Concentration

To illustrate the ambient temperature effect on particle number concentration, the control site CPC data were dichotomized into four ambient temperature groups and presented in Figure 5. We selected the particle number concentration data when the CPC was at the downwind side of either SPID or Staples Street, and the wind speed was in the range of 2.6 ± 0.8 m/sec (average ± 1 SD). The temperature variation experienced during this study was sufficient to investigate the relationship between ambient temperatures and observed UFP number concentrations. Particle number concentration decayed exponentially (solid line) throughout the measured ambient temperature range. This is in agreement with a previous study conducted in Los Angeles, which showed a similar relationship between particle number concentration and ambient temperature (dashed line).[30] The resulting equations with R^2 values from both studies are also given in the figure.

When the exhaust gases do not achieve the critical saturation vapor pressure ratios necessary to nucleate new particles at higher dilution temperature, lower UFP concentrations would be expected.[31] Lower ambient temperatures contribute to significantly increased nucleation mode particle formation in vehicle exhaust sampled on the freeway and in dilution tunnel experiments.[32,33] A study conducted near a suburban-agricultural freeway in northern California reported significant correlations between downwind particle number concentrations and ambient temperature.[13] In a laboratory dynamometer study, particle number concentrations decreased by up to one order of magnitude when the dilution air temperature increased from 13 to 48 °C.[31]

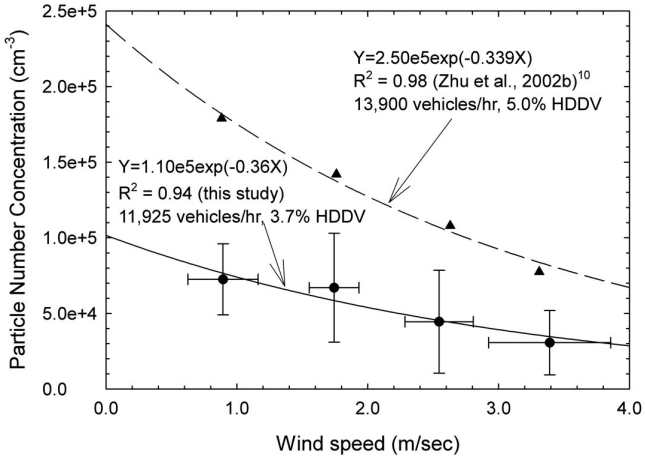

Figure 4. UFP number concentrations at the fixed sampling site as a function of wind speed. Error bars represent 1 SD.

Effects of Traffic on UFP Number Concentration

Traffic Density and Composition. Average diurnal traffic flow patterns on Staples Street and SPID for all sampling days are provided in Figures 6a and 6b, respectively. Data were separated between weekdays and weekends. In Figure 6a, the total traffic density on Staples Street during the weekdays increased from 2035 vehicles/hr between 7:00 a.m. and 8:00 a.m. to 2921 vehicles/hr between 8:00 a.m. and 9:00 a.m., and then decreased to 2401 vehicles/hr around 10:00 a.m. The total traffic density was relatively constant and gradually reached the maximum of 3284 vehicles/hr at 6:00 p.m. During

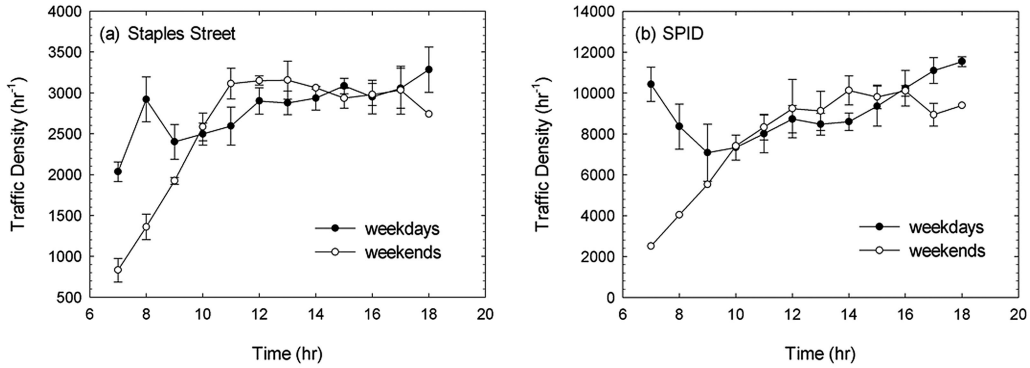

Figure 6. Hourly average traffic density on (a) Staples Street and (b) SPID. Error bars represent 1 SD.

weekends, the traffic density along Staples Street continued to rise from 833 vehicles/hr at 7:00 a.m. to a peak value of approximately 3150 vehicles/hr from 11:00 a.m. to 1:00 p.m. and remained relatively stable at 3000 vehicles/hr until 6:00 p.m. Then a decrease of the traffic density to 2740 vehicles/hr was observed at the end of the sampling time.

As shown in Figure 6b, a steady decrease in traffic along SPID was observed from 7:00 a.m. (10,427 vehicles/hr) to 9:00 a.m. (7080 vehicles/hr). The traffic density then continued to increase steadily although there was a slight decrease in the middle of the day between 12:00 p.m. and 1:00 p.m.. The traffic density reached a peak value of 11,537 vehicles/hr at 6:00 p.m.. Similar to Staples Street, the total traffic density on SPID during weekends started to rise steadily from 2510 vehicles at 7:00 a.m. to 9140 vehicles/hr at 12:00 p.m., and then increased slowly to 9395 vehicles/hr at 6:00 p.m.

Although the traffic patterns along Staples Street and SPID were similar on weekends, they were quite different from each other on weekdays. Both of the traffic patterns along Staples Street and SPID were distinct between weekdays and weekends. The weekdays' average hourly total traffic density was higher than that of the weekends along both Staples Street (2795/hr and 2572/hr for weekdays and weekends) and SPID (9102/hr and 7880/hr for weekdays and weekends).

The traffic along Staples Street for both weekdays and weekends was dominated by LDGVs, which made up of 96.4 and 96.6% of the total traffic, respectively. The composition of the traffic along SPID was also dominated by LDGVs, but the total number of HDDVs traveling on SPID was 2.2 times (weekdays) and 2.3 times (weekends) higher than the corresponding traffic along Staples Street and accounted for up to 3.7% of the total vehicle volume.

Diurnal Profile of UFP Number Concentrations on a Weekday versus a Weekend. Figure 7 shows UFP number concentration measured by the CPC as a function of time at the fixed sampling site on the southeast corner of the intersection on one weekday (May 15, 2007) and one weekend (June 2, 2007). Because wind direction and speed, ambient temperature, and RH all affect UFP formation, transport, and transformation in the atmosphere, we selected May 15, 2007 and June 2, 2007, with similar meteorological conditions, to compare weekday and weekend particle number concentration diurnal profiles.

In Figure 7a, the UFP number concentration decreased by nearly a factor of 5, from 33,622 cm^{-3} to 7255 cm^{-3}, from early morning to midday. Peak concentrations occurred both in the morning and afternoon rush hours as seen in Figure 6b. The diurnal variations of the UFP number concentration for the weekend did not show a similar pattern. In Figure 7b, less traffic was present in the early morning on weekends than on weekdays, resulting in lower particle number concentration levels during that time period. The weekend total traffic density on both Staples Street and SPID increased from 7:00 a.m. to 10:00 a.m. (Figure 6, a and b). This was clearly noticeable in the weekend UFP number concentrations from 8:00 a.m. to 10:00

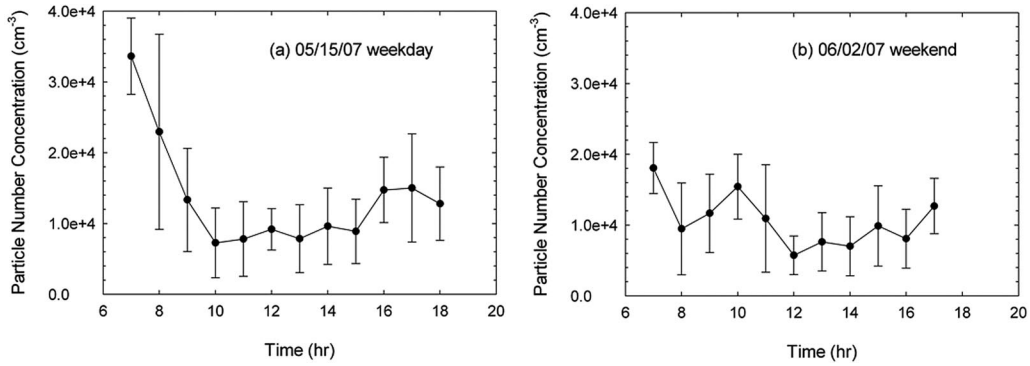

Figure 7. Diurnal variations of the mean UFP number concentration at the fixed sampling site on (a) May 15, 2007 (weekday) and (b) on June 2, 2007 (weekend). Error bars represent 1 SD.

a.m. Two concentration peaks were observed at 7:00 a.m. and 10:00 a.m. The weekday average hourly UFP number concentration (15,609 cm^{-3}) was higher than that of the weekend (9577 cm^{-3}), corresponding to the traffic density levels discussed above.

It is noted that although the traffic density was not the highest for both Staples Street and SPID at 7:00 a.m., the UFP number concentration in that hour was much greater than the other time periods for both weekdays and weekends. It was even higher than the concentration of late afternoon when the traffic density was the greatest. Higher particle number concentrations have been related to lower ambient temperature and higher RH near two different California freeways.[13,30] In this study, lower temperature (24.9 °C for weekdays, 27.5 °C for weekends) and higher RH (73% for both weekdays and weekends) were observed in the dawn compared with the daily average data of 28 °C/29.1 °C and 64%/67% for weekdays and weekends, respectively. Lower ambient temperatures in the early morning may result in higher particle number concentrations of 11,500 cm^{-3} and 4800 cm^{-3} than daily mean on the weekdays and weekends, respectively, on the basis of the exponential regression equation obtained in this study (Figure 5). In addition, the lower atmospheric mixing layer in the early morning may also weaken the dispersion of UFPs and cause high UFP number concentrations. Moreover, an important source of UFPs in the afternoon is the secondary formation through photochemical mechanisms.[34] This, in combination with a higher afternoon mixing layer, often reduces the apparent effect of afternoon/evening traffic on UFP number concentration.

Correlation between Particle Number Concentration and Traffic Density

At the fixed sampling site, when the wind was blowing from the north, the UFP number concentration was expected to be mainly influenced by the traffic on SPID. When the wind direction reversed from north to southwest, the UFP concentration was more heavily influenced by the traffic on Staples Street. To test the relationship between the UFP number concentration and total traffic density and HDDV traffic density, hourly averaged data from Staples Street and SPID were analyzed separately (Figure 8). We selected the particle number concentration data when the ambient temperature was in the range of 23.4 ± 6.1 °C (average ± 1 SD) and wind speed was in the range of 2.6 ± 0.8 m/sec (average ± 1 SD) to lower the influence by meteorological variations.

On Staples Street, the coefficient of determination when only the contribution of HDDVs was considered (R^2 = 0.38) was higher than that for the total traffic density (R^2 = 0.19; Figure 8, a and b). There are two possible explanations for this finding. First, there were various local traffic influences such as changing vehicle speed on Staples Street because of the traffic lights, and

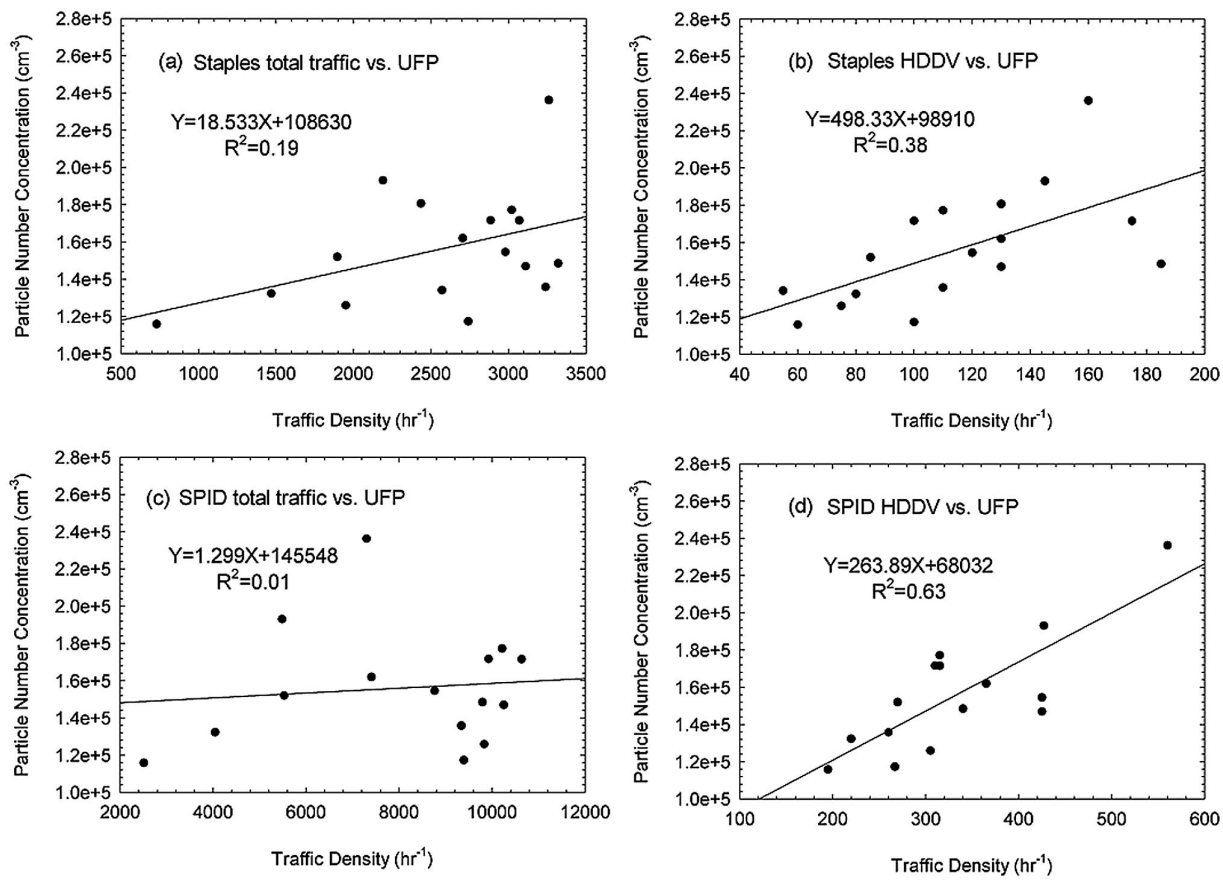

Figure 8. Correlations between UFP number concentrations and (a) total traffic density on Staples Street, (b) HDDV traffic density on Staples Street, (c) total traffic density on SPID, and (d) HDDV traffic density on SPID.

the vehicles traveling on SPID turning right on Staples Street to become Staples Street traffic flow. Second, theHDDVs can emit up to 19–24 times more $PM_{2.5}$ per unit mass fuel burned than LDGVs,[35,36] resulting in much greater emissions of UFPs by HDDVs than LDGVs, although the total traffic was dominated by LDGVs.

During northerly wind periods, the UFP number concentration was mainly influenced by the SPID traffic. A significantly higher correlation was observed between HDDV traffic density on SPID and UFP number concentration ($R^2 = 0.63$) than total traffic density on SPID ($R^2 = 0.01$; Figure 8, c and d). Thus, the HDDV traffic density on SPID was found to be a comparatively better indicator to estimate downwind particle number concentrations at the intersection.

The Impact of Traffic Lights on UFP Number Concentration

Figure 9 shows high temporal variation of UFP number concentrations at the fixed sampling site when the wind was blowing from southwest and traffic on Staples Street dominated measured concentrations. The average UFP number concentration measured when the light was green (G) was 4758 cm^{-3}, much lower than the 21,428 cm^{-3} observed when the light was red (R). This situation was observed repeatedly throughout the measurements. The concentration changes between the red and green traffic lights reflect the effects of vehicle speed on UFP number concentrations. It has been reported that UFP exposure peaks among cyclists were entirely attributable to traffic congestion, waiting at traffic lights, and traveling directly behind accelerating vehicles.[37] The highest UFP concentrations were observed when vehicles were idling, accelerating, and starting from a standing start, such as from a stoplight.[38,39] In this study, greater amounts of UFPs were observed when traffic was idling at the red lights than when traffic continued to run during the green lights.

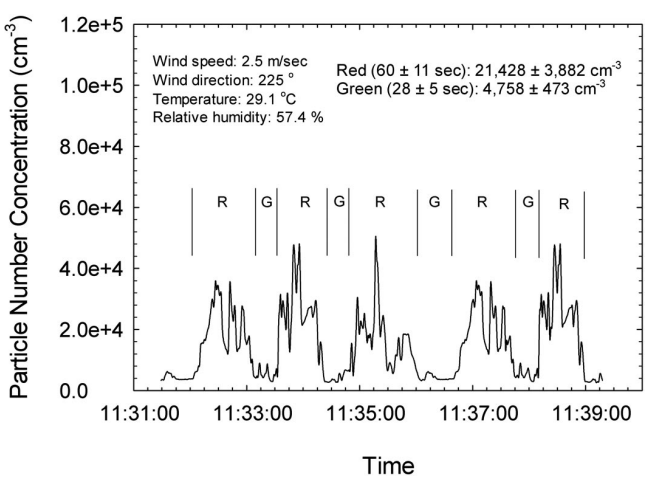

Figure 9. Time-series plot for the impact of traffic lights on UFP number concentration of the fixed sampling site. Meteorological conditions, average duration of traffic lights, and corresponding particle number concentrations are also given in the figure.

CONCLUSIONS

In this study, UFP number concentration and size distribution data collected at a busy urban intersection-were presented and their relationships with meteorological parameters and traffic were investigated. The analysis showed that wind speed and direction had a significant effect on the UFP number concentration, especially for nucleation mode (10–30 nm) particles. The highest and lowest particle concentrations were observed at the downwind side and the upwind side of both roadways, respectively. Exponential decay was found to be a good estimator to predict particle number concentration at different wind speeds and ambient temperatures, which is in agreement with previous studies.

In addition, a clear difference between weekdays and weekends with respect to the measured traffic densities and UFP number concentration was observed. Although the fixed sampling site was closer to Staples Street (5 m) than SPID (20 m), SPID contributed more to the observed UFP concentrations. There was a stronger correlation between UFP number concentration and HDDV traffic density than total traffic density. The UFP number concentration at red traffic lights (21,428 cm^{-3}) was 3.5 times higher than at green traffic lights (4758 cm^{-3}).

The results of this study highlight the strong spatial inhomogeneity of vehicular emitted UFPs and their strong dependence on the meteorology. Long-term data collection over complete diurnal and seasonal cycles is needed to more accurately assess vehicular-emitted UFP exposures in the future.

ACKNOWLEDGMENTS

This paper is based on work supported by the National Science Foundation funded Center of Research Excellence in Science and Technology-Research on Environmental Sustainability of Semi-Arid Coastal Areas (HRD-0734850). The authors would also like to thank the City of Corpus Christi and Texas Commission on Environmental Quality for their support and information provided for this research work. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors. The authors would like to express their sincere gratitude to Bob Castro, David Granado, Jayanth Pudota, and other students from Texas A&M University–Kingsville for their help in the field.

REFERENCES

1. Dockery, D.W. Epidemiologic Evidence of Cardiovascular Effects of Particulate Air Pollution; *Environ. Health Perspect.* **2001**, *109* (Suppl. 4), 483-486.
2. Pope, C.A.; Burnett, R.T.; Thun, M.J.; Calle, E.E.; Krewski, D.; Ito, K.; Thurnston, G.D. Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution; *J. Am. Med. Assoc.* **2002**, *287*, 1132-1141.
3. Bai, N.; Khazaei, M.; Van Eeden, S.F.; Laher, I. The Pharmacology of Particulate Matter Air Pollution-Induced Cardiovascular Dysfunction; *Pharmacol. Ther.* **2007**, *113*, 16-29.
4. Donaldson, K.; Li, X.Y.; MacNee, W. Ultrafine (Nanometre) Particle Mediated Lung Injury; *J. Aerosol Sci.* **1998**, *29*, 553-560.
5. Ibald-Mulli, A.; Wichmann, H.E.; Kreyling, W.; Peters, A. Epidemiological Evidence on Health Effects of Ultrafine Particles; *J. Aerosol Med.* **2002**, *15*, 189-201.

6. Oberdoster, G. Pulmonary Effects of Inhaled Ultrafine Particles; *Int. Arch. Occup. Environ. Health.* **2001**, *74*, 1-8.
7. Cass, G.R.; Hughes, L.A.; Bhave, P.; Kleeman, M.J.; Allen, J.O.; Salmon, L.G. The Chemical Composition of Atmospheric Ultrafine Particles; *Phil. Trans. R. Soc. Lond. A* **2000**, *358*, 2581-2592.
8. Kerminen, V.-M.; Pakkanen, T.A.; Makela, T.; Hillamo, R.E.; Sillanpaa, M.; Ronkko, T.; Virtanen, A.; Keskinen, J.; Pirjola, L.; Hussein, T.; Hameri, K. Development of Particle Number Size Distribution near a Major Road in Helsinki during an Episodic Inversion Situation; *Atmos. Environ.* **2007**, *41*, 1759-1767.
9. Weijers, E.P.; Khlystov, A.Y.; Kos, G.P.A.; Erisman, J.W. Variability of Particulate Matter Concentrations along Roads and Motorways Determined by a Moving Measurement Unit; *Atmos. Environ.* **2004**, *38*, 2993-3002.
10. Zhu, Y.; Hinds, W.C.; Kim, S.; Shen, S.; Sioutas, C. Study of Ultrafine Particles near a Major Highway with Heavy-Duty Diesel Traffic; *Atmos. Environ.* **2002**, *36*, 4323-4335.
11. Zhu, Y.; Hinds, W.C.; Kim, S.; Sioutas, C. Concentration and Size Distribution of Ultrafine Particles near a Major Highway; *J. Air & Waste Manage. Assoc.* **2002**, *52*, 1032-1042.
12. Stanier, C.O.; Khlystov, A.Y.; Pandis, S.N. Ambient Aerosol Size Distributions and Number Concentrations Measured during the Pittsburgh Air Quality Study (PAQS); *Atmos. Environ.* **2004**, *38*, 3275-3284.
13. Nanzetta, M.K.; Holmen, B.A. Roadside Particle Number Distributions and Relationships between Number Concentrations, Meteorology, and Traffic along a Northern California Freeway; *J. Air & Waste Manage. Assoc.* **2004**, *54,* 540-554.
14. Ruellan, S.; Cachier, H. Characterization of Fresh Particulate Vehicular Exhausts near a Paris High Flow Road; *Atmos. Environ.* **2001**, *35*, 453-468.
15. Molnar, P.; Janhall, S.; Hallquist, M. Roadside Measurements of Fine and Ultrafine Particles at a Major Road North of Gothenburg; *Atmos. Environ.* **2002**, *36*, 4115-4123.
16. Westerdahl, D.; Fruin, S.; Sax, T.; Fine, P.M.; Sioutas, C. Mobile Platform Measurements of Ultrafine Particles and Associated Pollutant Concentrations on Freeways and Residential Streets in Los Angeles; *Atmos. Environ.* **2005**, *39*, 3597-3610.
17. Ketzel, M.; Wahlin, P.; Berkowicz, R.; Palmgren, F. Particle and Trace Gas Emission Factors under Urban Driving Conditions in Copenhagen Based on Street and Roof-Level Observations; *Atmos. Environ.* **2003**, *37*, 2735-2749.
18. Vakeva, M.; Hameri, K.; Kulmala, M.; Lahdes, R.; Ruuskanen, J.; Laitinen, T. Street Level versus Rooftop Concentrations of Submicron Aerosol Particles and Gaseous Pollutants in an Urban Street Canyon; *Atmos. Environ.* **1999**, *33*, 1385-1397.
19. Hughes, L.S.; Cass, G.R. Physical and Chemical Characterization of Atmospheric Ultrafine Particles in the Los Angeles Area; *Environ. Sci. Technol.* **1998**, *32*, 1153-1161.
20. Ruuskanen, J.; Tuch, T.; Ten Brink, H.; Peters, A.; Khlystov, A.; Mirme, A.; Kos, G.P.A.; Brunekreef, B.; Wichmann, H.E.; Buzorius, G.; Vallius, M.; Kreyling, W.G.; Pekkanen, J. Concentrations of Ultrafine, Fine and $PM_{2.5}$ Particles in Three European Cities; *Atmos. Environ.* **2001**, *35*, 3729-3738.
21. Morawska, L.; Thomas, S.; Gilbert, D.; Greenaway, C.; Rijnders, E. A Study of the Horizontal and Vertical Profile of Submicrometer Particles in Relation to a Busy Road; *Atmos. Environ.* **1999**, *33*, 1261-1274.
22. Hitchins, J.; Morawska, L.; Wolff, R.; Gilbert, D. Concentrations of Submicrometre Particles from Vehicle Emissions near a Major Road; *Atmos. Environ.* **2000**, *34*, 51-59.
23. Harrison, R.M.; Jones, M.; Collins, G. Measurements of the Physical Properties of Particles in the Urban Atmosphere; *Atmos. Environ.* **1999**, *33*, 309-321.
24. Morawska, L.; Jayaratne, E.R.; Mengersen, K.; Jamriska, M.; Thomas, S. Differences in Airborne Particle and Gaseous Concentrations in Urban Air between Weekdays and Weekends; *Atmos. Environ.* **2002**, *36*, 4375-4383.
25. Kittelson, D.B.; Watts, W.F.; Johnson, J.P. Nanoparticle Emissions on Minnesota Highways; *Atmos. Environ.* **2004**, *38*, 9-19.
26. Holmes, N.S.; Morawska, L.; Mengersen, K.; Jayaratne, E.R. Spatial Distribution of Submicrometre Particles and CO in an Urban Microscale Environment; *Atmos. Environ.* **2005**, *39*, 3977-3988.
27. *U.S. Census* 2000; U.S. Census Bureau; available at *http://factfinder.census.gov/servlet/GCTTable?_bm=y&-geo_id=04000US48&-_box_head_nbr=GCT-PH1&-ds_name=DEC_2000_SF1_U&-redoLog=false&-mt_name=DEC_2000_SF1_U_GCTPH1_ST2&-format=ST-7* (accessed 2008).
28. Shi, Z.; He, K.; Yu, X.; Yao, Z.; Yang, F.; Ma, Y.; Ma, R.; Jia, Y.; Zhang, J. Diurnal Variation of Number Concentration and Size Distribution of Ultrafine Particles in the Urban Atmosphere of Beijing in China; *J. Environ. Sci.* **2007**, *19*, 933-938.
29. Charron, A.; Harrison, R.M. Primary Particle Formation from Vehicle Emissions during Exhaust Dilution in the Roadside Atmosphere; *Atmos. Environ.* **2003**, *37,* 4109-4119.
30. Zhu, Y.; Kuhn, T.; Paul, M.; Hinds, W.C. Comparison of Daytime and Nighttime Concentrations Profiles and Size Distributions of Ultrafine Particles near a Major Highway; *Environ. Sci. Technol.* **2006**, *40*, 2531-2536.
31. Abdul-Khalek, I.; Kittelson, D.; Brear, F. The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements; Society of Automotive Engineers (SAE) Technical Paper No. 011142; SAE: Warrensdale, PA, 1999.
32. Kittelson, D. B.; Johnson, J.; Watts, W. F.; Wei, Q.; Drayton, M.; Paulsen, D.; Bukowiecki, N. Diesel Aerosol Sampling in the Atmosphere; Society of Automotive Engineers (SAE) Technical Paper No. 012212; SAE: Warrensdale, PA, 2000.
33. Wei, Q.; Kittelson, D.B.; Watts, W.F. Single-Stage Dilution Tunnel Performance; Society of Automotive Engineers (SAE) Technical Paper No. 010201; SAE: Warrensdale, PA, 2001.
34. Kim, S.; Shen, S.; Sioutas, C.; Zhu, Y.; Hinds, W.C. Size Distribution and Diurnal and Seasonal Trends of Ultrafine Particles in Source and Receptor Sites of the Los Angeles Basin; *J. Air & Waste Manage. Assoc.* **2002**, *52,* 297-307.
35. Kirchstetter, T.W.; Harley, R.A.; Kriesberg, N.M.; Stolzenburg, M.R.; Hering, S.V. Corrigendum to "On-Road Measurement of Fine Particle and Nitrogen Oxide Emissions from Light- and Heavy-Duty Motor Vehicles"; *Atmos. Environ.* **2002**, *36*, 6059.
36. Fraser, M.P.; Buzcu, B.; Yue, Z.W.; McGaughey, G.R.; Desai, N.R.; Allen, D.T.; Seila, R.L.; Lonneman, W.A.; Harley, R.A. Separation of Fine Particulate Matter Emitted from Gasoline and Diesel Vehicles Using Chemical Mass Balancing Techniques; *Environ. Sci. Technol.* **2003**, *37*, 3904-3909.
37. Kaur, S.; Clark, R.D.R.; Walsh, P.T.; Arnold, S.J.; Colvile, R.N.; Nieuwenhuijsen, M.J. Exposure Visualization of Ultrafine Particle Counts in a Transport Microenvironment; *Atmos. Environ.* **2006**, *40*, 386-398.
38. Fruin, S.; Westerdahl, D.; Sax, T.; Sioutas, C.; Fine, P.M. Measurements and Predictors of On-Road Ultrafine Particle Concentrations and Associated Pollutants in Los Angeles; *Atmos. Environ.* **2008**, *42*, 207-219.
39. Kittelson, D.B.; Watts, W.F.; Johnson, J.P.; Schauer, J.J.; Lawson, D.R. On-Road and Laboratory Evaluation of Combustion Aerosols. Part 2: Summary of Spark Ignition Engine Results; *J. Aerosol Sci.* **2006**, *37*, 931-949.

About the Authors

Yungang Wang is a graduate student and Dr. Yifang Zhu is an assistant professor, both at the Department of Environmental Engineering of Texas A&M University–Kingsville (TAMUK), Kingsville, TX. Robert Salinas is an undergraduate student from the Department of Chemical Engineering. David Ramirez is an assistant professor and Saritha Karnae is a research engineering associate in the Department of Environmental Engineering at TAMUK. Dr. Kuruvilla John is a professor of Environmental Engineering and an interim dean at TAMUK. Address correspondence to Dr. Yifang Zhu, Environmental Engineering Department, Texas A&M University–Kingsville, 700 University Boulevard, MSC 213, Kingsville, TX 78363; phone: +1-361-593-3898; fax: +1-361-593-2069; e-mail: yifang.zhu@tamuk.edu.