Atmospheric Pollution Research 4 (2013) 329-335

Atmospheric Pollution Research
www.atmospolres.com

Personal exposure of commuters in public transport to $PM_{2.5}$ and fine particle counts

Burcu Onat, Baktygul Stakeeva

Istanbul University, Faculty of Engineering, Department of Environmental Engineering, 34320 Avcilar, Istanbul, Turkey

ABSTRACT

To investigate fine particulate air pollution generated by public transport and its microenvironment, $PM_{2.5}$ measurements and particle number counts for six particle size ranges (0.3–0.5 µm, >0.5–1.0 µm, >1.0–3.0 µm, >3.0–5.0 µm, >5.0–10 µm and >10 µm) were obtained for four public transport modes: bus, metro–bus, car and walking. The measurements were repeated for each transport mode twice a day for 7–10 measurement days. The highest average $PM_{2.5}$ concentration was measured inside a bus (106 µg/m^3) during rush hours. The highest single peak measurement was a concentration of 316 µg/m^3 for walking during non–rush hours. The $PM_{2.5}$ level in a car with the air conditioning fan off was approximately 2.5 times lower than the level with the air conditioning fan on. Moderate correlations were found between $PM_{2.5}$ concentrations and wind speed. Weak correlations were found between $PM_{2.5}$ concentrations, relative humidity and temperature. The results showed that the diameters of most of the particles were smaller than 0.5 µm, regardless of the transport mode. The average fine particle number (size range 0.3–0.5) for all transport modes ranged from 54 647 to 209 746 particles/10^3 cm^3 during rush hours and from 49 423 to 184 866 particles/10^3 cm^3 during non–rush hours.

Keywords: *Exposure concentrations, urban transport microenvironment, $PM_{2.5}$, particle number*

Corresponding Author:
Burcu Onat
☎ : *+90-212-473-7070 (ext:17722)*
🖷 : *+90-212-473-7180*
✉ : *bonat@istanbul.edu.tr*

Article History:
Received: 02 April 2013
Revised: 02 June 2013
Accepted: 04 June 2013

doi: 10.5094/APR.2013.037

1. Introduction

Traffic emissions result in small–scale spatial variations and affect urban and regional background air pollution concentrations. Short–term and long–term exposure to traffic–related air pollution may shorten life expectancy (Hoek et al., 2002). Traffic is a major emission source of particles especially in urban areas (Weijers et al., 2004; Gertler, 2005). Cohort studies suggest that exposure to particulate matter (PM) air pollution is associated with respiratory and cardiovascular diseases and lung cancer (Dockery et al., 1993; Pope et al., 1995). The number and mass concentrations of particles have been observed to increase with increasing traffic intensity. The majority of fine particles originate from exhaust emissions, wear of tire and brake systems (Riediker et al., 2004). The number of particles is a more sensitive indicator of the contribution of traffic than the aerosol mass because traffic emits mostly fine particles that dominate the number, rather than the mass (Weijers et al., 2004; Cheng et al., 2009). Recently, many studies of fine particle concentrations and particle numbers inside vehicles such as buses, minibuses, cars and trains, as well as for walking and in the microenvironment, have been conducted (Alm et al., 1999; Adams et al., 2001; Chan et al., 2002a; Chan et al., 2002b; Levy et al., 2002; Gomez–Perales et al., 2004; Gulliver and Briggs, 2004; Han et al., 2005; Kaur et al., 2005a; Kaur et al., 2005b; Kaur et al., 2007; Zhu et al., 2007; Tittarelli et al., 2008; Cheng et al., 2009; Kaminsky et al., 2009). Most of these studies have suggested that the health risk may be related to particle number rather than mass (Asmi et al., 2009).

Although atmospheric particles have been widely studied, there have been very few studies of exposure to particles during transport in Turkey (Onat and Stakeeva 2012; Sahin et al., 2012). In metropolitan areas in particular, traffic is the major particle source that affects passengers' and drivers' particle exposure. Buses, metro–buses and cars are the major transportation types in Istanbul, Turkey where there is no subway system. Walking is a universal and common form of transport. The preferred transport mode is by metro–bus because metro–buses travel on separate access roads. Direct exposure to airborne particles can be highly variable, depending on the traffic intensity, transport type, vehicle type and age and driving behavior in the traffic microenvironment. The goal of this study is to assess personal exposure to fine particles and to investigate differences in concentrations and particle numbers for different transport modes. Measurements of particle numbers and particle concentrations for the four transport modes considered were obtained in October–November 2008. The effects of wind speed, temperature and humidity on particle numbers and concentrations were also investigated.

2. Materials and Methods

2.1. Field study

Istanbul, the most densely populated city in Turkey that is separated into two parts by the Bosphorus: the Anatolian side and the European side. The study area is between the Avcilar and Bakirkoy districts on the European side of Istanbul (Figure 1). The

D–100 highway passes through the residential areas. Figure 1 illustrates the studied routes along the D–100 highway for metro–buses, cars, buses and walking. The metro–bus travels on the access road that is closed to other vehicles in the middle of the D–100 highway.

The routes for roadway transport were selected because they are representative of typical urban commuting routes in residential and commercial districts in Istanbul. The traffic volume on this highway is very high; the average daily traffic volume is more than 100 000 vehicles. The average journey time on the selected routes ranges from 12 to 19 minutes and the average journey distances change between 1.5 km and 10 km (Table 1). Air conditioning is used in metro–buses and cars while natural ventilation is used in buses. The preferred mode of transport in Istanbul is by car and the number of cars in Istanbul is approximately 3 millions. The number of buses and metro–buses in Istanbul are 5 349 and 410, respectively. Walking exposure in the traffic microenvironment was considered as out–vehicle exposure.

2.2. Measurements

In this study, $PM_{2.5}$ concentrations were measured using a portable real–time aerosol monitor (pDR 1200 model, Thermo, USA) and particle counts were obtained using a handheld airborne particle counting device (model 3016, Lighthouse, Fremont, USA). Particle counts and $PM_{2.5}$ concentration measurements were obtained simultaneously. The portable real–time aerosol monitor uses the light scattering method. The instruments flow rate range is 1–5 L/min and particles with diameters between 1 and 10 µm can be detected. In this study, the flow rate was adjusted to 4 L/min for $PM_{2.5}$ concentration monitoring and the data logging interval was set at 30 s. The particle counter employs light–scattering technology and a laser diode optical sensor to detect and count particles in six size ranges (0.3–0.5 µm, >0.5–1.0 µm, >1.0–3.0 µm, >3.0–5.0 µm, >5.0–10 µm and >10 µm). The instrument samples air continuously at 2.83 L/min. Particles smaller than 0.3 µm in diameter cannot be detected by the instrument. The particle counter has relative humidity and temperature sensors, and all collected data are stored in the instrument's memory. During the field study, weather parameters (temperature and relative humidity) were recorded with the particle counter. Wind speed data were obtained from the Ataturk Airport meteorological station which is 500 m away from the study area. SPSS statistics 17.0 program was used for the statistical testing of the results.

Two researchers participated to measure the exposure measurements. All researchers attended a training covering the operation of equipments and the schedule of the study. The sampling heads of the instruments were positioned in the personal breathing zone, which is usually considered to be within 30 cm of the mouth during monitoring (Adams et al., 2001).

Measurements were obtained between 8 October and 16 November 2008. No measurements were obtained on rainy days. Measurements were obtained twice a day, during the morning (08:00–10:30) rush hours and during midday (12:00–14:00) non–rush hours. The journeys were made in one direction and measurements were obtained for 7 to 10 days for four modes of transport: bus, metro–bus, car (air conditioning fan on/off) and walking (Table 2).

The car used in this study was a 2006 Mazda–3 four–door sedan with a 105–HP–1.6–1 engine (Euro 4). The metro–bus was a 2007 Mercedes–Benz Capacity with a 349–HP engine (Euro 4–5). The bus has old technology including a pre–Euro model engine. During all of the data collection in the metro–bus, the windows were closed and the air conditioning was on. The windows were closed during data collection in the car, and the ventilation settings in the car were as follows: (i) air conditioning (AC) fan on or (ii) air conditioning (AC) fan off and recirculation (RC) on. The AC system intakes outdoor air when the AC fan is on. The AC system recirculates indoor air when the AC fan is off. The air conditioning speed was kept at medium during the study. In the bus, the windows were open and there was no air conditioning system.

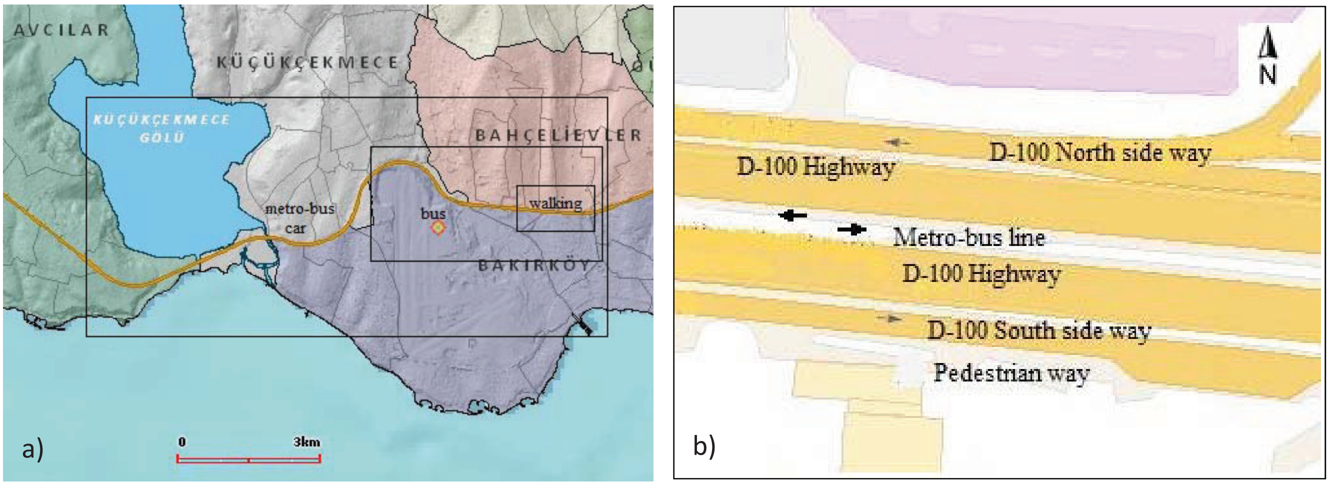


Figure 1. ***(a)*** *Study area* ***(b)*** *Selected routes for metro–bus, bus, car and walking along the D–100 highway.*

Table 1. *Features of the selected routes*

Transport mode	Ventilation type	Route	Travel distance (km)	Average travel time (min)
Bus	Opening window	Yenibosna–Sefakoy	5	12
Metro–bus	Air–conditioning	Sirinevler–Avcilar	10	18
Car	Air–conditioning	Sirinevler–Avcilar	10	19
Walking	–	Sirinevler–Yenibosna	1.5	15

Table 2. *$PM_{2.5}$ concentrations in different transportation modes*

Transportation Modes	N	$PM_{2.5}$ concentration (µg/m^3)							
		Non–rush hours				Rush hours			
		Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Bus	8	84.5	42.8	13.0	179.0	120.4	73.5	25.0	428.0
Metro–bus	7	39.9	16.0	11.0	120.0	45.4	18.6	14.0	178.0
Car									
Air conditioning fan on	10	55.1	11.0	21.7	150.0	67.9	25.1	18.0	144.0
Air conditioning fan off/RC on	10	31.4	17.7	2.0	94.0	30.6	16.2	6.0	150.0
Walking (*near the street*)	10	82.1	40.9	11.0	316.0	89.2	48.6	20.0	303.0

N: sample size, Mean: arithmetic mean, SD: standard deviation, Max: maximum, Min: minimum

2.3. QA/QC

The portable real–time aerosol monitor pDR 1200 was calibrated against a Partisol FRM Air Sampler (Model 2000, Thermo, USA) in the laboratory for quality assurance of the $PM_{2.5}$ measurements. The correlation coefficient (*r*) between the two methods is 0.99 and the slope of the regression line is 1.16 (Figure 2). The purge test was done to check the particle counter for zero count. The purge filter was a 0.2 micron, and 0.1 CFM filter. The purge filter was attached to the counter and ten one–minute samples were taken. It was seen no more than 1 count on average per one–minute sample.

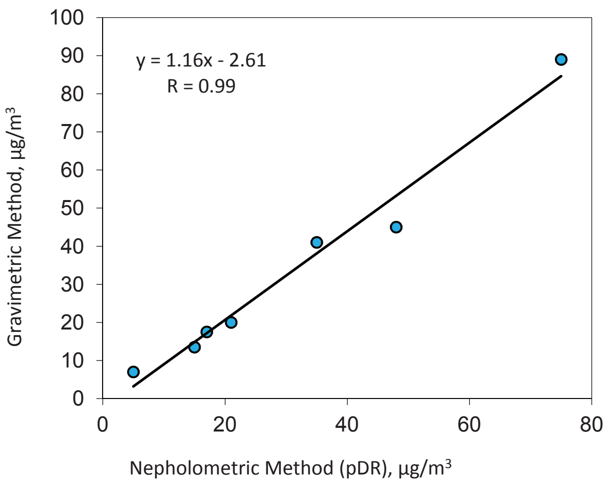


***Figure 2.** The correlation (r) and the slope of the regression between Nephelometric method and Gravimetric method for pDR real time monitors.*

3. Results and Discussion

3.1. $PM_{2.5}$ concentrations

The concentrations of $PM_{2.5}$ measured in October and November 2008 inside the bus, metro–bus and car and during walking are shown in Table 2. Forty five measurements were obtained for $PM_{2.5}$. The levels of $PM_{2.5}$ for the selected modes of transport ranged between 2.0 and 428 µg/m^3 and the highest concentrations were observed during the rush hours. In a previous study, the background concentration of the daily average $PM_{2.5}$ in the roadside environment was observed as 55.4±29.5 µg/m^3 (Onat et al., 2013). As Table 2 shows, the highest average $PM_{2.5}$ concentration was measured inside the bus 120.4±73.5 µg/m^3 during the rush hours and 84.5±42.8 µg/m^3 during the non–rush hours. The statistical significance of the rush hour and non–rush hour measurement difference inside the bus was assessed using Student's *t*–test, and no statistically meaningful difference in $PM_{2.5}$ concentrations was detected ($p>0.05$). Previous studies in Hong Kong and Guangzhou, China and in Mexico City, Mexico and Trujillo, Peru have found average exposure levels for $PM_{2.5}$ in non–air conditioned buses to be 93–145 µg/m^3 (Chan et al., 2002a; Chan et al., 2002b), and 137–161 µg/m^3 during rush hours (Gomez–Perales et al., 2004; Han et al., 2005), whereas the average exposure level for $PM_{2.5}$ in non–air–conditioned buses in Helsinki, Finland was found to be 34 µg/m^3 (Asmi et al., 2009). In the present study, the average concentrations measured in the bus were similar to those obtained in the previous studies mentioned except the Helsinki study. This difference is reported to be due to the background concentrations and traffic density in Helsinki being much lower than in the other cities or as mentioned due to seasonal variations affecting the results. It was suggested that it could partly be related to weak diurnal variation of number and mass concentrations in Helsinki during summer season and thus a more pronounced effect could be expected during other seasons (Asmi et al., 2009). The second highest average $PM_{2.5}$ concentration was recorded for walking (89.2±48.6 µg/m^3 for rush hours and 82.1±40.9 µg/m^3 for non–rush hours) (Table 2). There was no statistically meaningful difference between the rush–hour and non rush–hour $PM_{2.5}$ concentrations for walking ($p>0.05$). In this study, the average $PM_{2.5}$ personal exposure for walking was found to be greater than the range of values measured in London (27.7–37.7 µg/m^3) (Kaur et al., 2005a; Kaur et al., 2005b), but lower than the average in Taiwan (214 µg/m^3) (Kaur et al., 2007). Outside emissions are affected by heavy traffic, busy intersections and meteorology (Alm et al., 1999; Asmi et al., 2009; King et al., 2009). As Table 2 shows, lower concentrations were observed inside the metro–bus (45.4±18.6 µg/m^3 for rush hours and 39.9±16.0 µg/m^3 for non–rush hours). There was no statistically meaningful difference between the rush–hour and non rush–hour $PM_{2.5}$ concentrations inside the metro–bus ($p>0.05$).

The average $PM_{2.5}$ concentration inside the car during rush hours was 59.5±26.3 µg/m^3 for AC fan on and 27.8±11.5 µg/m^3 with the AC fan off. During non–rush hours, the average $PM_{2.5}$ concentration inside the car was 52.5±14.5 µg/m^3 with the AC fan on and 30.4±17.0 µg/m^3 with the AC fan off. The differences in $PM_{2.5}$ concentration inside the car with the AC fan off and with the AC fan were found to be statistically significant ($p<0.01$). The ventilation setting in the car greatly affected the mass and number of particles. The $PM_{2.5}$ level in the car with the AC fan off was approximately 2.5 times lower than the level with the AC fan on. The reason for this could be that with the fan on, a large amount of air in the cabin came from outside. The high in–vehicle exposures were related to outside emissions. Zhu et al. (2007) observed that the particle concentration outside the vehicle was varied significantly while driving on freeways. When the AC is on in re–circulate mode (RC on), the intake of not only exhaust emissions but also particles are prevented, which causes a reduction in particle concentration. In a recent study, Kaminsky et al. (2009) showed that particle count readings are generally the highest with the windows closed and the air conditioning on and observed that particle count readings with the windows closed and the AC on are more than three times higher than the readings with the windows closed and the AC off.

The $PM_{2.5}$ concentrations inside the metro–bus and car (AC fan off and RC on) were considerably lower than those observed inside the bus and for walking. The reason for the high $PM_{2.5}$ levels in the bus and for walking could be the suspension of particles because of the movement of vehicles and wind. The ventilation in the bus is through open windows, so polluted air circulates in the bus. The walking exposure to $PM_{2.5}$ was higher than the metro–bus and car exposures, but lower than the bus exposure. The highest $PM_{2.5}$ concentrations for walking (up to 316 µg/m^3) were observed in traffic congestion and at intersections.

The statistical testing for differences between transport modes was done. The differences in metro–bus/bus and metro–bus/walking were found to be statistically significant ($p<0.05$) for non–rush hours. There was no statistically meaningful difference between other transports for non–rush and rush hours ($p>0.05$).

The effects of wind speed, temperature and relative humidity were also investigated in the study. The effect of wind speed on $PM_{2.5}$ levels is presented in Figure 3. Wind speed had an effect on in–vehicle and walking exposures. During calm weather (≤2 m/s), higher $PM_{2.5}$ exposures were measured than during windy weather (>2 m/s). Moderate correlations were found between $PM_{2.5}$ concentrations and wind speed (0.70 for bus, 0.68 for walking, 0.66 for metro–bus and 0.56 for car). The statistical significance of the wind speed and particle concentration difference inside the car was evaluated by Student's *t*–test, and no statistically meaningful difference in $PM_{2.5}$ concentration was detected ($p>0.05$). The differences in $PM_{2.5}$ concentration inside the bus, metro–bus and during walking with the wind speed were found to be statistically significant ($p<0.01$). However, as Figure 4 shows, the correlations between $PM_{2.5}$ concentrations and temperature were weak (0.41 for bus, 0.075 for metro–bus and 0.10 for car). According to the Figure 4, there is a negative correlation between $PM_{2.5}$ concentrations and temperature. When temperature increased the particle concentration decreased. It was observed that there is a positive and weak correlation between $PM_{2.5}$ concentration and relative humidity, except the car.

A moderate correlation was found between $PM_{2.5}$ concentration and temperature for walking (0.68). Weak correlations were found between $PM_{2.5}$ concentrations and relative humidity (0.22 for bus, 0.49 for walking, 0.088 for metro–bus and 0.44 for car).

3.2. Particle counts

Figure 5 presents the particle count results for the six particle size ranges considered for the four transport modes. In general, the average levels of the six particle size fractions for all of transport modes during rush hours were greater than those during non–rush hours. Figure 5 show that most of the particles have diameters smaller than 0.5 µm, regardless of the transport mode. The average numbers of fine particles (size range 0.3–0.5 µm) inside the metro–bus and bus during rush hours were 151 000 particles/10^3 cm^3 (with a range of 54 000–367 000 particles/10^3 cm^3) and 209 000 particles/10^3 cm^3 (with a range of 95 000–346 000 particles/10^3 cm^3), respectively. The number of larger particles (>1 µm) was very small. In the car, with the AC fan on, the fine particle (size range 0.3–0.5 µm) number ranged from 45 000 particles/10^3 cm^3 to 220 000 particles/10^3 cm^3, while the range was between 25 000 particles/10^3 cm^3 and 133 000 particles/10^3 cm^3 with the AC fan off and RC on. The numbers of fine particles number (<1 µm) and coarse particles (>1 µm) for the bus and walking were observed to be higher than those observed in the metro–bus and the car. Fine particles are mostly caused by exhaust emissions, while coarse particles in the traffic microenvironment originate from resuspended particles. In Amsterdam, the highest particle numbers (up to 600x10^6 particles/10^3 cm^3 for a particle size range of 0.1–7 µm) were measured in traffic congestion or behind a heavy diesel–engine vehicle (Weijers et al., 2004).

The *t*–test indicated that the difference between the transport modes for first channel (0.3–0.5 µm) was not significant for rush hours ($p>0.01$) (Table 3). Considering the second channel and third channel (0.5 µm<particles<3.0 µm), the difference between car/metro–bus and walking/bus transport modes were not significant ($p>0.01$). It was observed that the difference between the all transport modes except walking–bus for rush hour were significant ($p<0.01$, $p<0.05$) for the last three channels (particles>3 µm).

Figure 6 shows that the particle size distributions and relative humidity levels for all of the transport modes. In general, higher relative humidity levels (>50%) increased the counts of particles <1.0 µm in size 1.1 to 2.1 times more than lower relative humidity levels (<50%) for the car, bus and metro–bus. However, this difference was not observed for walking. Most of relative humidity levels were higher than 50% during walking. Higher relative humidity levels (>75%) increased the counts of particles <1 µm in size by 1.6 to 1.8 times more and the counts of particles >1 µm in size by 1.2 to 1.6 times more than lower relative humidity levels (<75%) for walking. The results showed that the high relative humidity elevated the counts of particles <1 µm in size. The high humidity may cause growth of the hygroscopic particlesand may increase the contribution of the larger particles.

Particle concentrations inside vehicles are affected by the number of passengers. The number of passengers inside a vehicle influences ultrafine particle (UFP<100 nm) concentrations (Kaminsky et al., 2009) and the particle generation by human presence may increase the concentration (Zhu et al., 2007). Because UFP particles were not considered in this study, the effect of the number of passengers was not taken into account.

Table 3. *The p values (t-test) of the differences between all transport modes for particle numbers in each size fraction for rush hours and (non–rush hours)*

Transport modes	Particle Size (µm)					
	0.3–0.5	>0.5–1.0	>1.0–3.0	>3.0–5.0	>5.0–10.0	>10.0
Car–Metrobus	0.641 (0.614)	0.557 (0.998)	0.523 (0.040)	0.010 (0.000)	0.000 (0.006)	0.000 (0.000)
Car–Walking	0.263 (0.019)	0.111 (0.003)	0.005 (0.002)	0.000 (0.000)	0.001 (0.000)	0.000 (0.002)
Car–Bus	0.133 (0.018)	0.006 (0.001)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Metrobus–Walking	0.100 (0.034)	0.061 (0.002)	0.003 (0.001)	0.001 (0.003)	0.025 (0.010)	0.036 (0.163)
Metrobus–Bus	0.080 (0.057)	0.032 (0.001)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.019 (0.103)
Walking–Bus	0.608 (0.680)	0.629 (0.368)	0.080 (0.055)	0.058 (0.028)	0.005 (0.012)	0.000 (0.002)

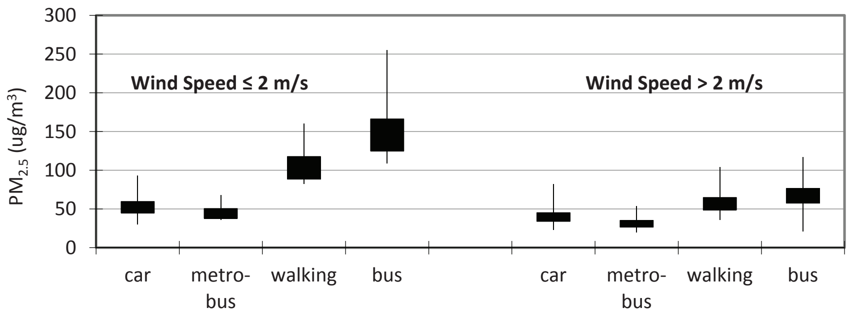


Figure 3. *The relation between $PM_{2.5}$ exposure levels and wind speed.*

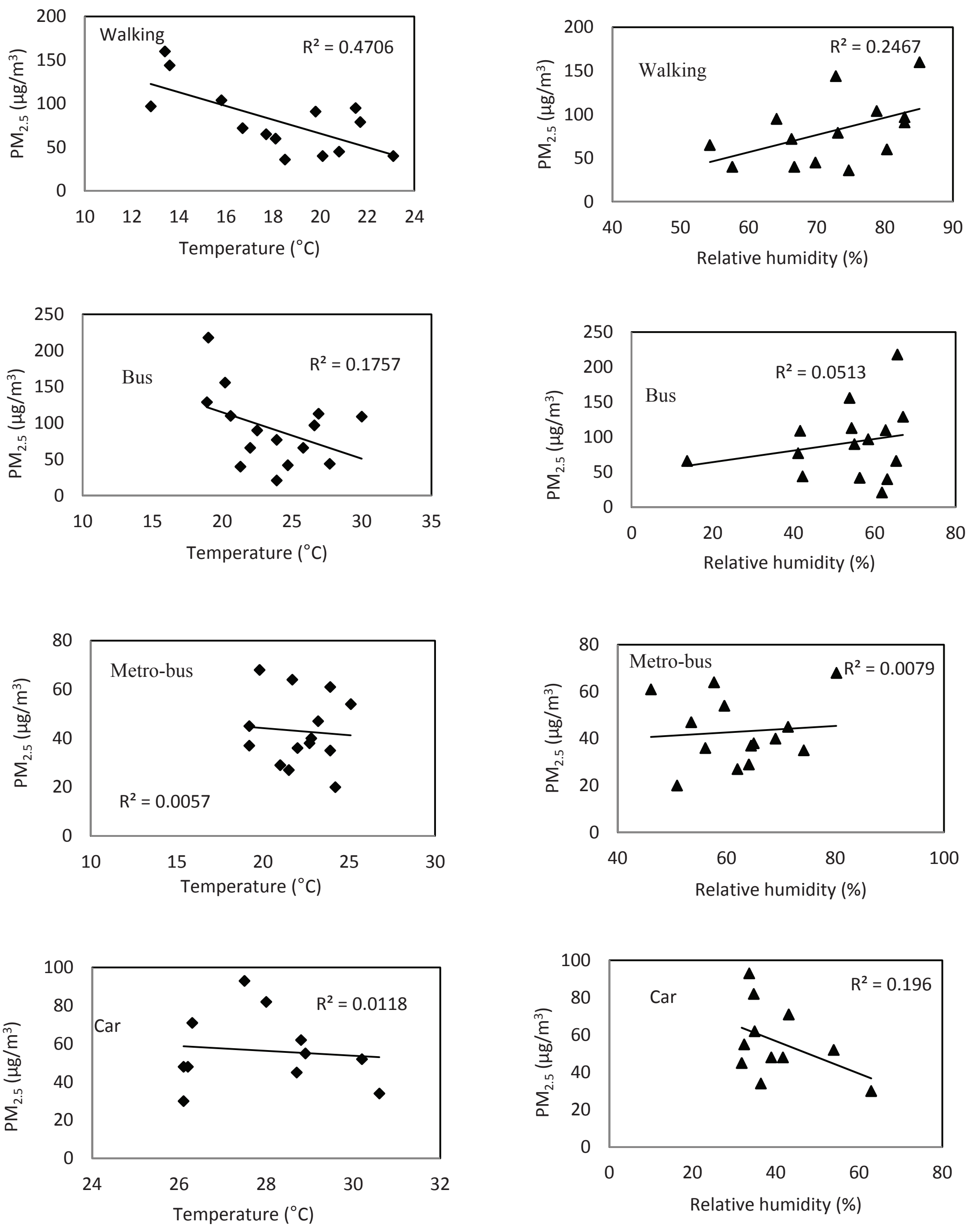
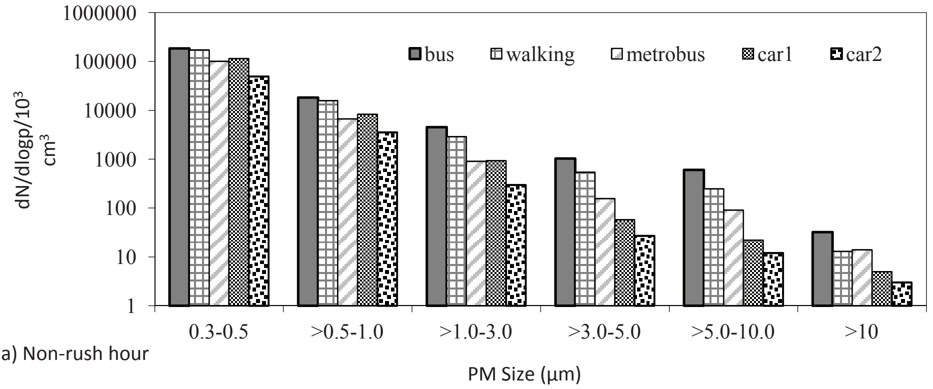
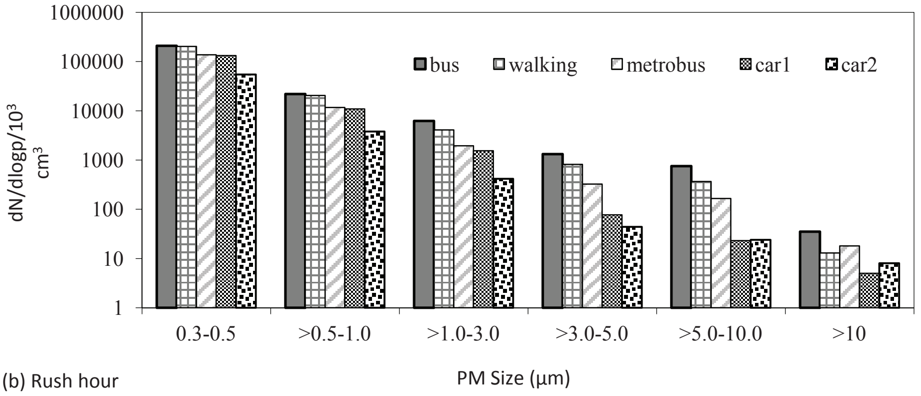


Figure 4. *Statistical relations between $PM_{2.5}$ exposure levels and temperature and humidity (AC fan on).*



(a) Non-rush hour



(b) Rush hour

Figure 5. *Particle number for six particle size fractions of different transport modes for* ***(a)*** *non–rush hours* ***(b)*** *rush hours (car1: AC fan on; car2: AC fan off).*

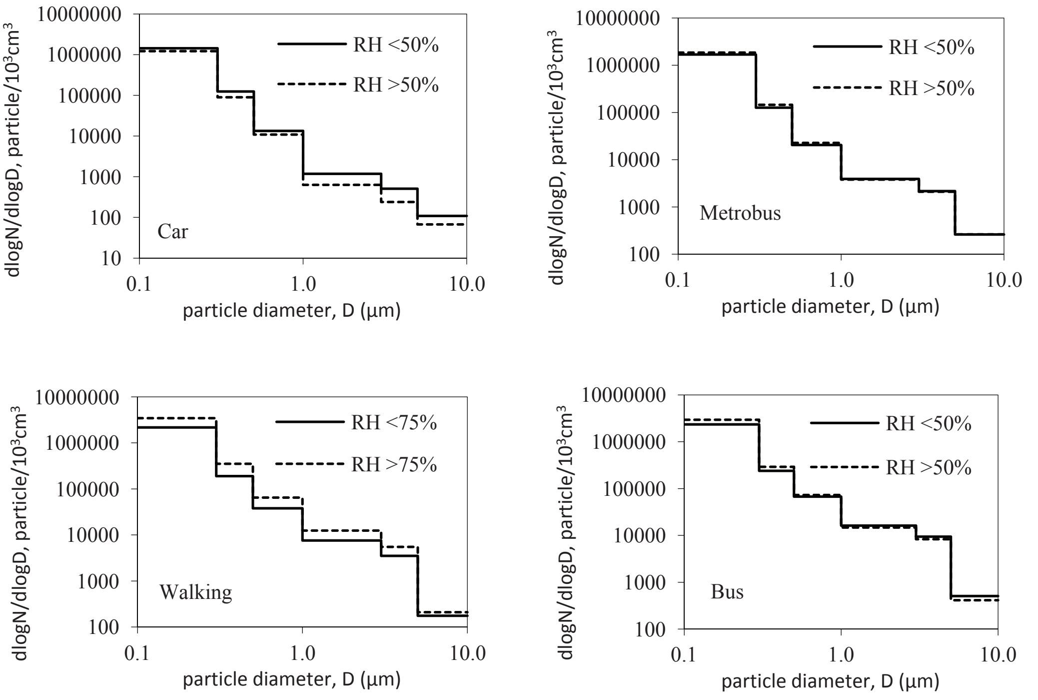


Figure 6.*The effect of the relative humidity to particle counts for different transport modes.*

4. Conclusions

Aerosol particle number and $PM_{2.5}$ concentrations were measured in a metro–bus, a bus, a car, and while walking in Istanbul during October and November 2008. For all four transport modes, the fine and coarse particle numbers and particle mass during rush hours were higher than the values during non–rush hours. The ventilation settings (AC fan on or off) affected the particle mass levels and numbers inside the car. The particle concentration encountered during walking exhibited peaks up to 316 $\mu g/m^3$. Commuters inside buses and those walking are more exposed to coarse particles (>1 µm) than commuters in metro–buses and cars. Wind speed affected exposures to $PM_{2.5}$ (which decreased during windy weather, >2 m/s). The numbers of particles <1 µm in size were higher at higher relative humidity levels. Particle counting provides additional information for analyzing the health effects of particulate matter. We suggest that the further epidemiological investigations are necessary to explain the relation between particle number and particle concentration in vehicles and health effects.

References

Adams, H.S., Nieuwenhuijsen, M.J., Colvile, R.N., 2001. Determinants of fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK. *Atmospheric Environment* 35, 4557–4566.

Alm, S., Jantunen, M.J., Vartiainen, M., 1999. Urban commuter exposure to particle matter and carbon monoxide inside an automobile. *Journal of Exposure Analysis & Environmental Epidemiology* 9, 237–244.

Asmi, E., Antola, M., Yli–Tuomi, T., Jantunen, M., Aarnio, P., Makela, T., Hillamo, R., Hameri, K., 2009. Driver and passenger exposure to aerosol particles in buses and trams in Helsinki, Finland. *Science of the Total Environment* 407, 2860–2867.

Chan, L.Y., Lau, W.L., Lee, S.C., Chan, C.Y., 2002a. Commuter exposure to particulate matter in public transportation modes in Hong Kong. *Atmospheric Environment* 36, 3363–3373.

Chan, L.Y., Lau, W.L., Zou, S.C., Cao, Z.X., Lai, S.C., 2002b. Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban, area of Guangzhou, China. *Atmospheric Environment* 36, 5831–5840.

Cheng, Y.H., Liu, C.C., Lin, Y.L., 2009. Levels of ultrafine particles in the Taipei Rapid Transit System. *Transportation Research Part D: Transport and Environment* 14, 479–486.

Dockery, D.W., Pope, C.A., Xu, X.P., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E., 1993. An association between air–pollution and mortality in six U.S. cities. *New England Journal of Medicine* 329, 1753–1759.

Gertler, A.W., 2005. Diesel vs. gasoline emissions: does PM from diesel or gasoline vehicles dominate in the US? *Atmospheric Environment* 39, 2349–2355.

Gomez–Perales, J.E., Colvile, R.N., Nieuwenhuijsen, M.J., Fernandez–Bremauntz, A., Gutiérrez–Avedoy, V.J., Paramo–Figueroa, V.H., Blanco–Jimenez, S., Bueno–Lopez, E., Mandujano, F., Bernabe–Cabanillas, R., Ortiz–Segovia, E., 2004. Commuters' exposure to $PM_{2.5}$, CO, and benzene in public transport in the metropolitan area of Mexico city. *Atmospheric Environment* 38, 1219–1229.

Gulliver, J., Briggs, D.J., 2004. Personal exposure to particulate air pollution in transport microenvironments. *Atmospheric Environment* 38, 1–8.

Han, X.L., Aguilar–Villalobos, M., Allen, J., Carlton, C.S., Robinson, R., Bayer, C., Naeher, L.P., 2005. Traffic–related occupational exposures to $PM_{2.5}$, CO and VOCs in Trujillo, Peru. *International Journal of Occupational and Environmental Health* 11, 276–288.

Hoek, G., Brunekreef, B., Goldbohm, S., Fischer, P., van den Brandt, P.A., 2002. Association between mortality and indicators of traffic–related air pollution in the Netherlands: a cohort study. *Lancet* 360, 1203–1209.

Kaminsky, J.A., Gaskin, E.A.L.M., Matsuda, M., Miguel, A.H., 2009. In–cabin commuter exposure to ultrafine particles on commuter roads in and around Hong Kong's Tseung Kwan O Tunnel. *Aerosol and Air Quality Research* 9, 353–357.

Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. *Atmospheric Environment* 41, 4781–4810.

Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2005a. Pedestrian exposure to air pollution along a major road in central London, UK. *Atmospheric Environment* 39, 7307–7320.

Kaur, S., Nieuwenhuijsen, M., Colvile, R., 2005b. Personal exposure of street canyon intersection users to $PM_{2.5}$, ultrafine particle counts and carbon monoxide in central London, UK. *Atmospheric Environment* 39, 3629–3641.

King, E.A., Murphy, E., McNabola, A., 2009. Reducing pedestrian exposure to environmental pollutants: a combined noise exposure and air quality analysis approach. *Transportation Research Part D: Transport and Environment* 14, 309–316.

Levy, J.I., Dumyahn, T., Spengler, J.D., 2002. Particulate matter and polycyclic aromatic hydrocarbon concentrations in indoor and outdoor microenvironments in Boston, Massachusetts. *Journal of Exposure Analysis & Environmental Epidemiology* 12, 104–114.

Onat, B., Stakeeva, B., 2012. Assessment of fine particulate matters in the subway system of Istanbul. *Indoor and Built Environment* 000, 1–10.

Onat, B., Sahin, U.A., Akyuz, T., 2013. Elemental characterization of $PM_{2.5}$ and PM_1 in dense traffic area in Istanbul, Turkey. *Atmospheric Pollution Research* 4, 101–105.

Pope, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath, C.W., 1995. Particulate air–pollution as a predictor of mortality in a prospective–study of us adults. *American Journal of Respiratory and Critical Care Medicine* 151, 669–674.

Riediker, M., Cascio, W.E., Griggs, T.R., Herbst, M.C., Bromberg, P.A., Neas, L., Williams, R.W., Devlin, R.B., 2004. Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men. *American Journal of Respiratory and Critical Care Medicine* 169, 934–940.

Sahin, U.A., Onat, B., Stakeeva, B., Ceran, T., Karim, P., 2012. PM_{10} concentrations and the size distribution of Cu and Fe–containing particles in Istanbul's subway system. *Transportation Research Part D: Transport and Environment* 17, 48–53.

Tittarelli, A., Borgini, A., Bertoldi, M., De Saeger, E., Ruprecht, A., Stefanoni, R., Tagliabue, G., Contiero, R., Crosignani, P., 2008. Estimation of particle mass concentration in ambient air using a particle counter. *Atmospheric Environment* 42, 8543–8548.

Weijers, E.P., Khlystov, A.Y., Kos, G.P.A., Erisman, J.W., 2004. Variability of particulate matter concentrations along roads and motorways determined by a moving measurement unit. *Atmospheric Environment* 38, 2993–3002.

Zhu, Y.F., Eiguren–Fernandez, A., Hinds, W.C., Miguel, A.H., 2007. In–cabin commuter exposure to ultrafine particles on Los Angeles freeways. *Environmental Science & Technology* 41, 2138–2145.