Asian Journal of Atmospheric Environment
Vol. 1-1, pp.1-8, December 2007

Vehicle-related Fine Particulate Air Pollution in Seoul, Korea

Gwi-Nam Bae*, Seung-Bok Lee and Su-Mi Park

Center for Environmental Technology Research, Korea Institute of Science and Technology, Seoul, Korea

*Corresponding author. Tel: +82-2-958-5676, E-mail: gnbae@kist.re.kr

ABSTRACT

Vehicle exhaust is a dominant source of air pollutants in urban areas. Since people are easily exposed to vehicle exhaust particles while driving a car and/or traveling via public transportation, air pollution near traffic has been extensively studied in developed countries. In this paper, investigations on vehicle-related fine particulate air pollution at roadsides and on roads in Seoul, Korea were reviewed to understand air pollution near traffic. Comparison of PM_{10} concentrations in Seoul showed that roadside air is more contaminated than urban air, implying that exposure levels near vehicular emissions are more critical to sensitive persons. Concentrations of ultrafine particles and BC (black carbon) at roadsides of Seoul fluctuate highly for short durations, responding to traffic situations. Diurnal variations of ultrafine particles and BC concentrations at roadsides seem to be affected by traffic volume, mixing layer height, and wind speed. Concentrations of ultrafine particles and BC decrease as distance from the road increases due to dilution during transport. On-road air pollution seems to be more severe than roadside air pollution in Seoul. Since nearby traffic air pollution has not been well understood in Seoul, further studies including various vehicular air pollutants and representative locations are needed.

Key words: Fine particle, Vehicle, Roadside, On-road, Urban air pollution, Seoul

1. INTRODUCTION

Urban air pollution is an important issue to environmental policy makers. Most countries have national ambient air quality standards regulating upper limits of time-average concentrations for SO_2, NO_2, CO, O_3, PM (particulate matter), and other pollutants (Bachmann, 2007). PM is a size-dependent pollutant and smaller PM is known to be more harmful to human health. PM regulation has changed from TSP (total suspended particles) to PM_{10} or from PM_{10} to $PM_{2.5}$ (Bachmann, 2007). In Korea, PM_{10} has been managed since 2001. In 2005, the Korean government established the Special Act on Metropolitan Air Quality Improvement, which aimed at reducing annual average concentrations of PM_{10} and NO_2 to 40 $\mu g/m^3$ and 22 ppb, respectively, by 2014. Recently, air quality studies on the Greater Seoul Metropolitan Area were reviewed, focusing on PM and ozone issues (Kim, 2006; Ghim, 2005).

As nanotechnology grows, environmental nanoparticles have been characterized. Important sources of nanoparticles can be categorized by stationary, mobile, occupational settings, and atmospheric conversion (Biswas and Wu, 2005). Recently, many investigations on the formation of ultrafine particles (nanoparticles) in urban areas have been reported (Watson *et al.*, 2006a, b; Woo *et al.*, 2001). In Korea, the number size distribution of urban ultrafine particles has been investigated since the mid-1980s. Size distribution ranging from 10 nm to 1 μm in diameter was observed using an EAA (electrical aerosol analyzer, TSI 3030) in Seoul (Kim *et al.*, 1991, 1986; Kim, 1988). Size distribution of Asian dust in Seoul was monitored using an OPC (optical particle counter, Hiac/Royco 5230) in the late 1990s (Chun *et al.*, 2001). Asian dust measurements using an OPC were also made in Anmyon Island (Chun *et al.*, 1999; Shin *et al.*, 1999). Recently, the number size distribution of urban aerosols ranging from 20 nm to 20 μm in diameter was monitored using an SMPS and an APS in Seoul (Bae *et al.*, 2003). Ultrafine particle measurements using an SMPS were made in the Ansan Area (Kim and Ahn, 2005).

Vehicle exhaust is a dominant source of air pollutants in urban areas. Although ultrafine particles are a distinct short-lived exposure phenomenon not covered in emission inventory approaches (McMurry *et al.*, 2004), nanoparticles are known to be emitted from diesel vehicles. Most PM emitted directly from vehicle exhaust is smaller than 1 μm in diameter (Kittelson, 2007). Toxicity of nanoparticles is an emerging social issue (Biswas and Wu, 2005). Since people are easily exposed to vehicle exhaust nanoparticles, air pollution near traffic has been extensively studied to characterize exposure levels of vehicle exhaust particles (Han and Naeher, 2006).

Fig. 1 demonstrates the location and experimental method used to characterize vehicle exhaust particles (Bae, 2005). Tailpipe measurements and urban air monitoring have been widely conducted to improve urban air quality. Recently, near-traffic air pollution has greatly interested policy makers as a local air pollution problem. They need to reduce exposure of toxic air pollutants to sensitive populations such as children. Diesel vehicles have been regulated based on PM mass in chassis or engine dynamometer tests. As the toxicity of diesel nanoparticles has been reported (Shin, 2005; Lloyd and Cackette, 2001), activities on the regulation of diesel nanoparticles were initiated by the working group 29 of GRPE under the UN/ECE (Park, 2005). Measurements and evaluation of diesel nanoparticles emerged as a new aerosol research field and new instruments with short response times of less than 1 second have been developed to meet vehicle applications (Lee, 2005b). Although the EURO 5 for diesel vehicles does not include number regulation of diesel particles, the next regulation will include it. Therefore, diesel particulate filters have been developed to meet tighter PM regulations (Lee, 2005a).

Although vehicle exhaust particles may contribute significantly to urban air pollution, urban air quality is determined by many emission sources, atmospheric reactions, and meteorological conditions. Therefore, the signature of vehicle exhaust particles could be well characterized by roadside and/or on-road measurements. Ten-year PM monitoring data in downtown Tokyo showed that fine particles smaller than 2.1 μm in diameter clearly decreased, but coarse particles ranging from 2.1 to 7 μm in diameter did not decrease (Minoura *et al.*, 2006). Therefore, vehicle-related PM studies should be more focused on $PM_{2.5}$ or ultrafine particles.

In this paper, previous investigations on vehicle-related fine particulate air pollution in Seoul, Korea were reviewed to understand air pollution near traffic. Roadside and on-road measurements were considered. Particle number size distribution and black carbon concentration were mainly discussed.

2. ROADSIDE AIR POLLUTION

In Korea, although the PM standard was changed from TSP to PM_{10} in 2001, PM_{10} has been monitored since 1995. Now, twenty seven urban air monitoring stations operate in Seoul. Since roadsides are influenced directly by vehicle exhaust, the roadside is considered a representative location to monitor vehicle-related air pollution. Seven roadside air monitoring stations have been managed in Seoul since 1997.

Annual average PM_{10} concentrations for urban air and roadside air monitoring stations in Seoul are plotted in Fig. 2. Recently, Asian dust has been fre-

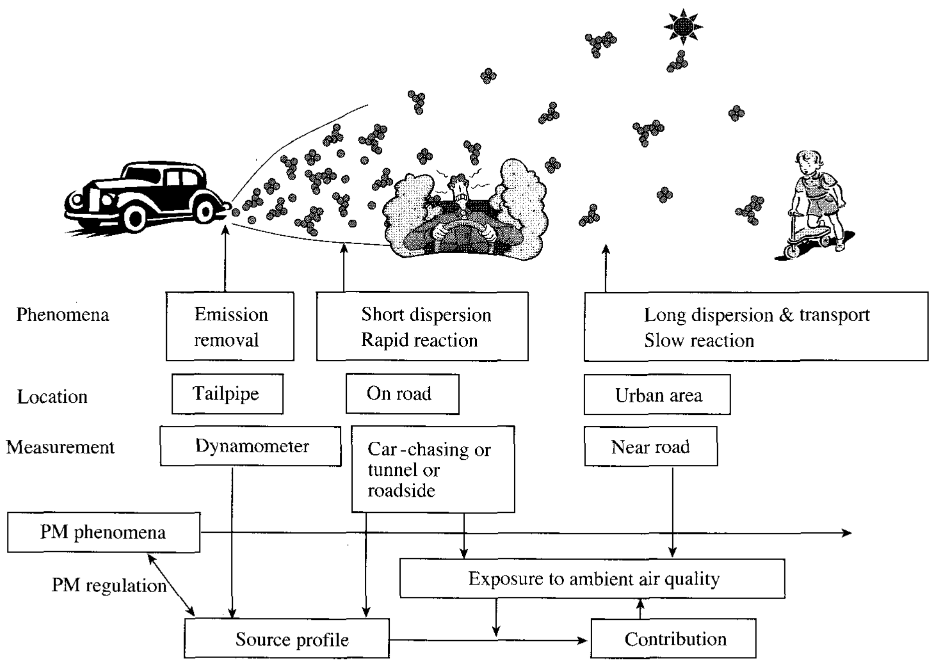

Fig. 1. Block diagram of vehicle nanoparticle studies on ambient air quality.

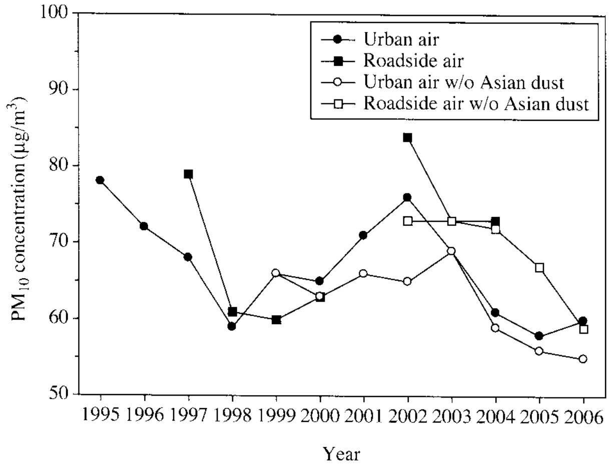

Fig. 2. Trends of annual average PM_{10} concentrations for urban air and roadside air in Seoul.

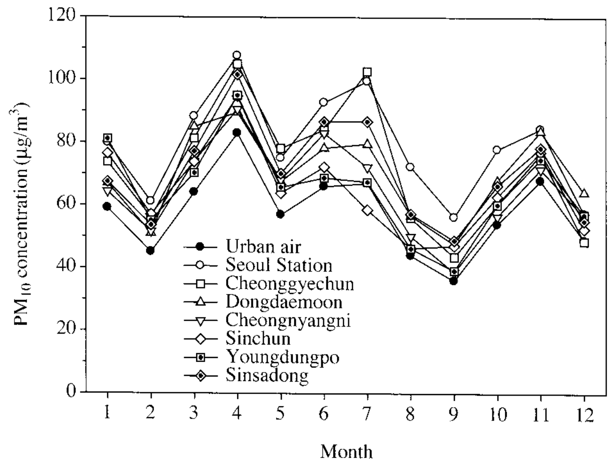

Fig. 3. Trends of monthly average PM_{10} concentrations in 2005 in Seoul for urban air and roadside air. PM_{10} concentrations includes Asian dust episodes.

quently transported to the Korean Peninsula, resulting in significant increases of PM_{10} concentrations. PM_{10} concentrations for urban air excluding Asian dust episodes increased until 2003, and thereafter decreased, as shown in Fig. 2. Even if the effect of meteorological factors on PM_{10} concentrations for urban air is excluded, the same trend is found (MOE, 2006). Apparent reductions in PM_{10} concentrations at the roadside can be seen from 2004, as shown in Fig. 2. The Ministry of Environment (2006) reported that recent environmental policies such as the spread of CNG buses and strict regulations for new vehicles might cause this improvement of roadside air pollution in Seoul. Also, reduction of 10 $\mu g/m^3$ in $PM_{2.5}$ concentration at the roadside could account for the reduction of 13 $\mu g/m^3$ in PM_{10} concentration at the roadside, implying that fine particles emitted from vehicles must be reduced.

Monthly average PM_{10} concentrations of 2005 in Seoul for urban air and roadside air are compared in Fig. 3. Here, Asian dust episodes are included. Both urban and roadside PM_{10} concentrations show similar seasonal trends. The highest PM_{10} concentrations are observed in April, and the lowest ones are found in September. Roadside PM_{10} concentrations are more spatially scattered in summer than in winter. Roadside PM_{10} concentrations are higher than in urban air, indicating that the roadside is more contaminated than urban air.

Recently, Kwon and An (2006) reported temporal and spatial distributions of PM_{10} concentrations near a road in Seoul. They showed that PM_{10} concentrations decrease with distance from the road, and vertical decreases in PM_{10} concentrations are greater than horizontal decreases. Bae *et al.* (2007) compared PM_{10} concentrations observed at two monitoring stations in the central area of Seoul. One was the Seodaemun-gu urban air monitoring station and the other was the Sinchon roadside air monitoring station. As shown in Fig. 4, diurnal variations of PM_{10} concentrations in March of 2005 are very similar to each other and PM_{10} concentrations at the roadside seem to be slightly higher than those in urban air.

However, the mass of diesel exhaust particles is dominant for submicron sizes and the number is predominant in ultrafine particles (Kittelson, 1998). Therefore, effect of vehicle exhaust particles could be well explained by submicron size data rather than PM_{10} even though data are obtained at the roadside. Particle number size distribution at a roadside can be used to determine the ambient air quality effect of vehicle exhaust particles under real driving conditions on roads (Kerminen *et al.*, 2007; Pirjola *et al.*, 2006; Charron and Harrison, 2003; Hitchins *et al.*, 2000).

A few studies on particle number size distribution have been carried out in Seoul since the mid-1980s. However, roadside measurements of the number concentration of particles in the range of 20-600 nm were recently conducted in Seoul (Bae *et al.*, 2007). The number concentration of particles, particularly ultrafine particles smaller than 100 nm, at a roadside fluctuates highly depending on traffic situations. Typical diurnal variations of ultrafine particles observed at a roadside are shown in Fig. 5 (Bae *et al.*, 2007). The lowest particle number concentration is observed between 3 a.m. and 5 a.m. The local highest particle number concentrations are observed during both morning and evening rush hours. Changes in

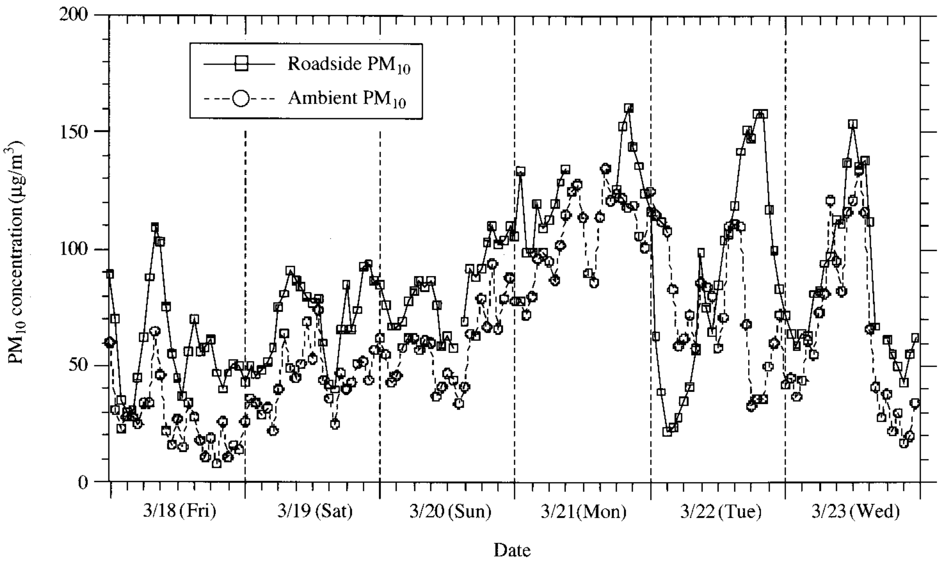

Fig. 4. Comparison of PM_{10} concentrations observed at two monitoring stations in Seoul during March of 2005 (Bae *et al.*, 2007).

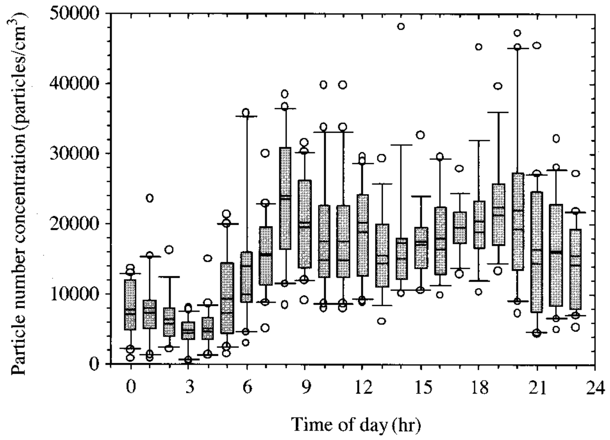

Fig. 5. Diurnal variation of ultrafine particle number concentrations at a roadside from March 18-23, 2005 (Bae *et al.*, 2007).

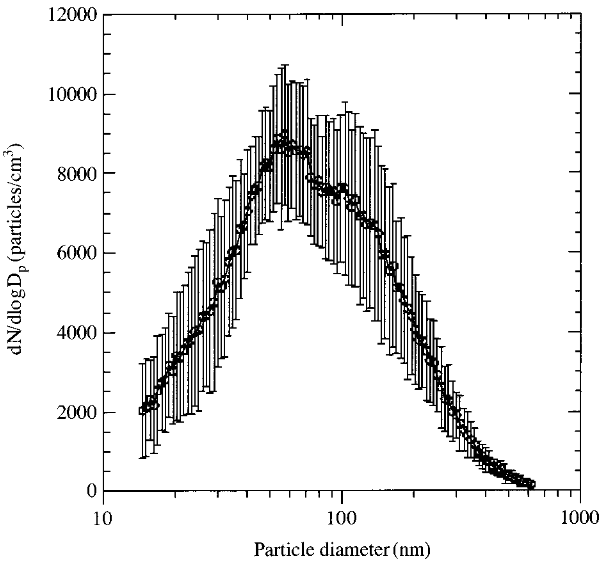

Fig. 6. Suggested background particle size distribution at a roadside (Bae *et al.*, 2007).

traffic volume account for the trend of hourly averaged number concentration from late evening to morning. Similar diurnal variation is also observed in PM_{10} (McMurry *et al.*, 2004). Although most of the particle size distribution is unstable, the relatively stable particle size distribution with a low concentration is observed between 3 a.m. and 4 a.m. As shown in Fig. 6, it could be considered the background particle size distribution in an urban area.

Particles emitted from vehicles are transported around a road. Locations away from the road are less contaminated due to dilution of vehicle exhaust during transport. Weekly variation of ratios of hourly averaged particle number concentrations at site 2 to that at site 1 is shown in Fig. 7 (Lee *et al.*, 2007a). Particle size distribution was concurrently monitored at two sites in Seoul. Site 1 was at the roadside and site 2 was 100-m away from the road. Average ratios are 0.56 ± 0.15 and 0.72 ± 0.10 for ultrafine particles (20-100 nm) and larger particles (100-600 nm), respectively. This indicates that smaller particles decrease more during transport from site 1 to site 2. This is consistent with previous investigations (Zhu *et al.*, 2002; Hitchins *et al.*, 2000).

BC (black carbon) is an indicator of diesel PM. Although some investigations on EC (elemental carbon) concentrations by filter sampling were conduct-

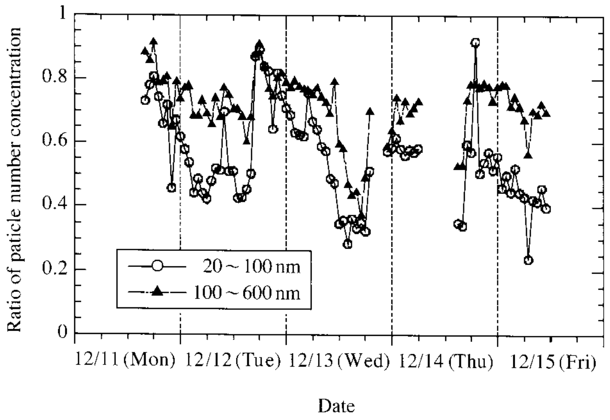

Fig. 7. Weekly variation of ratios of hourly averaged particle number concentrations at site 2 to that of site 1 from December 11 to 15, 2006 (Lee *et al.*, 2007a).

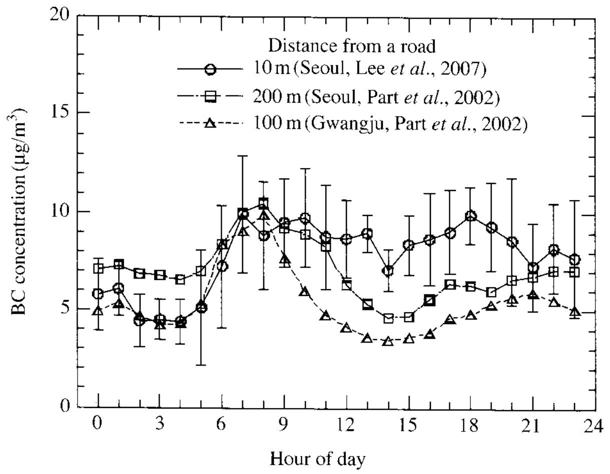

Fig. 8. Comparison of diurnal variations of BC concentrations between roadside and remote urban sites from arterial roads (Lee *et al.*, 2007b).

ed from the mid-1990s in Korea, real-time measurements of BC concentrations using an aethalometer are rare. Park *et al.* (2002) monitored BC concentrations at locations far from roads in Seoul and Gwangju. Lee *et al.* (2007b) conducted real-time BC measurements at a roadside in Seoul in May of 2005. Similar to ultrafine particles, BC concentrations highly fluctuate for a short duration and the lowest BC concentrations are observed between 2 a.m. and 5 a.m. Comparison of diurnal variations of BC concentrations between roadside and remote urban sites from an arterial road is plotted in Fig. 8 (Lee *et al.*, 2007b; Park *et al.*, 2002). During morning rush hours, BC concentrations increase rapidly at all locations. Decreasing BC concentrations around midday hours could be accounted for by the dilution effect caused by increases in both mixing layer height and wind speed.

3. ON-ROAD AIR POLLUTION

Vehicle drivers are subject to exposure to high concentrations of PM emitted from vehicle exhaust on roads. On-road measurement is one method to characterize vehicle-related air pollution. A mobile laboratory has been utilized to measure vehicle exhaust such as particle size distribution and gas concentrations under real on-road conditions (Kittelson *et al.*, 2006a, b, 2004; Gouriou *et al.*, 2004; Bukowiecki *et al.*, 2002). Bukowiecki *et al.* (2002) obtained an air pollution map showing air pollution levels over a region by on-road measurements in Switzerland. Gouriou *et al.* (2004) insisted on the necessity of on-road measurements for evaluating air pollutants exposure encountered by vehicle drivers and reported high particle number concentrations greater than 3×10^5 particles/cm^3 near the truck or during a stop phase on a road in France. Kittelson *et al.* (2004) found that the highest nanoparticle concentrations are associated with high-speed traffic and that measurements made in heavy traffic with low speeds produce lower number concentrations and larger particles. Simple on-road measurements have also been made for BC and total particle number concentrations in California, USA (Fruin *et al.*, 2004), and for black smoke, CO, and NO_x inside a taxi in Paris, France (Zagury *et al.*, 2000).

Although extensive on-road investigations on PM have been reported in foreign countries, a few investigations on BC in a driving passenger car were reported recently in Korea (Lee *et al.*, 2007c; Lee and Bae, 2006). BC concentrations were measured inside a passenger car using a portable aethalometer. Spatial distribution of BC concentrations over major roads in Seoul was monitored by driving a passenger car with open windows (Lee *et al.*, 2007c). BC concentrations seem to be dependent on the traffic flow situation according to time and on topographic features of the road. Fig. 9 shows an example of BC concentration distribution over roads traveled between the KIST (Korea Institute of Science and Technology) and the Olympic Park in Seoul. A BC concentration event higher than 100 μg/m^3 happened when a heavy-duty truck was overtaken on the morning of January 24, 2007.

BC concentrations in a car on a road depend on spatial location, time of day, and ventilation mode. Comparison of average BC concentrations measured

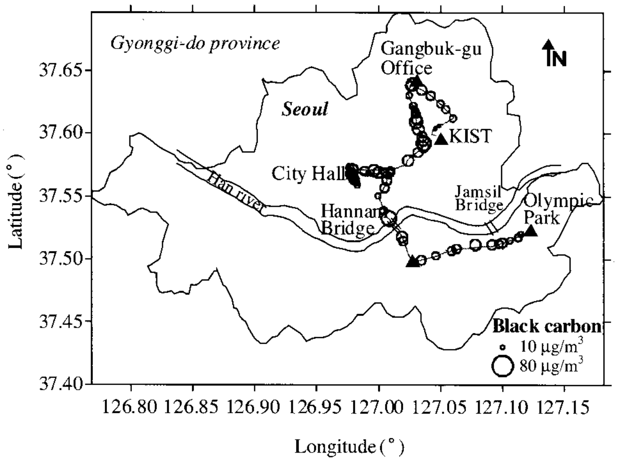

Fig. 9. Spatial distribution of BC concentrations over roads traveled between the KIST and the Olympic Park on January 24, 2007 (Lee *et al.*, 2007c).

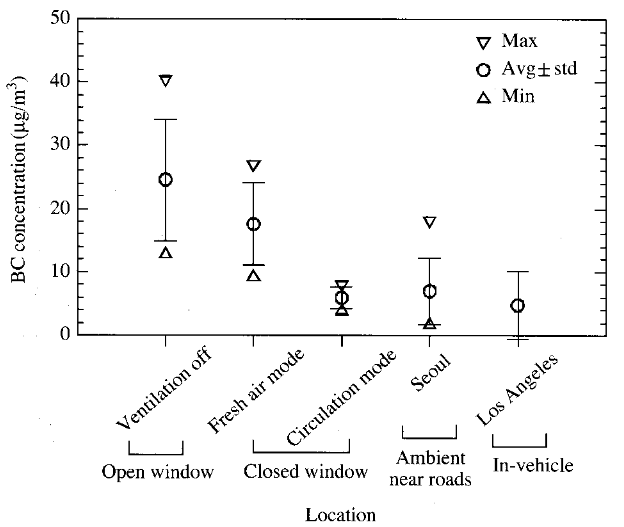

Fig. 10. Comparison of average BC concentrations measured in a vehicle and in ambient air (Lee and Bae, 2006).

in a vehicle and in ambient air is illustrated in Fig. 10 (Lee and Bae, 2006). For the circulation mode, average BC concentration was $5.9 \pm 1.7\ \mu g/m^3$ in the afternoon or evening, which was similar to a 24-hr average BC concentration ($7.0 \pm 5.2\ \mu g/m^3$) in ambient air at 200 m from a road in Seoul (Park *et al.*, 2002). For the fresh air mode, average BC concentrations measured in the morning rush hours, in the afternoon or evening, and after midnight were 22.8 ± 3.4, 15.9 ± 7.7, $3.7\ \mu g/m^3$, respectively. Average BC concentrations measured under open vehicular window conditions were 31.9 ± 9.2 and $19.4 \pm 5.9\ \mu g/m^3$ in the morning rush hours and in the afternoon or evening, respectively. These measured values are higher than those measured under closed window conditions. Average BC concentrations inside a passenger car with a fresh mode operation or open-window driving are significantly higher than the 24-hr average BC concentration measured at 200 m away from a road in Seoul.

4. SUMMARY

Traffic-related air pollution studies have been extensively conducted to understand urban air pollution and health effects of air pollutants. However, there has been less attention to this topic in Korea. In this paper, a few recent studies conducted at roadsides and on roads in Seoul were reviewed.

Comparison of PM_{10} concentrations obtained at both roadside air and urban air monitoring stations in Seoul showed that roadside air is more polluted than urban air. Vehicular air pollution is considered a local air pollution problem and $PM_{2.5}$ or ultrafine particles are important indicators for characterizing vehicular air pollution.

Concentrations of ultrafine particles and BC at a roadside fluctuate highly for a short duration, responding to the traffic situation. Diurnal variations of ultrafine particles and BC concentrations seem to be affected by traffic volume. The minimum concentration is observed between 3 a.m. and 5 a.m. and a relatively stable particle size distribution is monitored during that period. Concentrations of ultrafine particles and BC decrease as distance from a road increases due to the dilution process during transport. Particulate air pollution maps over roads could be obtained by in-vehicle measurements. Based on BC measurement data, on-road air pollution seems to be more severe than roadside air pollution.

In Korea, little information about traffic-related air pollution is available. To characterize urban air pollution, extensive studies on vehicle-related air pollutants such as ultrafine particles, BC, NO_x, and PAHs should be carried out in the near future. To characterize exposure levels to vehicular air pollution, these pollutants should also be monitored at various locations such as roadsides, on roads, near roads, and indoor environments near roads.

ACKNOWLEDGEMENTS

This study was supported by the CEFV (Center for Environmentally Friendly Vehicle) of Eco-STAR project from MOE (Ministry of Environment, Republic of Korea).

REFERENCES

Bachmann, J. (2007) Will the circle be unbroken: A history of the U.S. National Ambient Air Quality Standards. J. of the Air & Waste Management Association, 57, 652-697.

Bae, G.N. (2005) Studies on diesel nanoparticles in ambient air (in Korean). Auto Journal, 27(4), 16-20.

Bae, G.N., S. Huh, S.B. Lee, M. An, D. Park, and J. Hwang (2007) Ultrafine particle pollution level at the roadside of Seoul in spring (in Korean). Particle and Aerosol Research, 3(1), 29-40.

Bae, G.N., M.C. Kim, D.Y. Lim, K.C. Moon, and N.J. Baik (2003) Characteristics of urban aerosol number size distribution in Seoul during the winter season of 2001 (in Korean). J. of Korean Society for Atmospheric Environment, 19(2), 167-177.

Biswas, P. and C.-Y. Wu (2005) Nanoparticles and the environment. J. of the Air & Waste Management Association, 55, 708-746.

Bukowiecki, N., J. Dommen, A.S.H. Prévôt, R. Richter, E. Weingartner, and U. Baltensperger (2002) A mobile pollutant measurement laboratory - measuring gas phase and aerosol ambient concentrations with high spatial and temporal resolution. Atmospheric Environment, 36, 5569-5579.

Charron, A. and M. Harrison (2003) Primary particle formation from vehicle emissions during exhaust dilution in the roadside atmosphere, Atmospheric Environment, 33, 4109-4119.

Chun, Y., J. Kim, J.C. Choi, K.O. Boo, S.N. Oh, and M. Lee (2001) Characteristic number size distribution of aerosol during Asian dust period in Korea. Atmospheric Environment, 35, 2715-2721.

Chun, Y., J. Kim, J.C. Choi, and D.S. Shin (1999) The characteristics of the aerosol number concentration observed in Seoul and Anmyondo during an Yellow Sand phenomenon (in Korean). J. of Korean Society for Atmospheric Environment, 15(5), 575-586.

Fruin, S.A., A.M. Winer, and C.E. Rodes (2004) Black carbon concentrations in California vehicles and estimation of in-vehicle diesel exhaust particulate matter exposures. Atmospheric Environment, 38, 4123-4133.

Ghim, Y.S. (2005) Issues and tasks for air quality management in the Greater Seoul Metropolitan Area (in Korean). J. of Environmental Policy, 4(1), 1-19.

Gouriou, F., J.P. Morin, and M.E. Weill (2004) On-road measurements of particle number concentrations and size distributions in urban and tunnel environments. Atmospheric Environment, 38, 2831-2840.

Han, X. and L.P. Naeher (2006) A review of traffic-related air pollution exposure assessment studies in the developing world. Environmental International, 32, 106-120.

Hitchins, J., L. Morawska, R. Wolff, and D. Gilbert (2000) Concentrations of submicrometre particles from vehicle emissions near a major road. Atmospheric Environment, 34, 51-59.

Kerminen, V.M., T.A. Pakkanen, T. Mäkelä, R.E. Hillamo, M. Sillanpää, T. Rönkkö, A. Virtanen, J. Keskinen, L. Pirjola, T. Hussein, and K. Hämeri (2007) Development of particle number size distribution near a major road in Helsinki during an episodic inversion situation. Atmospheric Environment, 41, 1759-1767.

Kim, P.S. (1988) Physical characteristics of atmospheric aerosols in Seoul: Scattering of visible light (in Korean). J. of Korean Society for Atmospheric Environment, 4(2), 28-37.

Kim, P.S., Y.J. Kim, Y.H. Lee, S.H. Cho, and S.T. Ahn (1986) A study on the characteristics of urban aerosol concentration in the size range of 0.01-1.0 μm (in Korean). J. of Korean Society for Atmospheric Environment, 2(2), 41-50.

Kim, P.S., M.S. Oh, and E.H. Kim (1991) A study on the concentration and light extinction of atmospheric aerosol in Seoul (in Korean). J. of Korean Society for Atmospheric Environment, 7(3), 227-234.

Kim, Y.M. and K.H. Ahn (2005) Monitoring of airborne fine particle using SMPS in Ansan Area (in Korean). J. of Korean Society for Atmospheric Environment, 21(3), 295-301.

Kim, Y.P. (2006) Air pollution in Seoul caused by aerosols (in Korean). J. of Korean Society for Atmospheric Environment, 22(5), 535-553.

Kittelson, D.B. (1998) Engines and nanoparticles: A review. J. of Aerosol Science, 29, 575-588.

Kittelson, D.B. (2007) On-road particles-Characteristics and measurement, International Workshop on Vehicle-related Nanoparticles and Environmental Health, February 2, Seoul, Korea, 47-71.

Kittelson, D.B., W.F. Watts, and J.P. Johnson (2004) Nanoparticle emissions on Minnesota highways. Atmospheric Environment, 38, 9-19.

Kittelson, D.B., W.F. Watts, and J.P. Johnson (2006a) On-road and laboratory evaluation of combustion aerosols - Part 1: Summary of diesel engine results. J. of Aerosol Science, 37, 913-930.

Kittelson, D.B., W.F. Watts, J.P. Johnson, J.J. Schauer, and D.R. Lawson (2006b) On-road and laboratory evaluation of combustion aerosols - Part 2: Summary of spark ignition engine results. J. of Aerosol Science, 37, 931-949.

Kwon, O.Y. and Y.S. An (2006) Temporal and spatial distributions of PM_{10}, NO_x and O_3 around the road (in Korean). J. of Korean Society for Atmospheric Environment, 22(4), 440-450.

Lee, J.H. (2005a) The trend of diesel PM reduction research (in Korean). Auto Journal, 27(4), 26-28.

Lee, J.W. (2005b) Measurement technologies and evaluation of diesel nanoparticle (in Korean). Auto Journal, 27(4), 9-15.

Lee, S.B. and G.N. Bae (2006) Black carbon concentrations in a driving passenger car with ventilation mode (in Korean). Indoor Environment and Technology, 3(3), 260-272.

Lee, S.B., G.N. Bae, S. Huh, D. Park, and J. Hwang (2007a) Transport of traffic-related particles near the roadside, 18th International Symposium on Transport Phenomena, August 27-30, Daejeon, Korea, pp. 578-581.

Lee, S.B., G.N. Bae, S.M. Park, and S.G. Jung (2007b) Black carbon concentration level at a roadside of Seoul in spring (in Korean). J. of the Korean Society for Atmospheric Environment, 23(4), 466-477.

Lee, S.B., D.S. Byeon, S.M. Park, J.H. Lee, and G.N. Bae (2007c) Concentration levels of particulate matters on roads of Seoul in winter (in Korean), Environment Joint Conference of 2007, May 2-4, Busan, Korea, 55pp.

Lloyd, A.C. and T.A. Cackette (2001) Diesel engines: Environmental impact and control. J. of the Air & Waste Management Association, 51, 809-847.

McMurry, P., M. Shepherd, and J. Vickery (2004) Particulate Matter Science for Policy Makers-A NARSTO Assessment, Cambridge University Press, USA.

Minoura, H., K. Takahashi, J.C. Chow, and J.G. Watson (2006) Multi-year trend in fine and coarse particle mass, carbon, and ions in downtown Tokyo, Japan. Atmospheric Environment, 40, 2478-2487.

MOE (Ministry of Environment, Korea) (2006) Press Release 070307A2 (in Korean), Available from http://www.me.go.kr/webdata/070307A2.hwp

Park, S. (2005) World trends of particulate measurement programme (in Korean). Auto Journal, 27(4), 4-8.

Park, S.S., Y.J. Kim, and K. Fung (2002) $PM_{2.5}$ carbon measurements in two urban areas: Seoul and Kwangju, Korea. Atmospheric Environment, 36, 1287-1297.

Pirjola, L., P. Paasonen, D. Pfeiffer, T. Hussein, K. Hämeri, T. Koskentalo, A. Virtanen, T. Rönkkö, J. Keskinen, T.A. Pakkanen, and R.E. Hillamo (2006) Dispersion of particles and trace gases nearby a city highway: Mobile laboratory measurements in Finland, Atmospheric Environment, 40, 867-879.

Shin, D.C. (2005) Health effect of diesel exhausted nanoparticles (in Korean). Auto Journal, 27(4), 21-25.

Shin, D.S., S. Kim, J.S. Kim, and J.W. Cha (1999) Aerosol optical thickness of the Yellow Sand from direct solar radiation at Anmyon Island during the Spring of 1998 (in Korean). J. of Korean Society for Atmospheric Environment, 15(6), 739-746.

Watson, J.G., J.C. Chow, D.H. Lowenthal, N.M. Kreisberg, S.V. Hering, and M.R. Stolzenburg (2006a) Variations of nanoparticle concentrations at the Fresno Supersite. Science of the Total Environment, 358, 178-187.

Watson, J.G., J.C. Chow, K. Park, and D.H. Lowenthal (2006b) Nanoparticle and ultrafine particle events at the Fresno Supersite. J. of the Air & Waste Management Association, 56, 417-430.

Woo, K.S., D.R. Chen, D.Y.H. Pui, and P.H. McMurry (2001) Measurement of Atlanta aerosol size distributions: Observations of ultrafine particle events. Aerosol Science and Technology, 34, 75-87.

Zagury, E., Y.L. Moullec, and I. Momas (2000) Exposure of Paris taxi drivers to automobile air pollutants within their vehicles. Occupational and Environmental Medicine, 57, 406-410.

Zhu, Y., W.C. Hinds, S. Kim, S. Shen, and C. Sioutas (2002) Study of ultrafine particles near a major highway with heavy-duty diesel traffic. Atmospheric Environment, 36, 4323-4335.

(Received 9 July 2007, accepted 20 November 2007)