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IMPACTS OF TRAFFIC VOLUMES AND WIND DIRECTIONS ON AIR POLLUTION CONCENTRATIONS IN SEOUL, KOREA

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1. INTRODUCTION

Despite improvements in vehicle emission control technology, the rapid growth of vehicle ownership and average trip length during past decades has created an unhealthy environment in urbanized areas. Transportation is known to be responsible for a substantial share of urban air pollution emissions, such as carbon monoxide (CO), nitrogen dioxide (NO_2), volatile organic compounds (VOC), and ozone (O_3), a secondary product. It is reasonable to expect that, as vehicle-kilometers-traveled (VKT) increase, ambient air pollution concentrations also increase. Pollutants emitted by motor vehicles impact the spatial and temporal distribution of ambient concentrations, which are also determined by meteorological circumstance, such as wind direction (WD) (Faiz, 1993; Small and Kazimi, 1995; McHugh et al., 1997; Lau et al., 2008).

Integrated modeling systems for air quality management have been developed in several countries, including AirGIS in Denmark (Jensen et al., 2001), Air Quality Information System in Norway (Bøhler et al., 2002), and Traffic Emission Modelling and Mapping Suite in England (Namdeo et al., 2002). However, the quantitative relationship between pollution concentrations and traffic volumes, while accounting for WD impacts, has rarely been investigated. In this research, hourly VKT around air quality monitoring stations (AQM) are estimated and weighted by eight wind direction frequencies, and the relationships between monitored pollution concentrations and these WD-weighted VKT are examined.

2. RESEARCH METHOD AND DATA COLLECTION

To assess the relationship between pollution concentrations and WD-weighted VKT, three data sets are required: (1) hourly air pollution concentrations, (2) traffic assignment computed using a transportation network and a daily origin/destination (OD) matrix, and (3) hourly monitored WD frequencies and traffic counts. Several circular buffer zones, with a radius varying from 500 to 5,500 meters around each AQM, are delineated. Using GIS (Geographic Information System), these buffers are overlaid onto the assigned transportation network and VKT is calculated for each link within any circular buffer[1]. Using available hourly traffic counts data, the estimated daily VKT is divided into hourly VKTs. Regression models are estimated for five pollution concentrations (NO_2, SO_2, CO, PM10: particles of 10 micrometers diameter, and O_3) as dependent variables with hourly VKT as the explanatory variable. To account for the WD effect, the circular buffer zone is subdivided into eight sectors, each sector is overlaid onto the transportation network, and VKT for each sector is computed and weighted by WD frequency.

2.1 Air Pollution Data

Hourly air pollution concentrations have been measured at 34 AQMs in Seoul and have been downloadable from the National Institute of Environmental Research of Korea (NIER) website (2008). The AQMs are distributed over more than one location for each administrative district of the Seoul metropolitan area, as illustrated in Figure 1. Out of the 34 AQMs, 27 are classified as urban background AQMs, monitoring average air quality and assessing whether air quality standards are attained. The other 7 AQMs are located near crowded traffic roads to measure roadside air quality. In this research, the hourly-averaged

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[1] During geo-processing, a transportation link which crosses a buffer boundary is divided into two split links. Because the geo-processing does not change the attribute data, the split links have the same attribute data, in this case the same VKT. To correct the attribute data for the split links, it is necessary to calculate the length of original and split links and then applying the ratio to the attribute data.

pollution concentrations of NO_2, SO_2, CO, PM10, and O_3 are used to assess their relationships with VKT and WD-weighted VKT.

2.2 Traffic Assignment

The Seoul Development Institute (SDI) has released daily OD matrix and transportation network data for the Capital region of Korea, which includes the Seoul, Incheon, and Gyeonggi provinces (SDI, 2007). These OD and network data are used in a traffic assignment model, TransCAD®. This program allows for six assignment methods, including all-or-nothing, capacity restraint, incremental, stochastic, system optimum, and user equilibrium (UE). To choose the appropriate traffic assignment method, 56 road links are selected to compare link monitored traffic flows and assigned flows under the 6 methods. The UE is selected, and VKT is then calculated by multiplying link length and assigned traffic volume for each link (Kim and Guldmann, 2008).

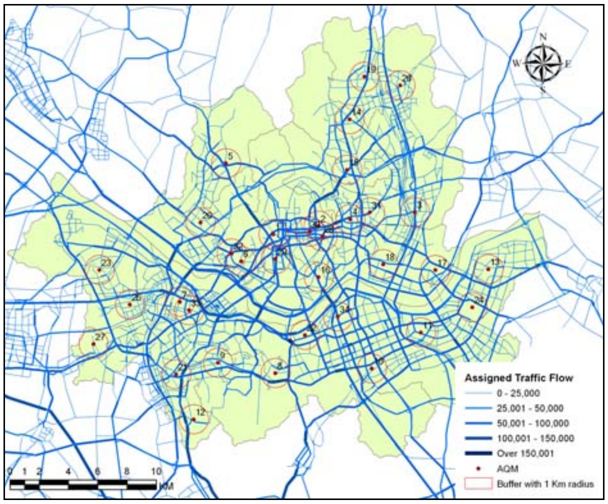

Fig. 1. Location of AQMs and assigned traffic flows in Seoul, Korea

Since AQM concentrations are measured hourly, the assigned daily traffic flows are broken down by hour, using the monitored traffic counts. The hourly traffic counts data were collected over a week at 4 different road classifications, including cordon line (39 locations), Han river bridges (18 locations), arterial roads (34 locations), and central business districts roads (26 locations). The traffic counts have been directed by the Seoul Metropolitan Police Agency (SMPA) and are reported on the Seoul city government website (Seoul City Government, 2008) and in the 2003 Seoul Traffic Survey Report (SMPA, 2004).

2.3 Wind Direction Monitoring Data

Hourly WD data have been downloaded from the Korea Meteorological Administration (2008) website. The frequencies for the eight WD sectors are computed based on 8,760 hourly observations (365 days × 24 hours) and the results are illustrated in Figure 2.

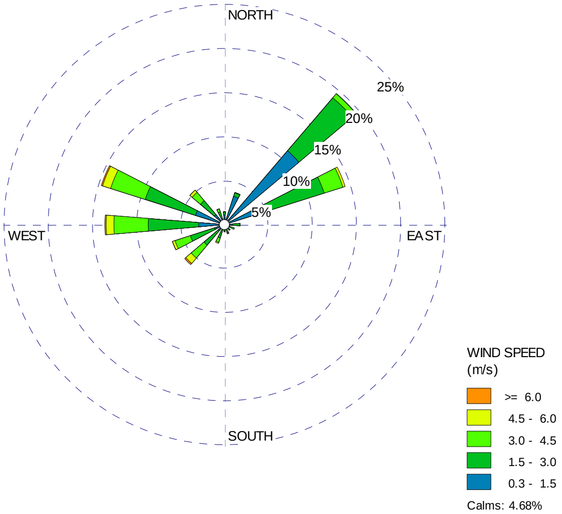

Fig. 2. Wind rose: 24 hrs × 365 days in Seoul

The prevailing WD in Seoul, Korea, is from West and North-East. Wind directions affect pollution concentrations, since pollutants are primarily dispersed downwind from sources. To account for WD impacts on pollution concentrations, the frequencies of the eight-sector wind directions are used for weighting the VKTs of each AQM. Let FWD_i and $CALM_i$ be the percentage of WD and calm wind in sector I, and VKT_i be the sum of all links VKTs in that sector. The weighted VKT (WVKT) variable is then computed as follows.

$$\mathrm{WVKT} = \sum_{i=1}^{8} \left(\mathrm{FWD_i} + \mathrm{CALM_i}\right) \times \mathrm{VKT_i} \qquad (1)$$

Figure 3 presents the eight sectors used to calculate the WD-weighted VKT for each AQM.

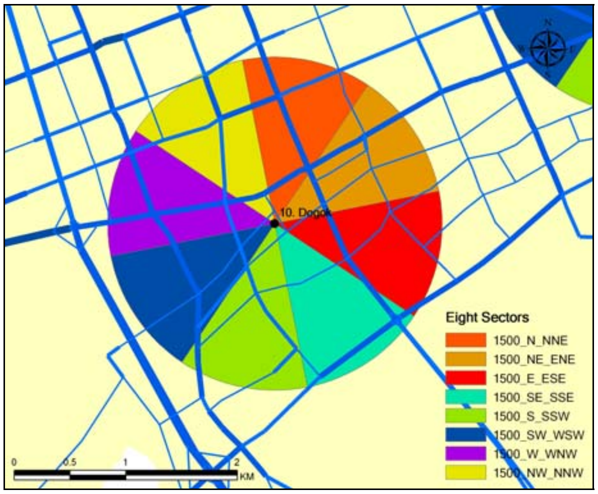

Fig. 3. Eight sectors for calculation of WD-weighted VKT

3. TRAFFIC AND POLLUTION CONCENTRATIONS

An overall understanding of pollution concentrations and traffic flows could be helpful to investigate vehicle emissions impacts on air pollution concentrations. Figure 4 through 8 display the hourly patterns of traffic flows and five air pollutants concentrations (NO_2, O_3, SO_2, CO, and PM10). Hourly roadside and background concentrations are calculated based on 7 and 27 AQMs, respectively.

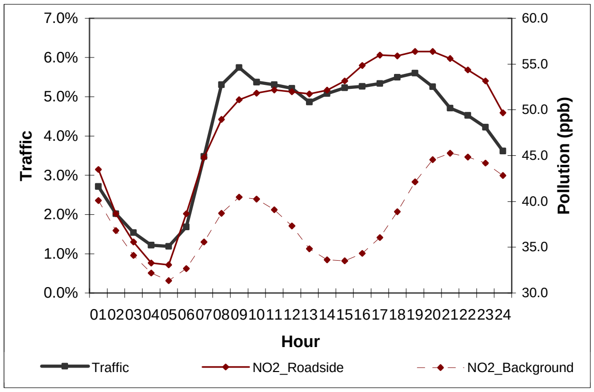

Fig. 4. Hourly traffic counts and NO_2 concentrations

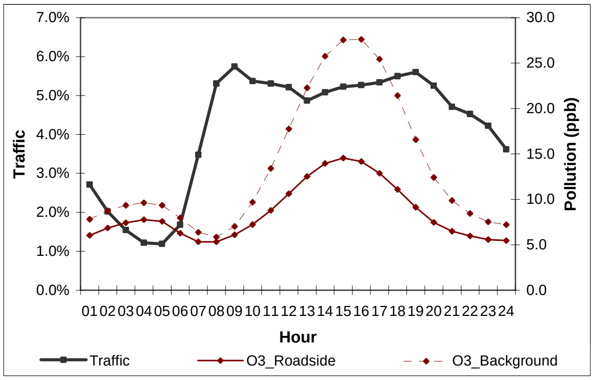

Fig. 5. Hourly traffic counts and O_3 concentrations

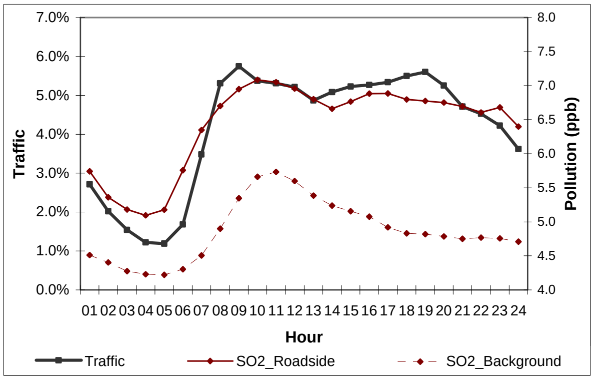

Fig. 6. Hourly traffic counts and SO_2 concentrations

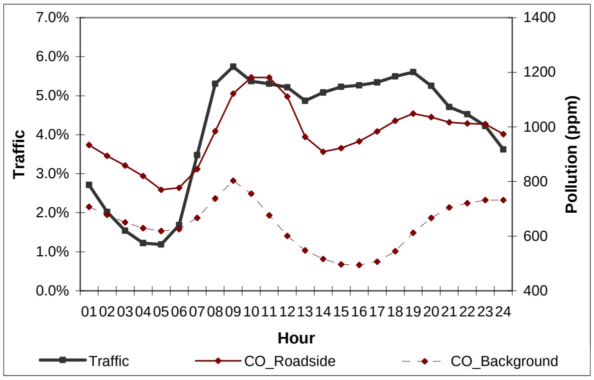

Fig. 7. Hourly traffic counts and CO concentrations

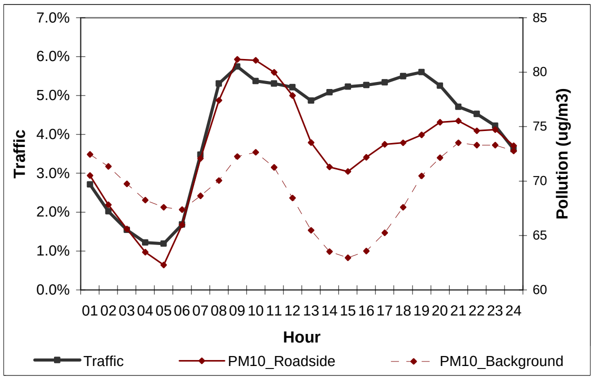

Fig. 8. Hourly traffic counts and PM10 concentrations

Traffic counts display a typical urban pattern characterized by two peaks, in the morning and the evening. As expected, roadside AQM concentrations are higher than background AQM concentrations, except for ozone (Pandey et al., 2008). Direct emissions[2] from motor vehicles, such

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[2] According to Derwent and Hertel (1998), over 90% of nitrogen compounds are emitted in the form of nitric oxide (NO). Only less than 10% of nitrogen is directly emitted NO_2 form. NO produced in the combustion process, however, mainly reacts with ambient O_3 within a few seconds after its emission, and is transformed into NO_2. Thus, strictly, NO_2 can be classified as a secondary product, but, because of its quick and complete reaction, NO_2 can be regarded as direct emission from vehicles.

as NO_2, SO_2, and CO, display close relationships with traffic counts.

During daytime, ozone concentrations observed at roadside monitoring stations are lower than those of background AQM in urban regions (Jo and Park, 2005). Since freshly emitted NO from motor vehicles scavenges nearby ozone and is converted into NO_2, higher VKTs can be expected to lead to lower ozone concentrations, according to the following:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad (2)$$

One other notable phenomenon is related to NO_2 concentrations at both roadside and background AQMs during late afternoon and evening. After the evening traffic peak, traffic flow decreases but NO_2 concentrations increase to a daily climax around 21:00 PM. There are two reasons for this pattern. One is that the ozone concentration accumulated during daytime is abundant enough so that emitted NO can be easily converted into NO_2. The other reason is that, in the presence of sunlight, NO_2 absorbs ultraviolet radiation and undergoes photolysis, reverting to NO and oxygen. After sunset, the NO_2 photolysis no longer takes place.

The relation between SO_2 concentrations and traffic counts deserves more attention, because only diesel vehicles emit SO_2. Due to the difference between gasoline and diesel prices in Korea, the number of diesel vehicles has increased recently (Korea Ministry of Environment, 2005). In 2003, the share of diesel vehicle registrations was 34.6%. So, to better understand hourly SO_2 concentrations, it would be necessary to measure hourly diesel vehicles VKTs.

4. WIND DIRECTION IMPACTS ON POLLUTION CONCENTRATIONS

Several studies have uncovered meaningful relationships between vehicle emissions and air pollution concentrations (Roorda-Knape et al., 1999; Potoglou and Kanaroglou, 2005; Kim and Guldmann, 2007; Lau et al., 2008). In addition, Kim and Guldmann (2008) find a significant relationship between annual average pollution

Table 1. Regression results between without and with wind direction impacts on VKT

Buffer Radius (meters)		Without Wind Direction Impacts					With Wind Direction Impacts				
		Parameter	St. Error	t Value	Pr > | t |	R^2	Parameter	St. Error	t Value	Pr > | t |	R^2
NO_2	500	1118.40	95.49	11.71	<.0001	0.14	6460.49	632.05	10.22	<.0001	0.11
	1000	410.09	26.61	15.41	<.0001	0.23	3089.95	183.74	16.82	<.0001	0.26
	1500	235.52	13.13	17.94	<.0001	0.28	1875.06	90.99	20.61	<.0001	0.34
	2000	141.73	7.96	17.81	<.0001	0.28	1157.81	54.17	21.37	<.0001	0.36
	2500	99.32	5.43	18.30	<.0001	0.29	789.11	36.82	21.43	<.0001	0.36
	3000	73.19	3.90	18.78	<.0001	0.30	591.54	26.05	22.70	<.0001	0.39
	3500	55.84	2.91	19.21	<.0001	0.31	457.70	19.64	23.31	<.0001	0.40
	4000	43.58	2.26	19.28	<.0001	0.31	357.29	15.25	23.43	<.0001	0.40
	4500	34.98	1.81	19.34	<.0001	0.31	289.58	12.41	23.34	<.0001	0.40
	5000	28.71	1.51	19.00	<.0001	0.31	235.72	10.48	22.49	<.0001	0.38
	5500	24.18	1.27	19.04	<.0001	0.31	197.96	8.87	22.32	<.0001	0.38
SO_2	500	202.54	14.48	13.98	<.0001	0.19	1243.25	95.44	13.03	<.0001	0.17
	1000	59.32	4.24	13.97	<.0001	0.19	451.74	29.33	15.40	<.0001	0.23
	1500	33.53	2.12	15.82	<.0001	0.24	244.65	15.30	15.99	<.0001	0.24
	2000	19.99	1.29	15.52	<.0001	0.23	137.92	9.41	14.66	<.0001	0.21
	2500	13.66	0.89	15.42	<.0001	0.23	94.81	6.38	14.85	<.0001	0.21
	3000	9.82	0.64	15.28	<.0001	0.22	72.18	4.55	15.87	<.0001	0.24
	3500	7.14	0.49	14.67	<.0001	0.21	52.80	3.50	15.07	<.0001	0.22
	4000	5.57	0.38	14.70	<.0001	0.21	41.67	2.72	15.34	<.0001	0.22
	4500	4.44	0.30	14.58	<.0001	0.21	33.78	2.21	15.30	<.0001	0.22
	5000	3.55	0.26	13.91	<.0001	0.19	27.01	1.86	14.54	<.0001	0.21
	5500	2.93	0.22	13.58	<.0001	0.18	22.16	1.58	14.03	<.0001	0.19
CO	500	214.0	27.1	7.91	<.0001	0.07	1632.5	173.5	9.41	<.0001	0.10
	1000	64.8	7.9	8.19	<.0001	0.08	657.1	53.3	12.34	<.0001	0.16
	1500	34.5	4.0	8.52	<.0001	0.08	350.1	28.0	12.52	<.0001	0.16
	2000	15.9	2.5	6.39	<.0001	0.05	169.5	17.4	9.73	<.0001	0.10
	2500	11.3	1.7	6.64	<.0001	0.05	127.0	11.7	10.84	<.0001	0.13
	3000	7.7	1.2	6.20	<.0001	0.05	95.6	8.4	11.36	<.0001	0.14
	3500	5.9	0.9	6.38	<.0001	0.05	74.8	6.4	11.73	<.0001	0.14
	4000	4.5	0.7	6.20	<.0001	0.05	56.4	5.0	11.29	<.0001	0.14
	4500	3.6	0.6	6.20	<.0001	0.05	44.5	4.1	10.93	<.0001	0.13
	5000	2.9	0.5	5.92	<.0001	0.04	35.2	3.4	10.31	<.0001	0.12
	5500	2.4	0.4	6.02	<.0001	0.04	29.1	2.9	10.06	<.0001	0.11
PM10	500	482.91	105.07	4.60	<.0001	0.03	5610.07	663.71	8.45	<.0001	0.08
	1000	71.82	31.08	2.31	0.02	0.01	988.76	217.16	4.55	<.0001	0.02
	1500	33.21	15.95	2.08	0.04	0.01	418.98	114.79	3.65	0.00	0.02
	2000	8.57	9.67	0.89	0.38	0.00	151.20	69.59	2.17	0.03	0.01
	2500	5.72	6.64	0.86	0.39	0.00	102.47	47.35	2.16	0.03	0.01
	3000	2.07	4.81	0.43	0.67	0.00	61.79	34.26	1.80	0.07	0.00
	3500	3.35	3.61	0.93	0.35	0.00	58.47	26.06	2.24	0.03	0.01
	4000	4.05	2.81	1.44	0.15	0.00	53.69	20.26	2.65	0.01	0.01
	4500	4.01	2.25	1.78	0.08	0.00	47.10	16.45	2.86	0.00	0.01
	5000	3.20	1.87	1.71	0.09	0.00	39.12	13.69	2.86	0.00	0.01
	5500	2.29	1.57	1.46	0.15	0.00	30.55	11.56	2.64	0.01	0.01

concentration and daily VKT, and this significance is enhanced if WD impacts are considered in the explanatory variable, VKT.

In this research, 11 circular buffers, with radius varying from 500 to 5500 meters, are delineated around AQMs, and VKTs for each buffer zone are calculated using geo-processing analyses and Python® scripts. To assess WD impacts, each circular buffer zone is divided into 8 sectors and VKT for each sector is calculated, and then WD frequency for each sector is applied as a weighting factor of VKT. The regression results without and with WD impacts are presented in Table 1 for each of the four pollutants: NO_2, SO_2, CO, and PM10. The regression models are estimated with hourly data, so that the number of observations used for each regression equation is 816 (34 AQMs × 24 hrs).

As expected, in most cases, consideration of WD impacts provides better regression results. The explanatory power of the model varies with the size of the buffer, both without and with WD impacts. In the case of NO_2, the explanatory power increases with the radius of the circular buffer, with the highest R^2 occurring around 4 km, similar to what Kim and Guldmann (2008) reported while using annual average concentrations as dependent variables. On the other hand, VKT and WVKT for buffers of less than 1.5 km radius provide the best explanations for SO_2, CO, and PM10 concentration. According to Zhu et al. (2002), concentrations of ultra fine particles (diameter less than 0.1 micrometers) are decreasing by 60 to 80% within 100 meters downwind from a road. Therefore, in the PM10 case, the 500-meter buffer provides the best explanation. Sources of PM10 vary widely, from man-made to natural sources, including dusts from roads, construction sites and agricultural land, motor vehicle emissions, exhaust of internal combustion engines, marine aerosol, pollen, secondary products such as ammonium nitrate and sulfate, and wind blowing from China (yellow sand phenomenon). For these reasons, the overall goodness of fit for PM10 models is lower than for the other models.

CO is produced by the incomplete combustion of carbon-containing materials, and motor vehicles are its major source in urban areas. The VKT and WVKT variables, however, do not provide as good results as in the NO_2 and SO_2 models. One possible reason is that the molecular weight of CO is less than that of air, thus freshly emitted hot CO from a tailpipe tends to be buoyant. This may accelerate the vertical rather than the horizontal dispersion of CO.

Ozone, a secondary product, is created by two precursors, NO_2 and VOC. A mid-afternoon high-temperature and clear sky is the best condition to produce O_3 (Derwent and Hertel, 1998). In addition, accumulated NO_2 and VOC concentrations and their mixing ratio play important roles in creating ozone. The process of ozone creation is highly non-linear, in accordance with the status of NO_2, VOC, and weather conditions, and, as shown in Equation (2), ambient

Table 2. Ozone regression results between without and with wind direction impacts on VKT(Buffer radius 4,500 meters)

	Time	Without Wind Direction Impacts					With Wind Direction Impacts				
		Parameter	St. Error	t Value	Pr > | t |	R^2	Parameter	St. Error	t Value	Pr > | t |	R^2
O_3	00-01	-13.64	5.16	-2.64	0.01	0.18	-64.62	21.57	-3.00	0.01	0.22
	01-02	-17.33	7.41	-2.34	0.03	0.15	-82.41	30.58	-2.69	0.01	0.19
	02-03	-22.75	9.86	-2.31	0.03	0.14	-110.21	44.00	-2.50	0.02	0.16
	03-04	-25.07	12.74	-1.97	0.06	0.11	-139.79	66.23	-2.11	0.04	0.12
	04-05	-22.29	13.20	-1.69	0.10	0.08	-115.28	63.20	-1.82	0.08	0.09
	05-06	-16.92	9.50	-1.78	0.08	0.09	-84.44	45.12	-1.87	0.07	0.10
	06-07	-7.94	3.97	-2.00	0.05	0.11	-41.32	19.45	-2.12	0.04	0.12
	07-08	-3.98	2.22	-1.80	0.08	0.09	-28.39	13.57	-2.09	0.04	0.12
	08-09	-4.46	2.13	-2.09	0.04	0.12	-27.43	11.50	-2.39	0.02	0.15
	09-10	-9.08	2.69	-3.38	0.00	0.26	-55.34	15.65	-3.54	0.00	0.28
	10-11	-14.19	3.53	-4.02	0.00	0.34	-103.24	24.89	-4.15	0.00	0.35
	11-12	-19.55	4.68	-4.18	0.00	0.35	-133.73	32.11	-4.16	0.00	0.35
	12-13	-25.19	6.52	-3.86	0.00	0.32	-180.35	48.35	-3.73	0.00	0.30
	13-14	-27.79	7.31	-3.80	0.00	0.31	-196.59	53.83	-3.65	0.00	0.29
	14-15	-30.03	7.67	-3.91	0.00	0.32	-219.53	58.96	-3.72	0.00	0.30
	15-16	-31.41	7.78	-4.04	0.00	0.34	-213.13	54.26	-3.93	0.00	0.33
	16-17	-30.75	7.08	-4.34	0.00	0.37	-210.80	50.46	-4.18	0.00	0.35
	17-18	-26.83	5.72	-4.69	<.0001	0.41	-191.98	44.92	-4.27	0.00	0.36
	18-19	-21.10	4.24	-4.98	<.0001	0.44	-145.54	29.46	-4.94	<.0001	0.43
	19-20	-17.89	3.52	-5.08	<.0001	0.45	-117.24	21.28	-5.51	<.0001	0.49
	20-21	-15.79	3.25	-4.87	<.0001	0.43	-114.16	19.98	-5.71	<.0001	0.50
	21-22	-12.92	2.91	-4.44	0.00	0.38	-74.78	14.34	-5.22	<.0001	0.46
	22-23	-11.85	3.26	-3.64	0.00	0.29	-71.12	16.50	-4.31	0.00	0.37
	23-24	-11.55	3.61	-3.20	0.00	0.24	-63.71	17.10	-3.73	0.00	0.30

ozone is consumed by NO for NO_2 conversion. Hourly ozone concentrations are interconnected with the vehicle emissions in previous hours, including NO, NO_2, and VOC. Thus, time-series data, especially on an hourly base, may not be appropriate to explain O_3 concentrations. In this research, ozone models are estimated using cross-sectional data for 34 AQM, a 4.5 km buffer radius, and 24 hours. The 4.5 km is the best buffer radius distance found in Kim and Guldmann (2008). The results are presented in Table 2.

In any given hour, which implies steady-state meteorological conditions, the cross-sectional O_3 concentrations are determined by the ratio of O_3 creation and destruction. As seen in Table 2, all O_3 model coefficients are negative, which implies that, under the same weather conditions, ozone concentrations are negatively related to VKT. As mentioned above, freshly emitted NO from motor vehicles reacts with nearby O_3, which decreases ozone concentration. Thus NO-abundant regions, such as highly urbanized areas, can dominate the ozone destruction process rather than its creation. Consideration of WD impacts on VKT increases the model explanatory power, except between 11 AM to 7 PM.

5. CONCLUSION

The relationships between hourly VKTs around AQMs and five air pollutants concentrations (NO_2, O_3, SO_2, CO, and PM10) are investigated. The hourly VKTs have positive relationships with NO_2, SO_2, CO, and PM10 concentrations. On the other hand, O_3 concentration is negatively correlated with VKTs. WD-weighted VKTs increase explanatory powers in most cases. In the case of O_3, however, WVKTs during the afternoon 8 hours do not enhance model predictability, which calls for further research.

References

1. Bøhler, T., K. Karatzas, G. Peinel, T. Rose, and R. San Jose (2002). Providing multi-modal access to environmental data–customizable information services for disseminating urban air quality information in APNEE. *Computers, Environment and Urban Systems* 26, pp. 39-61.
2. Derwent, R.G. and O. Hertel (1998). “Transformation of Air Pollutants” in J. Fenger, O. Hertel, and F. Palmgren(eds.) *Urban Air Pollution-European Aspects*. Dordrecht, Netherlands: Kluwer Academic Publishers, pp. 137-160.
3. Faiz, A.(1993). Automotive emissions in developing countries—relative implications for global warming, acidification and urban air quality. *Transportation Research* A 27, pp. 167–186.
4. Jensen, S.S., R. Berkowicz, H.S. Hansen, and O. Hertel (2001). A Danish decision-support GIS tool for management of urban air quality and human exposures. *Transportation Research Part D.* Vol. 6, pp. 229-241.
5. Jo, W.K. and J.H. Park (2005). Characteristics of roadside air pollution in Korean metropolitan city (Daegu) over last 5 to 6 years: temporal variations, standard exceedances, and dependence on meteorological conditions. *Chemosphere* 59, pp. 1557–1573.
6. Kim, Y. and J.M. Guldmann (2007). Urban Air Pollution, Traffic Volume, and Road Congestion, Presented at 48th Annual Meeting of the Association of Collegiate Schools of Planning, Milwaukee, WI, October 2007.
7. Kim, Y. and J.M. Guldmann (2008). A GIS-Based Analysis of Traffic-Related Air Pollution in Seoul, Korea, *Transportation Research Record*, submitted for publication.
8. Korea Meteorological Administration (2008). Meteorological data application website, http://minwon.kma.go.kr/index.jsp, Accessed March 31, 2008.
9. Korea Ministry of Environment (2005). *2005 Environment White Paper.* Seoul, Korea.
10. Lau, J., W.T. Hung, C.S. Cheung, and D. Yuen (2008). Contributions of roadside vehicle emissions to general air quality in Hong Kong. *Transportation Research Part D* 13, pp. 19–26.
11. McHugh, C.A, D.J. Carruthers, and H.A. Edmunds (1997). ADMS-Urban: an air quality management system for traffic, domestic and industrial pollution. *International Journal of Environment and Pollution*, Vol. 8, Nos. 3-6, pp. 666-674.
12. Namdeo, A., G. Mitchell, and R. Dixon (2002). TEMMS: An integrated package for modelling and mapping urban traffic emissions and air quality. *Environmental Modelling and Software* 17, pp. 179-190.
13. NIER (2008). Request for data disclosure. http://www.nier.go.kr/, Accessed March 10, 2008
14. Pandey, S.K., K-H. Kim, S-Y. Chung, S-J. Cho, M-Y. Kim, and Z-H Shon (2008). Long-term study of NOx behavior at urban roadside and background locations in Seoul, Korea. *Atmospheric Environment* 42, pp. 607-622.
15. Potoglou, D. and P.S. Kanaroglou (2005). Carbon monoxide emissions from passenger vehicles: predictive mapping with an application to Hamilton, Canada. *Transportation Research Part D* 10, pp. 97-109.
16. Roorda-Knape, M.C., N.A.H. Janssen, J. de Hartog, P.H.N. Von Vliet, H. Harssema, and B. Brunekreef (1999). Traffic related air pollution in city districts near motorways. *The Science of the Total Environment* 235, pp. 339-341.
17. SDI (2007). Future traffic demand data in Seoul. http://sdihard.webhard.co.kr, Accessed January 5, 2007 (Not available now).
18. Seoul City Government (2008). Traffic counts data http://www.seoul.go.kr/info/organ/subhomepage/traffic/traffic_data/statisitcs/traffic/1203450_11162.html, Accessed May 5, 2008
19. SMPA (2004). *2003 Seoul Traffic Survey Report*, Seoul, Korea.
20. Small, K.A. and C. Kazimi (1995). On the cost of air pollution from motor vehicles, *Journal of Transport Economics and Policy* 29, pp. 7-32.
21. 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, pp. 4323-4335.