Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

International Symposium of Transport Simulation (ISTS'18) and the International Workshop on Traffic Data Collection and its Standardization (IWTDCS'18)

A Study on Road Network Perimeter Control Policy for Reducing Air Pollution in Urban Area

Sunghoon Kim[a], Sehyun Tak[b], Yeeun Kim[a], Hwasoo Yeo[a]*

[a]*Department of Civil and Environmental Engineering at KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea*
[b]*The Korea Transport Institute, 370 Sicheong-daero, Sejong-si, 30147, Republic of Korea*

Abstract

This study provides a new perspective of direct management of the air pollution in terms of urban road traffic. First, an estimation model for the level of area-wide air pollution is studied. Such study is conducted with the properties of the macroscopic fundamental diagram (MFD), which represents the aggregated traffic state of a specified urban region. The model is confirmed by comparing the simulated and real-world data on the macroscopic traffic property. Second, based on the estimation model, the effects of different network perimeter control policies on air quality of urban region are tested with simulation experiments. The tests show that the perimeter control policies give positive or negative impacts on the area-wide air pollution depending on the traffic demand patterns. This study shows a possibility of new development of signal control strategies, which can be established upon the analysis on the influence of the direct traffic control on the air pollutant emissions in the urban area.

© 2018 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
"Peer-review under responsibility of the scientific committee of the International Symposium of Transport Simulation (ISTS'18) and the International Workshop on Traffic Data Collection and its Standardization (IWTDCS'18)"

Keywords: air pollution; macroscopic fundamental diagram; perimeter control; urban road network; urban traffic simulation

1. Introduction

Road transportation has an intimate relationship with the atmospheric environment of urban area. Accordingly, various technological and political efforts have been attempted in order to improve urban air quality. The majority of such efforts are in the way of indirectly controlling the urban traffic demand, such as billing vehicles for entering specific urban area, limiting parking spaces, and encouraging the use of public transit. However, the existing environment-related transportation policies are being applied by just restraining the people's needs without proving a quantitative evaluation on the urban air pollution. Restraint policies without quantitative assessment can lead to

2352-1465 © 2018 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)
"Peer-review under responsibility of the scientific committee of the International Symposium of Transport Simulation (ISTS'18) and the International Workshop on Traffic Data Collection and its Standardization (IWTDCS'18)"

dissatisfaction of both urban road users and local authorities. Furthermore, the effect of such policies differs depending on the characteristics of regions (Höglund, 2004). In addition, due to the growth in urban population and city-centered life patterns, the indirect approaches of traffic control is even more difficult nowadays.

In order to tackle these immediate concerns, there are two main objectives in this study. First, in terms of quantitative evaluation on urban air quality, an estimation model for the level of area-wide air pollution is studied. Such study is conducted with the properties of the macroscopic fundamental diagram (MFD), which represents the aggregated traffic state of a specified urban region. The model is confirmed by comparing the simulated and real-world data on the macroscopic traffic property. Second, based on the estimation model, the effects of different network perimeter control policies on air quality of urban region are tested with simulation experiments. The results would provide a new perspective of direct management of the air pollution in terms of urban road traffic.

2. An area-wide estimation model for air pollution due to traffic

Most studies on the relationship between traffic and air pollutant emissions have focused on the impact of driving behaviors by analyzing the acceleration, cruising, deceleration, and idling of individual vehicles (Shabihkhani and Gonzales, 2014). However, in terms of urban area, there are several factors that influence the behaviors of the individual vehicles. The infrastructure design, which includes road capacity, road network topology, and available parking spaces, is one of the factors that indirectly gives systematic influences on the movements of individual vehicles. The traffic signal control system is also a major factor because vehicles' movements are directly controlled by traffic signals. The traffic condition of the road network is also an important factor, since the frequencies of stop-and-go and idling behaviors increase particularly when traffic congestion occurs in the urban area.

Therefore, in order to estimate, control and reduce the air pollutant emissions due to urban traffic, it is necessary to consider the aggregated traffic behavior at the network level. Especially, it would be more realistic to implement the related policies at the aggregated level, as it is difficult to individually apply the emission control policies to every vehicle. In addition, the traffic volume and the amount of air pollutant emissions change in real time in urban areas. Many air pollution monitoring stations are operated at certain locations over the world, but the data detected at the individual stations represent only localized impacts and do not display comprehensive air pollution conditions across the entire urban area. Hence, it is limited to directly analyze the relationship between the traffic and air pollutant emission with the data of individual monitoring stations alone. To tackle these concerns, this study aims to utilize the properties of the macroscopic fundamental diagram (MFD) for analyzing the aggregated traffic condition and its impact on air pollutant emissions. Such analysis with a macroscopic view can provide a comprehensive estimate of the emissions from individual vehicles in an urban area.

The MFD represents the relationship between space-mean traffic flow, density, and speed of a network with n road links as in Fig. 1. There have been growing interests in the MFD-related researches recently, since the existence of such concept were validated about a decade ago (Geroliminis and Daganzo, 2008). The main purpose of observing the aggregated traffic behavior is to determine if the performance of an urban road network achieves the desired target. Based on the observed information, traffic managers can apply appropriate traffic policies for improving the urban mobility or atmospheric environment.

For the area-wide estimation modeling for air pollution due to urban traffic, the average speed of road network is chosen for the property representing the traffic condition in an urban area. For the air pollutant, the emission of pollutant matter (PM) is particularly selected for the relationship analysis in this study, since it is deeply related to the increases of cardiovascular, respiratory, stroke, and mortality (Hong et al. 2002). The relationship between the network average speed and PM emission of urban network i is to be analyzed through the following linear regression equation.

$$PM_i = \beta_1 \cdot V_i + \beta_0 \tag{1}$$

where PM_i is the amount of the PM emission, V_i is the average speed of network i, β_1 is the regression coefficient, and β_0 is the constant term.

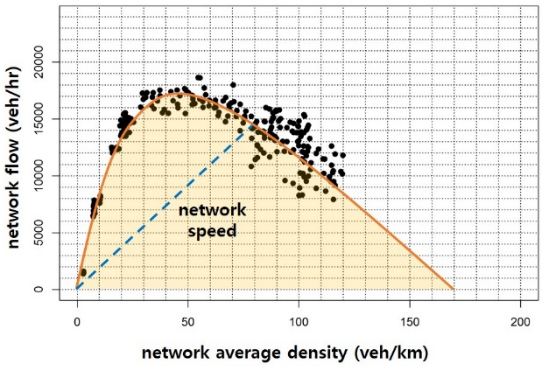

Fig. 1. The macroscopic fundamental diagram

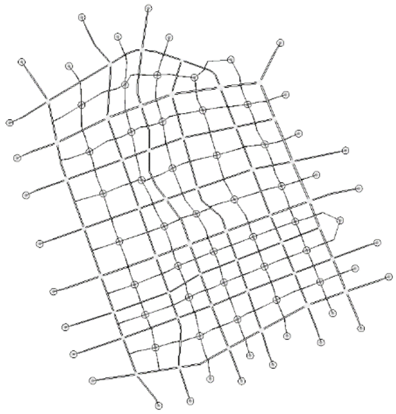

Fig. 2. Road network of AIMSUN simulation (Gangnam district)

3. Comparison between simulation and real data for validation

For the relationship analysis, we run the AIMSUN microscopic simulation program (AIMSUN, 2011) with a given scenario and generate simulated network traffic data and environmental data. The simulated relationship between the aggregated traffic and PM emission will be compared with the relationship derived from the real data.

3.1. Study site

The study site for the relationship analysis is the Gangnam district, which is located Seoul, South Korea and has the size of 15km^2. The site is one of the regions with the highest average traffic volume per day in the city (about 1 million), and it has the characteristics like the isolated network due to the highways and rivers in the periphery. Since the central business district and the commercial area are integrated in this study site, the daily traffic inflow and outflow are relatively higher than other regions.

3.2. Simulation description

For the relationship analysis, we create the road network of the study site by using the AIMSUN program as shown in Fig. 2. There are total 308 of bi-directional road links, and 44 of them are connected to the outside the study site. A total of 69 centroids are created in each of the outer and inner zones for generating and accepting the urban traffic. Hence, the traffic origin-destination (OD) matrix is generated based on these centroid. For generating the simulated traffic and environmental data to be compared with the real data, we apply homogeneously distributed OD traffic with 300 thousands of total volume. Then, we run the simulation program with the given traffic demand for 6 hours and extract the MFD-related properties such as space-mean speed, outflow, and average traffic density at every 1 minute. We also obtain the simulated environmental data such as the PM emission. These simulation data are generated based on the traffic parameters and environmental model (Panis et al., 2006) provided in the simulation program.

3.3. Real-world data

For the real traffic data, we use the data of road link speed provided by Seoul city. These data contain the speed information of the road links (km/h) in the study site, they are obtained by processing the GPS-based locations of 8,740 taxies in 2015. For the real environmental data, we use the data of the air pollution monitoring stations located in the city, which are shown in Fig. 3a. Three monitoring stations within the study site are particularly selected as shown in Fig. 3b. The study site is partitioned as in the figure through the Voronoi diagram based on the locations of the monitoring stations. It is assumed that the information detected in each station represents the total air pollution level of the each partitioned zones. These data are also provided by Seoul city and contain the information on the PM concentration (μg/m^3) within the study site in 2015. Both of the processed traffic and environment data are in the format of every hour.

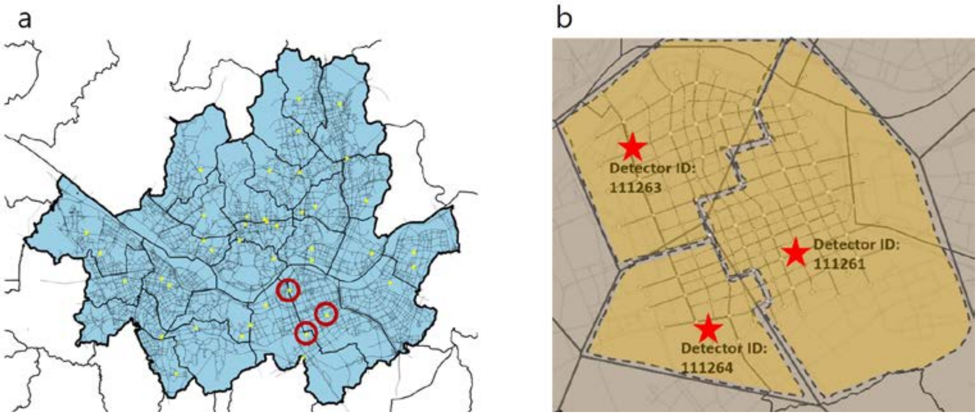

Fig. 3. (a) Air pollution monitoring stations in Seoul; (b) Detecting ranges of the stations in the study site

In order to analyze the effect of traffic on the PM emissions, the appropriate dates for the data should be selected for the analysis, because the pollutant concentration is influenced by meteorological conditions like rain and wind. For such matter, we firstly select the data of 120 clear days that were barely influenced by the weather. Out of these days, we secondly select the data of 47 days that were mainly the days after rain or snowfall. In these selected days, the floating air pollutants temporarily sink to the surface due to the precipitation phenomenon, so that the effect of air pollutant caused only by the urban traffic can be seen more clearly.

3.4. Comparison result

Fig. 4 shows the simulated MFD of the study site. As intended for the comparison analysis, the simulated traffic shows three different states. It shows that the aggregated network performance (travel production) increases under the network density of 20 veh/km, reaches the maximum level at 20~60 veh/km, and decreases for greater density values. Fig. 5 shows the comparison of the linear regression analyses on the relationship between the network average speed and PM10 concentration of the both simulated data and real data. Note that the PM10 emission data (g/km) obtained in the simulation is converted into PM10 concentration (μg/m^3) by considering the road length of the network and the area of the study site. This is done for the comparison purpose, because the real data only have the information on the concentration within the detecting range.

As we can see in the comparison, the adverse impact of road traffic on air pollution increases as the network average speed decreases. However, there is a slight differences at different values of the average speed. When the average speed of the aggregated traffic is lower than 30km/h, the simulated results are slightly higher than the actual observations, and the data dispersion is large as well. Such dispersion may be due to the spatial homogeneity issue, which concerns the scattered network performance that usually occur at the oversaturated traffic state (Buisson and Ladier, 2009; Knoop et al., 2013). This issue may be investigated further at a later stage. On the other hand, the real data show consistent trend with low dispersion, because the data represent the average of daily traffic patterns. Nonetheless, the relationship between the average speed and PM10 concentration of the both simulated data and real data show very similar linearity. The coefficient values are -0.7706 and -0.7582 for the simulated data and the real data, respectively. Hence, based on the estimation model derived from the simulation, the effect of perimeter control on PM10 emission due to urban traffic is tested in the following section.

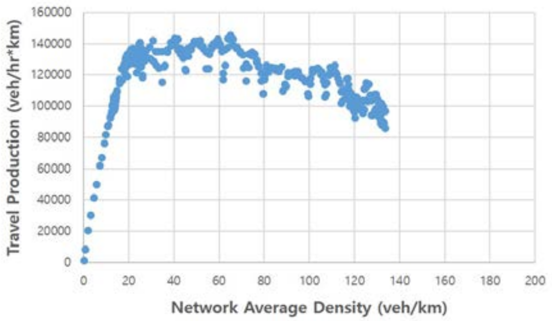

Fig. 4. Simulated macroscopic fundamental diagram

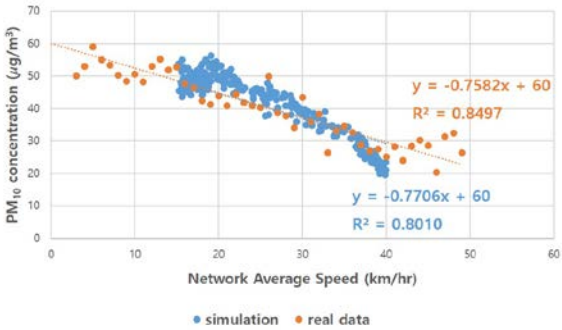

Fig. 5. Comparison between simulation and real data

4. Effect of perimeter control on air pollutant emission

Perimeter control is a recently developed urban traffic control concept, which aims to control traffic demands for a specific road networks prior to managing the internal traffic inside each of the networks. The interests in such concept have been growing since Daganzo (2007) that suggests to limit the network inflow at the minimum level when a network reaches a certain congestion level. There are several subsequent studies that attempted to solve the network gating problem for a single network (Keyvan-Ekbatani et al., 2012) or the transfer flow problem among multiple networks (Geroliminis et al., 2013), by using dynamic control algorithms.

In this study, the focus is in seeing the effect of perimeter control on the PM10 emission rather than finding the optimal control solution over time. Hence, rather than applying dynamic perimeter control, we test a few fixed control cases at different network inflow levels to see the effect on the PM10 emission.

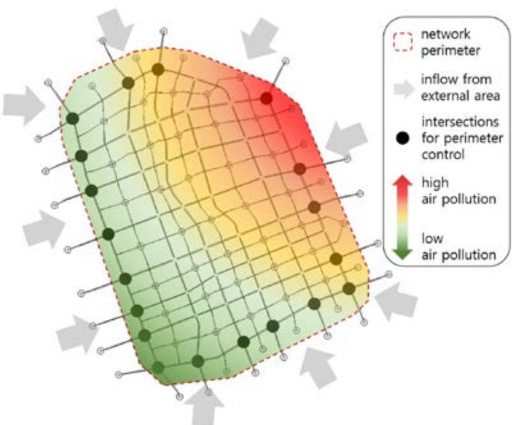

Fig. 6. Perimeter control and its effect on air pollutant emission

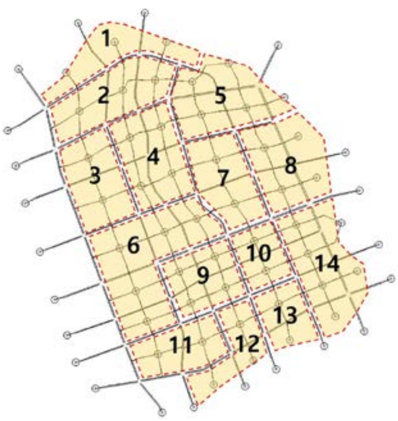

Fig. 7. Local divisions of the study site

4.1. Test scenarios

For traffic demand of the tests, two different traffic demands are applied to the simulation. One is the traffic demand before noon that includes the morning peak hours (5-11 AM) and the other is the afternoon demand that includes the evening peak hours (4-10 PM). These are the real world traffic demands that are also provided by Seoul city. Note that, since the study area is the major business area of Seoul, the majority of the real-world traffic travel from outside to inside of the network during morning peak hours (about 200 thousands), whereas the majority of traffic travel from inside to outside of the network during evening peak hours (about 180 thousands).

For the perimeter control of the tests, we set up scenarios to control the traffic inflow from the outside area by adjusting green signal splits at the intersections located around the study site in Fig. 6. The default green split towards inside the network at each intersection is 40 sec. For increasing or decreasing the inflow level of the study site, the green split value is differed by scenarios. The green split is set to -20 sec, -10 sec, +0 sec, +10 sec, +20 sec from the default value, and these values are applied to both of the before and after noon traffic demands. Hence, there are results of 10 different scenarios.

4.2. Test results

Fig. 8a and b show the macroscopic traffic behaviors of the morning period and evening period scenarios, respectively. In the both morning and evening cases, when the inflow level is decreased by perimeter control (green and blue dots), the traffic does not fall into the oversaturated state and recovers to unsaturated state. On the other hand, when the inflow level is increased (yellow and red dots), the traffic congestion is more severe compared to the default case (black dots). These diagrams show the behaviors of the traffic loading and recovery of the road network at different time periods (morning and evening). However, with these diagrams, it is still difficult to see how the traffic and signal control affect the air quality over the urban area. Hence, we use the estimation model to see such effects.

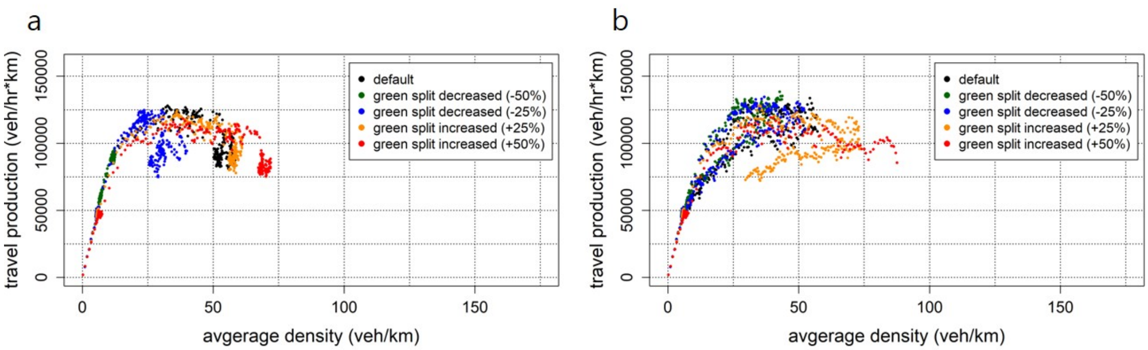

Fig. 8. Aggregated network traffic; (a) morning period; (b) evening period

The study site has 14 local divisions as in Fig. 7, and the concentration levels of each of these divisions are estimated based on the average speed values. The estimated values of the local divisions are presented in Fig. 9, which shows the average PM10 concentrations of the different scenarios.

In the morning period cases, when the inflow level is decreased the pollutant concentration decreases. On the other hand, when the inflow level is increased the pollutant concentration increases. These are very intuitive results, because this is due to that the majority of the traffic are generated from outside the area, and allowing less vehicles to enter the area positively affects both the traffic state and air quality. The cases of decreasing the inflow by 25% and 50% shows great difference. However, on the other hand, it is estimated that the effect of decreasing inflow is much greater than the effect of increasing the flow. There are not much difference between the cases of increasing the inflow by 25% and 50%. These cases shows the example of when increasing the green splits is not effective, because the inflow capacity in such cases is influenced more by the infrastructural conditions (number of road links and number of lanes at network perimeter) rather than by the signal timings.

In the cases of the evening period, the larger inflow level leads to the higher pollutant concentration as expected. However, the results are different from the morning cases. Increased inflow level means that the outflow level is decreased due to the control constraints, and since the majority of the traffic are generated from inside and travel towards outside the area in the evening cases, the demand throughput of the network is much less than the morning case. Hence the increased inflow level leads to the greater negative impacts on the pollutant concentration compared to the morning cases. On the other hand, when the network inflow is decreased, the outflow is increased by allowing more vehicles to leave the area, and this gives positive impacts on the pollutant concentration. However, the positive impact is less than the morning cases because the majority of traffic are generated inside the area and there are more amount of traffic within the study site.

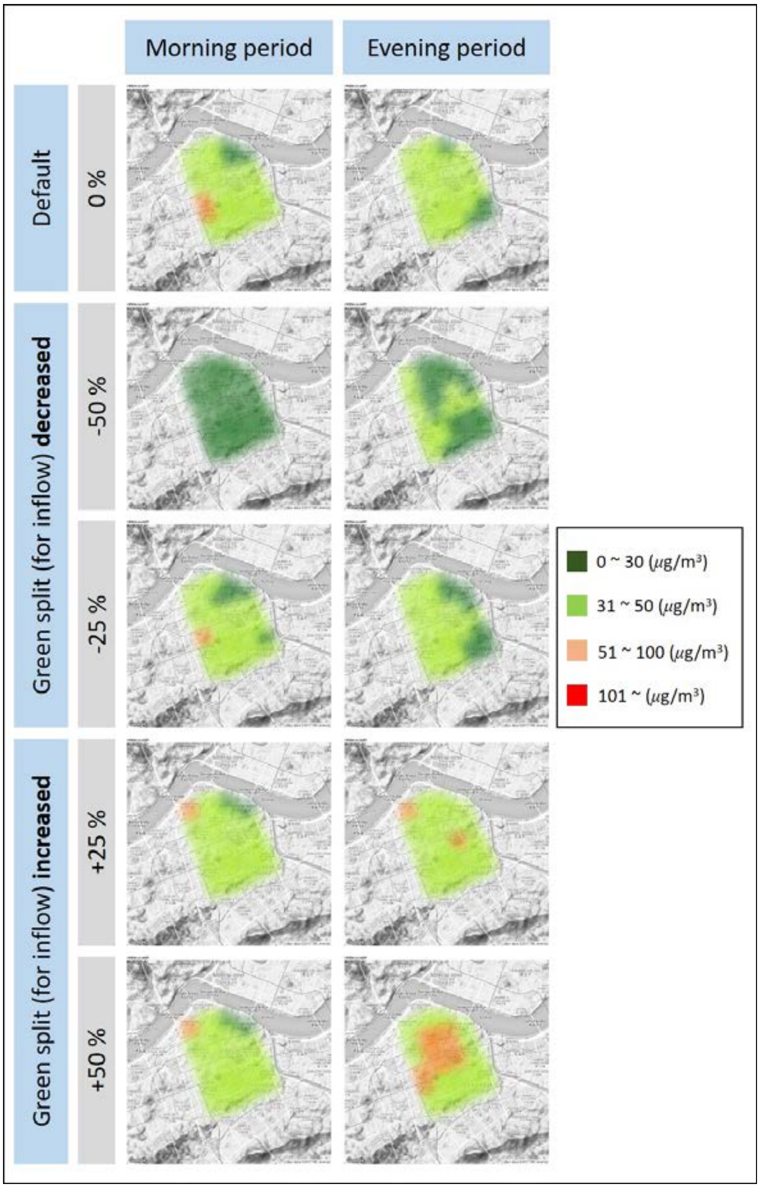

Fig. 9. Estimated PM10 concentration at different perimeter control policies

5. Conclusion

In this study, an estimation model for the level of area-wide air pollution is studied in terms of quantitative evaluation on urban air quality. Such study is conducted with the properties of the macroscopic fundamental diagram (MFD), which represents the aggregated traffic state of a specified urban region. The model is confirmed by comparing the relationship between the aggregated traffic behaviour and air pollutant emission of both the simulated and real-world data.

Then, based on the estimation model, the effects of different network perimeter control policies on air quality of urban region are tested with simulation experiments. The tests show that the perimeter control policies may give positive or negative impacts on the area-wide air pollution depending on the traffic demand patterns. Therefore, when establishing dynamic perimeter control at later stage, the regional-based travel patterns (Yildirimoglu and Geroliminis, 2014) majorly should be taken account into, for reducing air pollution due to traffic congestion. The effect of such control on the neighbouring urban regions should be considered as well.

This study shows a possibility of new development of signal control strategies, which can be established upon the analysis on the influence of the direct traffic control on the air pollutant emissions in the urban area. Such new perspective could be a part of the basis for further development of the environment-related traffic management strategies.

Acknowledgement

This work was supported by a grant (17CTAP-C129888-01) from Technology Advancement Research Program (TARP) funded by Ministry of Land, Infrastructure, and Transport of Korean government.

References

AIMSUN, 2011. AIMSUN Version 7 Users Manual. Barcelona: TTS-Transport Simulation Systems.

Buisson, C., Ladier, C., 2009. Exploring the impact of homogeneity of traffic measurements on the existence of macroscopic fundamental diagrams. Transportation Research Record: Journal of the Transportation Research Board 2124, 127-136.

Geroliminis, N., Daganzo, C. F., 2008. Existence of urban-scale macroscopic fundamental diagrams: some experimental findings. Transportation Research Part B-Methodological 42.9, 759-770.

Geroliminis, N., Haddad, J., Ramezani, M., 2013. Optimal perimeter control for two urban regions with macroscopic fundamental diagrams: a model predictive approach. IEEE Transactions on Intelligent Transportation Systems 14.1, 348-359.

Höglund, P. G., 2004. Parking, energy consumption and air pollution. Science of the Total Environment 334, 39-45.

Hong, Y. C., Lee, J. T., Kim, H., Ha, E. H., Schwartz, J., Christiani, D. C., 2002. Effects of air pollutants on acute stroke mortality. Environmental Health Perspectives 110.2, 187-191.

Keyvan-Ekbatani, M., Kouvelas, A., Papamichail, I., Papageorgiou, M., 2012. Exploiting the fundamental diagram of urban networks for feedback-based gating. Transportation Research Part B-Methodological 46.10, 1393-1403.

Knoop, V. L., Hoogendoorn, S. P., Van Lint, J. W. C., 2013. The impact of traffic dynamics on macroscopic fundamental diagram, Transportation Research Board 92nd Annual Meeting, Washington, DC.

Panis, L. I., Broekx, S., Liu, R., 2006. Modelling instantaneous traffic emission and the influence of traffic speed limits. Science of the Total Environment 371, 270-285.

Shabihkhani, R., Gonzales, E. J., 2014. Macroscopic relationship between network-wide traffic emissions and fundamental properties of the network, Symposium Celebrating 50 Years of Traffic Flow Theory, Portland, Oregon.

Yildirimoglu, M., Geroliminis, N., 2014. Approximating dynamic equilibrium conditions with macroscopic fundamental diagrams. Transportation Research Part B-Methodological 70, 186-200.