Vehicle-Actuated Signal Control System To Mitigate Environmental Impacts Due To Road Traffic: Measurements and Simulations

Y. Tsubota[a], K. Watanabe[b] and H. Kawashima[c]

[a] *Earth Science Department, Keio Senior High School, Yokohama, Japan (tsubota@hc.cc.keio.ac.jp)*

[b] *Faculty of Science and Technology, Keio University, Yokohama, Japan (kazu@ae.keio.ac.jp)*

[c] *Faculty of Science and Technology, Keio University, Yokohama, Japan (kawashima@ae.keio.ac.jp)*

Abstract: Air quality indices were measured at major intersections during winter, when the level of air pollution exceeds environmental standards. Variation in nitrogen dioxide (NO_2) concentration showed a similar periodicity to that of the traffic signal cycle. Variation in suspended particulate matter (SPM) concentration also showed that of a periodic pattern, but the phase of SPM was different from that of NO_2. Surveys of traffic conditions (traffic volume, types of vehicles, rate of route selection and traffic signal pattern) were carried out at three intersections during morning rush hour. It was found that total traffic volume depended mainly on the number of small cars, but the levels of air pollution along the roadside seemed to depend mainly on the number of heavy-goods vehicles (HGV). The observed traffic condition was simulated using a microscopic traffic simulator, VISSIM. VISSIM was also used to estimate the emissions of NO_x and SPM from vehicles. The observed periodic pattern of variation in NO_x concentration was reproduced by the traffic simulation. After confirming the reliability of the traffic simulation model, effectiveness of various traffic signal control systems in reducing the level of air pollution at an intersection was tested in simulation using data of observed traffic conditions. The results indicate that NO_x concentration in the air at an intersection can be minimized by using a traffic signal cycle that is appropriate for the traffic conditions. However, the appropriate signal cycle depends on traffic volume. The currently used traffic signal control system uses a fixed-time signal cycle, which is different from the signal cycle that minimized the NO_x concentration in simulations. Therefore, a new vehicle-actuated signal control system was designed and evaluated with respect to the observed traffic conditions. In simulations, the signal cycle was determined by the size of traffic volume. The results showed that the introduction of the new vehicle-actuated signal control system would reduce travel time, NO_x and SPM emissions.

Keywords: Signal control; Traffic; Emission; Air pollutants; Traffic simulation

1. INTRODUCTION

Air pollution due to road traffic is a serious problem in urban areas [Tokyo Metropolitan Government, 2000], especially near major intersections where traffic congestion occurs every morning. The level of air pollution monitored at Ikegami-Shincho Monitoring Station is the one of the worst in Japan [Kawasaki City Government, 1999], often exceeding the environmental standard for nitrogen dioxide (NO_2) concentration. Much interest has been shown by national and local governments in intelligent transport systems (ITS) as a means for solving the problem of air pollution due to road traffic. The establishment of an ITS-type road network infrastructure would enable continuous monitoring of traffic in urban areas and the immediate implementation of measures to reduce air pollution caused by traffic congestion. It would be possible to develop an even more sophisticated traffic control system by using artificial intelligence [Bielli et al., 1994]. In the present study, the effectiveness of vehicle-actuated signal control, as an ITS strategy requiring real-time traffic information and real-time traffic signal control capability, for solving the problem of air pollution at intersections was investigated.

The objective of this study was to develop a reliable vehicle-actuated signal control system to mitigate adverse impacts on the environment due to road traffic. More specific objectives were to:

- determine the dynamic features of air pollutants at the roadside,
- determine the dynamic features of the traffic condition at intersections in the morning rush hour,
- evaluate the currently used traffic signal control system,
- design a new signal control system including modification of the signal phase, and
- evaluate the effectiveness of the newly developed signal control system.

2. MEASUREMENTS IN KAWASAKI CITY

Measurements were carried out in the Ikegami-shincho area, Kawasaki City from 5:00 a.m. to 10:00 a.m. on October 27, 2000 and from 6:00 a.m. to 8:30 a.m. on December 22, 2000 as shown in Figure 1.

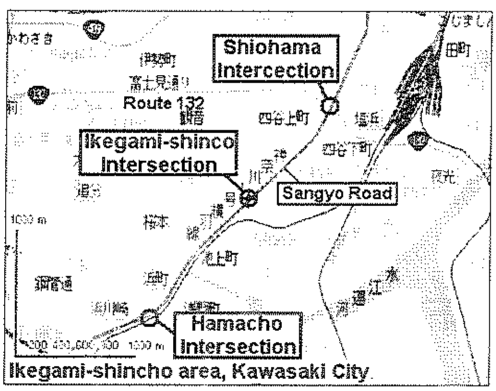

Figure 1. Study site (Ikegami-shincho, Kawasaki City, Japan).

2. 1 Measurement of Air Quality Indices

Air quality indices were measured along Sangyo Road near traffic signals at the Ikegami-shincho intersection. Temperature, relative humidity, air pressure, wind speed and direction, and concentrations of carbon dioxide (CO_2), nitrogen dioxide (NO_2), and suspended particulate matter (SPM) were measured as air quality indices. Since the measurement devices were set near intersections where vehicles stop and start running again in accordance with traffic signals, periodic fluctuations in CO_2, NO_2, and SPM concentrations were found (Figure 2). Wind speeds also showed a periodic pattern but with a shorter periodicity.

The environmental standard for NO_2 concentration is a daily mean value, calculated by hourly mean values, of 0.04 ppm to 0.06 ppm. Although the NO_2 concentrations were measured every second in this study, they exceed the environmental standard for NO_2 concentrations. The environmental standard for SPM concentration is a daily mean value of less than 0.1 mgm^{-3} and an hourly mean value of less than 0.2 mgm^{-3}. The observed SPM concentration level was about half of the environmental standard concentration.

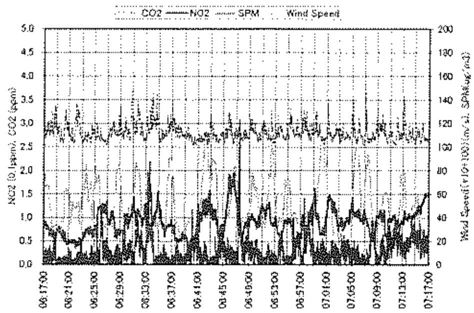

Figure 2. Measurement of air quality indices at Ikegami-shincho in Kawasaki City on December 22, 2000.

2.2. Traffic Conditions and Traffic Signal Control

Surveys of traffic conditions (traffic volume, types of vehicles, rate of route selection and traffic signal pattern) were carried out at Shiohama intersection, Ikegami-shincho intersection and Hamacho intersection. The currently used signal control systems were reviewed with respect to signal cycle, split, and offset. Traffic volume on Sangyo Road northbound for Tokyo is also regulated by the traffic signals at the Ikegami-shincho intersection as shown in Figure 3.

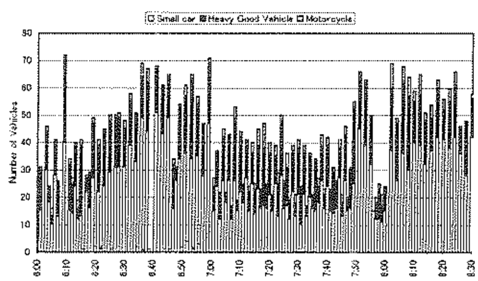

Figure 3. Variation in traffic volume in the Ikegami-shincho area along Sangyo Road northbound for Tokyo.

Traffic volume is defined as the number of vehicles that pass one point of a road per unit of time. The vehicles were aggregated by vehicle type, i.e., small car, heavy-goods vehicle (HGV), and motorcycle. The number of small cars peaked at about 6:35 - 7:00 a.m. and 8:00 - 8:15 a.m. The number of HGVs remained almost constant. Thus, the change in traffic volume was mainly due to a change in the number of small cars. Since no remarkable peak of NO_2 and SPM concentrations were not found in the measurements of air quality indices, it was thought that total traffic volume had little effect on air quality along Sangyo Road in the morning. The results suggested that exhaust emission from HGVs greatly affect the air quality.

The traffic signal control system at Ikegami-shincho intersection consists of three signal phases (see Table 1). The lengths of the signal phases are shown in Figure 4. The signal cycle and split time were compared with the volume of traffic northbound on Sangyo Road, but no obvious relationship was found. After 7:00 a.m., the signal cycle and split were almost fixed at 120 seconds and 44%, respectively. These findings suggest that adverse effects on the environment could be reduced by adjusting the traffic signal control system according to traffic conditions.

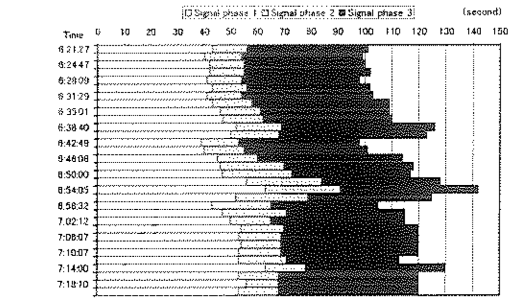

Figure 4. Traffic signal patterns at Ikegami-shincho intersection.

Patterns of northbound traffic at the Ikegami-shincho intersection were also analyzed, and the results are shown in Figure 5. The percentage of vehicle turning right at the intersection fluctuated depending on the time of day. This finding suggests that signal cycle and split should be modified in real time in accordance with traffic conditions.

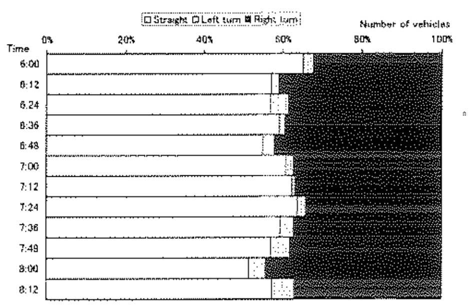

Figure 5. Changes in patterns of northbound traffic at Ikegami-shincho intersection.

The relationships between patterns of changes in traffic signals and air quality indices are shown in Figure 6. Fluctuations in NO_2 and SPM concentrations were found to be closely related to patterns of changes in traffic signals. Although further measurements are required in order to determine the exact phase relationships among NO_2 concentration, SPM concentration and patterns of changes in traffic signals, it is clear that appropriate signal control can improve air quality near an intersection. NO_2 and SPM concentrations showed periodicities similar to that of the traffic signal cycle. However, the phases of NO_2 and SPM concentrations were different. Therefore, signal control might not enable reductions in the concentrations of NO_2 and SPM. Since the level of NO_2, but not those of SPM, exceeded the environmental standards, the establishment of an appropriate strategy to reduce NO_2 concentrations seems to be of greater importance.

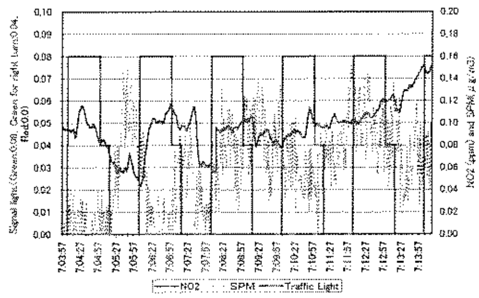

Figure 6. Fluctuations in NO_2 and SPM concentrations and patterns of change in traffic signals.

3. NUMERICAL SIMULATIONS OF OBSERVED TRAFFIC FLOW

3.1 Traffic simulator VISSIM

VISSIM is a microscopic, time-step and behaviour-based simulation model developed to model urban traffic and public transit operation by PTV Planung Transport Verkehr AG in Germany. It is able to simulate one-second movements of individual vehicles using Wiedemann's driver model [Wiedemann, 1974]. Widermann's driver model is a decision-based model that enables subsequent actions of a driver, such as acceleration, deceleration and changing lanes, to be determined on the basis of predefined model specifications such as probability distribution of acceleration, deceleration, maximum speed, and minimum speed. VISSIM also enables computation of exhaust emission from each vehicle based on the speed of the vehicle. It is also possible to compute exhaust emission from a vehicle based on acceleration and deceleration of the vehicle using the MODEM emission inventory [Jost et al., 1992].

VISSIM has a signal control module called VAP (vehicle-actuated programming). VAP enables construction of a specific signal control algorithm in a virtual road network. Vehicle detectors can be set at an intersection, and traffic signals can be controlled on the basis of information obtained from the detectors. Exchange of traffic information among detectors set at different intersections is also possible.

3.2 Simulated NO_2 and SPM Concentrations and Traffic Signal Patterns

A road network consisting of 84 links and 45 nodes was built in VISSIM (see Figure 7). Each link is a small segment of a road, and thus one road consists of several links. The input data for each link are length, number of lanes, capacity of vehicles, and speed limit for each vehicle type. Data on the traffic signal cycles and route selection rates based on observations carried out on December 22 were inputted into each intersection node. In the simulation, vehicles entered the road network from origin nodes. Data on traffic volume used in the simulation were based on traffic volume observed in a two-minute interval at each location. Data on vehicle types (i.e., small car, heavy-goods vehicle and motorcycle) based on observations were also used in the simulation.

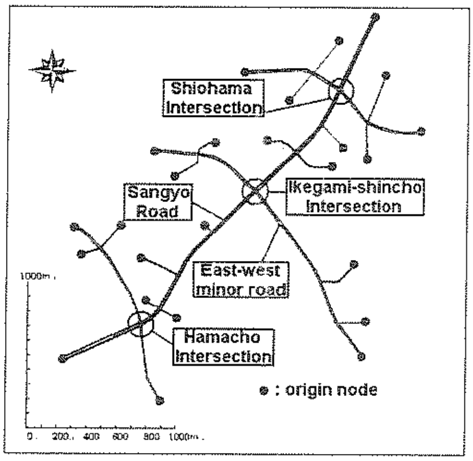

Figure 7. Road network of the study site reproduced in the VISSIM traffic simulator.

The correlation coefficient between simulated and observed traffic volumes was 0.98. Therefore, we concluded that VISSIM could reproduce the observed traffic flow pattern. Emission coefficient tables for NO_x and SPM were taken from an environmental white paper by Tokyo Metropolitan Government. The periodic changes in NO_x and SPM concentrations were reproduced according to the traffic signal cycle as shown in Figure 8. However, the phase difference between chances in NO_x and SPM concentrations could not be reproduced by VISSIM.

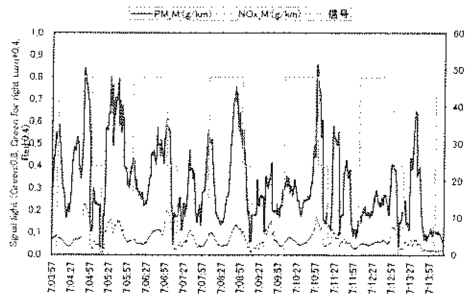

Figure 8. Simulated variations in NO_x and SPM concentrations by VISSIM.

4. PROPOSED VEHICLE-ACTUATED SIGNAL CONTROL

Preliminary traffic simulations indicate that there is a signal cycle that minimizes the NO_x concentration for the observed traffic condition. However, the appropriate signal cycle depends on traffic volume. The currently used traffic signal control uses a fixed-time signal cycle after 7:00 a.m. Moreover, the observed signal cycle (120 seconds) was different from the signal cycle that could minimize NO_2 and SPM concentrations in simulations. The signal cycle should be adjusted by traffic conditions. Therefore, a new vehicle-actuated signal control system was designed on the basis of measurements at the intersections. First, the currently used three-signal-phase system was reviewed to improve the safety. Then a new vehicle-actuated signal control system aimed at reducing the air pollution level at an intersection was designed by using vehicle detectors set not only on the northbound lane but also on other lanes.

4.1 Evaluation and modification of the signal phase

Three-dimensional monitoring of traffic flow patterns, which is possible using the VISSIM, was used to check the safety conditions of traffic at the intersection. A three-signal-phase system is currently used at the Ikegami-shincho intersection (Table 1). In signal phase 1, vehicles turning right from the south might collide with vehicles coming straight from the north. If there is a right-turning HGV from the north, it is difficult for driver of vehicles turning right from the south to see vehicles coming straight from the north as shown in Figure 9. In order to improve safety for drivers turning right on Sangyo Road, a four-signal-phase system was designed (see Table 1). However, this four-signal-phase system can not improve safety for drivers turning right on the east-west minor road intersected by Sangyo Road at the Ikegami-shincho intersection. However, since the traffic volume and ratio of vehicles turning right on the east-west minor road are both small, this modification seems to be sufficient for the time being.

Table 1. Compositions of the traffic signal phases. Numbers in circles indicate lanes at Ikegami-shincho intersection (see Figure 10)

Currently used signal control		Proposed vehicle-actuated signal control	
Signal phase 1	①②③④	Signal phase 1	①②
Signal phase 2	③④	Signal phase 2	①③
Signal phase 3	⑤⑥⑦⑧	Signal phase 3	③④
		Signal phase 4	⑤⑥⑦⑧

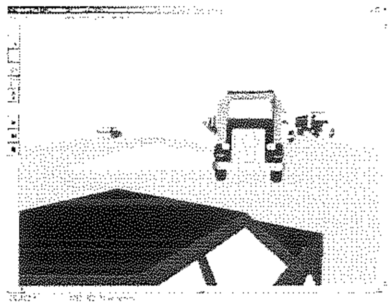

Figure 9. Screen image of VISSIM simulation for Ikegami-honcho intersection: scene from a vehicle turning right from the south on Sangyo Road.

4.2 Dynamic signal control using micro traffic-actuated control

The traffic volume in the four different directions at an intersection are generally different. Duration of green time should be determined according to the traffic volume for each direction instead of fixed green-time. Two following concepts were used as a basis for the design of the new vehicle-actuated signal control system: (1) traffic signal control should be location-specific and (2) green time should be variable and determined by traffic volume for a certain direction. In accordance with these two basic concepts, vehicle detectors were set on all lanes as shown in Figure 10. A new vehicle-actuated signal control algorithm has been designed on the basis of information obtained from the vehicle detectors.

Time headway was used as an index of traffic conditions. Time headway is defined as the time interval between two vehicles passing a certain detector. If the time headway is shorter than 3 seconds, traffic conditions are judged to be crowded. In this case, green time for that direction will be extended as long as the crowed conditions persist. However, it is also necessary to define the maximum and minimum green-times in advance, as shown in Table 2.

The green time of signal phase 3 is determined as follows. When the green time of signal phase 3 is between maximum and minimum green times, termination of green time for signal phase 3 is determined by detectors 3 and 4. If one of the detectors indicates time headway of less than three seconds, the green time of signal phase 3 will be extended. If both detectors indicate time headway of more than three seconds, signal phase 3 ends and signal phase 4 starts. If the green time of signal phase 3 becomes longer than the maximum extendible time, i.e., twenty seconds, signal phase 3 ends immediately. This is the algorithm of the proposed vehicle-actuated signal control system.

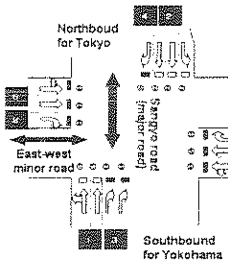

Figure 10. Illustration of Ikegami-honcho intersection. Numbers in circles indicate lanes in relation to specific signal-phases (see Table 1). Numbers in black boxes indicate vehicle detectors.

Table 2. Maximum and minimum green times and number of detectors set at Ikegami-shincho intersection.

Ikegami-shincho	mimum (s)	maximum (s)	detector
Stage 1	30	45	2
Stage 2	20	40	1
Stage 3	5	20	3, 4
Stage 4	30	50	5, 6, 7, 8
Signal cycle	85	155	

5. RESULTS AND DISCUSSION

The proposed vehicle-actuated signal control system was introduced at Ikegami-shincho, Shiohama and Hamacho intersections in a VISSIM traffic network, and ten simulations were executed using different random seeds. The effects of the proposed signal control system on NO_x and SPM concentrations are shown in Figure 11 and Figure 12, respectively. The rate of reduction in NO_x and SPM concentrations over a period of five hours, from 5:00 a.m. to 10:00 a.m., were 1.97 % and 2.21%, respectively.

The proposed signal control system significantly improved travel time and thus average speed of northbound vehicles on Sangyo Road as shown in Table 3. Travel time for the total network was reduced by 5.6% by using the proposed signal control system. Considering the relation between a vehicle's speed and emission coefficient, improvement in average speed inferred the mitigation of the environmental impacts.

The proposed signal control system was specifically designed for the observed traffic conditions.

However, traffic conditions depend on time of the day and day of the week. Therefore, it is necessary to develop an algorithm that automatically creates appropriate traffic signal phases based on the monitored traffic conditions. Moreover, an algorithm to determine maximum and minimum green times for major and minor roads based on the monitored traffic volume is needed.

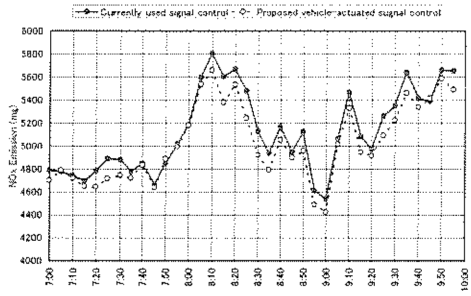

Figure 11. Comparison of simulated NO_x emissions.

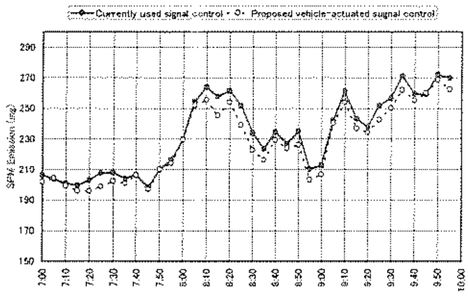

Figure 12. Comparison of simulated SPM emissions.

A new algorithm for calculating emission based on the vehicle's acceleration and deceleration may also be needed. Also, we should use a micro meteorology model together with a microscopic traffic simulator to simulate SPM concentrations since about 50% of SPM originates from the road surface [Tokyo Metropolitan Government, 2000].

Table 3. Improvement in travel time due to the proposed vehicle-actuated signal control system.

Travel time sections	Present method A(minute)	method B (minute)	Difference A − B(minute)	Improvement (%)
Sangyo road northbound	470	413	57	12.1
Sangyo road southbound	424	419	5	1.2
Minor road	177	180	-3	-1.4
Total of the network	**1071**	**1012**	**59**	**5.5**

6. CONCLUSIONS

The following results were obtained from measurements and traffic simulations.

· Concentrations of air pollutants, such as NO_2, SPM, and CO_2, at the roadside near traffic lights show fluctuated patterns of which the periodicities corresponds to that of the traffic signal cycle.

· Total traffic volume depends mainly on the number of small cars, but levels of air pollution along the roadside seems to depend on the number of heavy-goods vehicles in the morning.

· Modification of the traffic signal phase will improve traffic safety and enable smoother traffic flow.

· Utilization of the proposed vehicle-actuated signal control system improves average travel time for a network.

· Utilization of the proposed vehicle-actuated signal control system reduces air pollutants emitted by vehicles.

· A microscopic traffic-simulator is a useful tool for evaluating ITS features.

However, a simple microscopic traffic simulator is not sufficient for assessment of air quality at the roadside. Improvements in the traffic simulator and/or inclusion of a microscopic atmospheric model are needed for accurate assessment of air quality.

7. ACKNOWLEDGEMENTS

This research project was commissioned by the National Institute for Land and Infrastructure Management.

8. REFERENCES

Bielli, M, G. Amrosine, and M. Boero, Eds, Artificial Intelligence Applications to Traffic Engineering, VSP, Utrecht, Netherlands, p.324pp., 1994.

Jost P., D. Hassel, F. J. Weber, and K. S. Sonnborn, Emission and fuel consumption modfeling based on continuous measurements, DRIVE project V 1053, 1992.

Kawasaki City Govornment, Air pollution in Kawasaki city No.38 (in Japanese), Kawasaki city govornment, Kawasaki, Japan, 264pp., 1999.

Ministry of Construction, Public Works Research Institute and Keio University, The report about the introductory effect of ITS and fundamental research of AHS technology, Yokohama, Japan, 2000.

Tokyo Metropolitan Government, Environmental White Paper for Tokyo 2000 (in Japanese), Tokyo Metropolitan Government, Tokyo, Japan, 127pp., 2000.

Wiedmann, R., imulation des Strassenverkehrsflusses, Schriftenreihe des Instituts fur Verkerswesen der Universitaet Karlsruhe, Heft 8., Germany, 1974.