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Roadside Air Quality Simulation Model in Japan Clean Air Program

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1. INTRODUCTION

1.1 Overview of JCAP

The Japan Clean Air Program (JCAP) is a joint research project sponsored by the Japan Petroleum Energy Center, conducted by automobile manufacturers and oil companies in Japan, and supported by the Ministry of Economy, Trade and Industry of Japan. The aim of JCAP is to improve ambient air quality. Phase 1 of the project (JCAP I) was conducted from Japanese FY 1997 through FY 2001, and Phase 2 (JCAP II) ran from FY 2002 to the end of FY 2006.

In JCAP II, the possibility of achieving zero-emission vehicles by combining automotive and oil technologies was studied, and the sources of atmospheric fine particles were researched. Air quality simulation models were also developed to evaluate and propose various strategies for improving air quality (JCAP, 2007).

The third phase of the project (tentatively called Post-JCAP) started from FY 2007, aimed mainly at developing strategies to reduce nitrogen dioxide (NO_2) and fine particle concentrations along roadsides.

1.2 Air Quality Situation in Japan

In Japan, air quality is measured continuously at monitoring stations located around the nation. The average air quality of the regions monitored by background monitoring stations has improved recently, mainly due to efforts to reduce automobile and industrial emissions. Meanwhile, air quality along urban main roads, monitored by roadside monitoring stations, still shows some high concentration points, which represent problems yet to be solved.

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1.3 Air Quality Simulation Models in JCAP

Yoshikawa and co-workers have studied and developed roadside air quality simulation models with the aim of applying them to real urban roadside situations. A computational fluid dynamics (CFD) model was developed first and applied to a tracer gas diffusion field experiment in a real street canyon (Yoshikawa et al., 1998). Subsequently, relatively simple traffic and emission models were developed in JCAP I and applied to analyze real roadside air quality(Yoshikawa et al., 2003a, 2003b)

In JCAP II, each sub-model was improved in accuracy and its ability to represent real-world conditions. Finally, an integrated Roadside Air Quality Simulation Model (RsAQSM) was developed in JCAP II to simulate roadside air quality, analyze the factors causing high concentrations, and study strategies for addressing air quality problems (Yoshikawa et al., 2007)

1.4 Organization of this Paper

This paper is organized as follows. Section 2 gives an overview of RsAQSM developed in JCAP II. The general structure of the model is described, followed by a detailed description and validation of the three sub-models making up RsAQSM. Section 3 describes the application of RsAQSM to evaluate strategies for improving urban air quality along an actual urban road.

2. JCAP II ROADSIDE AIR QUALITY SIMULATION MODEL (RsAQSM)

2.1 General Structure of RsAQSM

2.1.1 Characteristics of Roadsides Areas with High Concentrations The values measured at roadside monitoring stations are key indices for evaluating the air quality along urban roads and in adjacent areas. The circumstances around roadside monitoring stations that show high concentrations tend to have the following characteristics.

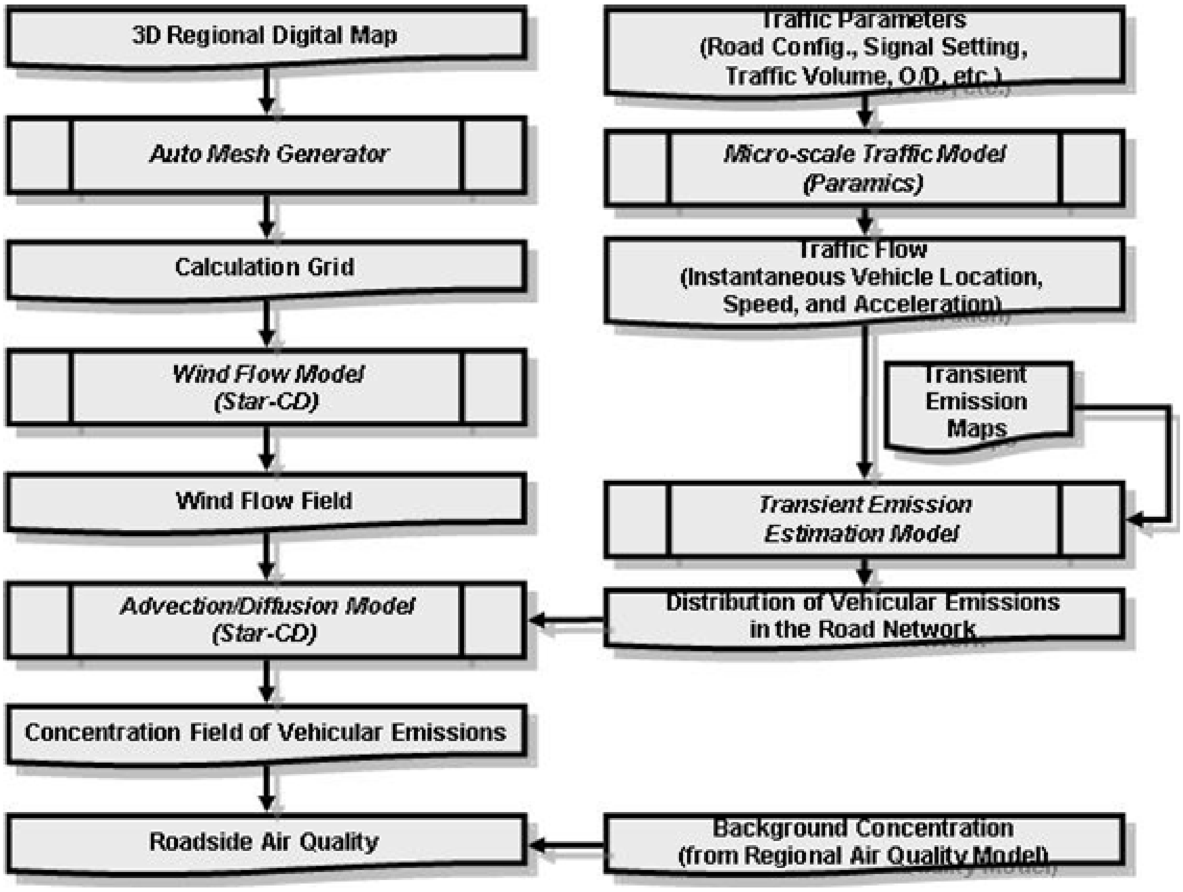

Figure 1 General Structure of Roadside Air Quality Simulation Model (RsAQSM) ***RsAQSM consists of three sub-models; a micro-scale traffic Model, a transient emission estimation model, and a CFD model.***

- Traffic volumes on the roads in the area are heavy, resulting in frequent congestion and acceleration/deceleration of vehicles near intersections.
- Street canyons are formed by buildings flanking both sides of the main roads, and they often have elevated roads built over them.

These circumstances lead to:

- Frequent congestion and acceleration/deceleration of vehicles, resulting in high levels of exhaust emissions.
- The semi-closed space formed along the roads tends to stagnate exhaust emissions in the immediate area, resulting in high concentration zones near roads.

2.1.2 Requirements of RsAQSM Therefore, in order to predict roadside air quality accurately, the following capabilities are necessary:

i) prediction of detailed vehicular behavior, including congestion, acceleration and deceleration;

ii) estimation of transient exhaust emissions of individual vehicles in relation to the detailed behavior;

iii) prediction of wind flow and advection/diffusion of exhaust emissions, taking into account the detailed shapes of roadside structures such as surrounding buildings or elevated roads.

2.1.3 General Structure of RsAQSM Based on these requirements, an integrated model of RsAQSM was constructed in this study, which consists of:

ii) a transient emission estimation model, and

iii) a wind and advection/diffusion model

as sub-models.

The general structure of RsAQSM and the flow of the calculations are shown in Figure 1. First, the detailed traffic flow on the road network in the target area is calculated with a micro-scale traffic model (top right), and then the distribution of vehicular emission gases in the network is calculated with a transient emission estimation model. A calculation grid (top

Figure 2 Map around Kamiuma Intersection ***Two major roads, Rt. 246 and Loop 7 cross on the ground, with the latter passing under the former, while the Met. Expway is built over Rt. 246.***

left) is generated based on a 3D digital map representing the detailed shapes of structures in the area, and the wind flow field in the area is calculated with a CFD model. Transport of the emission gases by the wind flow is then calculated to obtain the concentration field due to vehicular emissions. Finally, the total concentration field is obtained by adding the background concentration calculated with a regional air quality model. The details of the sub-models and model validation are described in the following sections.

2.2 Target Area Chosen for Validation of RsAQSM

The area around the Kamiuma intersection in the Setagaya Ward of Tokyo, shown in Figure 2, was chosen as the target area for validation of the sub-models.

The Kamiuma intersection is located at the outer rim of the Tokyo metropolitan area. National Route 246 and Metropolitan Route Loop-7 intersect here, with the latter passing under the former. Metropolitan Expressway No. 3 also overlaps Route 246. Average traffic volumes on these three roads are approximately 2,500, 3,700, and 4,300 vehicles/hour, respectively. Medium-height buildings of five to ten stories flank the roads, forming street canyons, while behind the buildings are residential areas with low-rise houses of one to three stories.

Table 1 Input and Output Data for Micro-Scale Traffic Simulation Model, Paramics

Input Data

Road Network	Origin-Destination
- Links (Roads)	- Origin
- Nodes (Intersections)	- Destination
- Signal Timing	- Starting Time
- Restrictions	- Vehicle Type
- Others	- Traffic Volume

Output Data

Instantaneous Variables
- Second-by-second Position, Speed of Individual Vehicles

Statistical Variables
- Link Traffic Volume
- Link Average Vehicular Speed
- Vehicular Speed Distribution
- Vehicular Acceleration Distribution
- Others

2.3 Micro-scale Traffic Simulation Model

2.3.1 General Features A traffic simulation model, positioned at the uppermost level of RsAQSM, must be able to:

i) identify individual vehicles and their types,
ii) take account of driver behavior,
iii) take account of traffic conditions such as the presence and timings of traffic signals, curb parking, bus lanes, or traffic restrictions, and

Figure 3 Calculation Image of Micro-Scale Traffic Simulation Model, Paramics ***Behavior of each vehicle is calculated second by second.***

iv) output second-by-second data on the position, speed, and acceleration/deceleration of vehicles.

Among the micro-scale traffic simulation models satisfying these criteria, Paramics (PARAllel MICroscopic traffic Simulator) (Paramics., 2007) was employed in this study as a base model. Paramics was developed by the University of Edinburgh in cooperation with the Department of Transport of the United Kingdom. Because the model is suited for traffic in the UK, a driver behavior model developed by the Japan Automobile Research Institute (Suzuki et al., 2004) was embedded in Paramics to suit traffic conditions in Japan. Table 1 shows the input/output data of the model. Figure 3 shows an image of the calculation.

2.3.2 Validation of the Micro-Scale Traffic Simulation Model A comparison was made of the traffic conditions around the Kamiuma intersection. The road network used in the traffic simulation model to represent the area consisted of 128 links (road elements), 61 nodes (joints of the links), and 14 intersections with traffic signals. Road configurations were taken from digital road map data. Hourly data for the origin and destination of vehicle trips for each vehicle type were constructed based on traffic census data. Fixed-route buses and curb parking (which disturbs the traffic flow) were also considered.

A field survey was conducted in the area around the Kamiuma intersection in June 2003 to measure traffic volumes, vehicle types and speeds, signal timings, and other data. A 24-hour episode in the survey period was simulated to verify the model's ability to represent traffic volumes and link-averaged vehicle speeds. For the 24-hour comparison, the correlation factor and root-mean-square (RMS) error for the traffic volume were 0.99 and less than 10%, and 0.90 and less than 30% for the average speed. These results verified the good representability of the model.

2.4 Transient Emission Estimation Model

2.4.1 General Features The transient emission estimation model estimates second-by-second transient emission levels and allocates the results to vehicle positions, based on the detailed data of vehicle behavior calculated with the micro-scale traffic simulation model. Accumulating transient emission data for all vehicles over the target time period results in a time-averaged distribution of

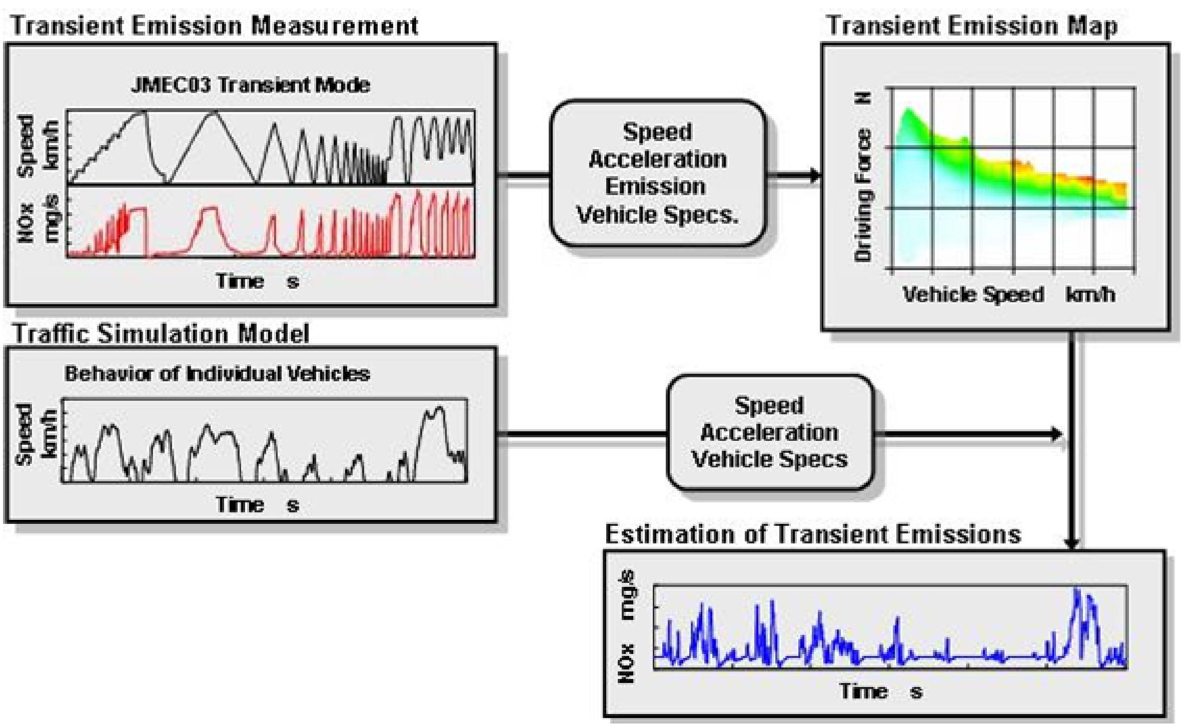

Figure 4 General Structure of Transient Emission Estimation Model employed in RsAQSM *Transient emission maps were prepared from chassis dynamometer test data for many vehicle categories. Vehicle behaviors were calculated with the traffic simulation model. Transient vehicle emissions were estimated by combining these data.*

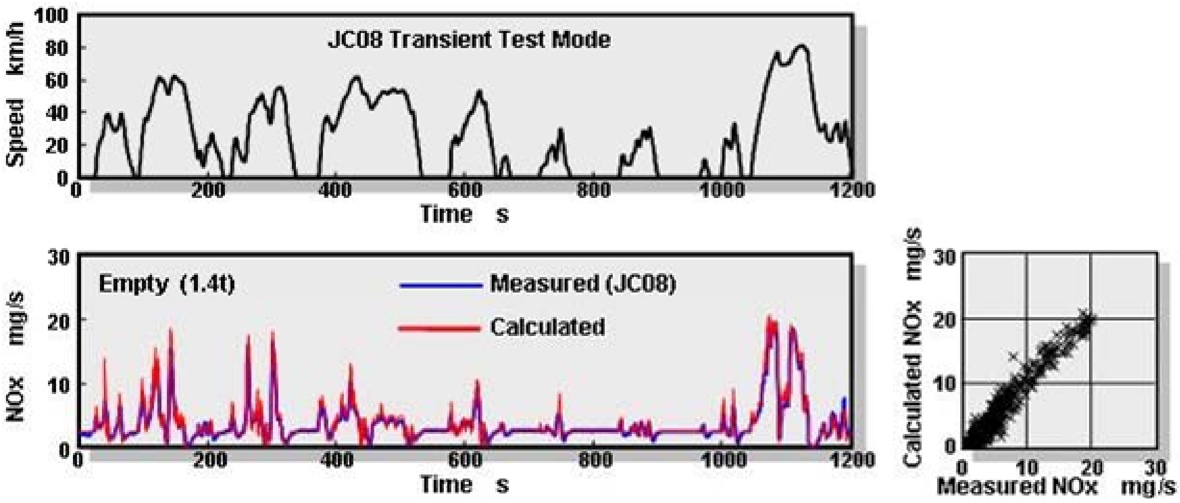

Figure 5 Validation of the Transient Emission Estimation Model ***Transient emission profile for the JC08 test mode was measured on a chassis dynamometer and compared with the estimated transient emission profile calculated using the measured vehicle speed profile and procedure in Figure 4.***

exhaust emissions for the entire road network. Figure 4 shows the structure of the model.

Since on-road vehicle behavior is essentially transient and emission characteristics for transient behavior are not the same as for a steady-state condition, transient emission characteristic maps for each vehicle category were prepared to estimate emission profiles for actual traffic behavior. Transient emission data were collected in chassis dynamometer tests using a transient driving mode (JMEC3), which was developed in JCAP II to cover a wide range of actual driving conditions. The data were compiled into transient emission rate maps as a function of vehicle speed and driving force, which make it easy to consider the effect of road grades or load levels.

To obtain a reasonable representation of vehicles in the real world, in-use vehicles on the road were categorized by emission regulation categories (e.g., gasoline passenger vehicle, diesel heavy-duty truck), order of emission regulation enforcement in Japan (e.g., 1978 regulations for gasoline vehicles, 2005 long-term regulations for diesel vehicles), engine size, gross vehicle weight class, and type of emission reduction devices used and others. According to this categorization, more than 130 types of vehicles were tested.

In the output of the traffic simulation model, each vehicle was assigned to categories broader than the emission map categories. Therefore, the map applied to each vehicle was selected randomly from the maps corresponding to the broader category according to the ratios of the vehicle traffic volume.

2.4.2 Validation of the Transient Emission Estimation Model The actual and estimated transient emission profiles for another transient driving test mode (JC08) are compared in Figure 5. The estimated values were calculated according to the procedure in Figure 4, using the transient vehicle speed and load data obtained from the chassis dynamometer tests conducted under JC08 instead of

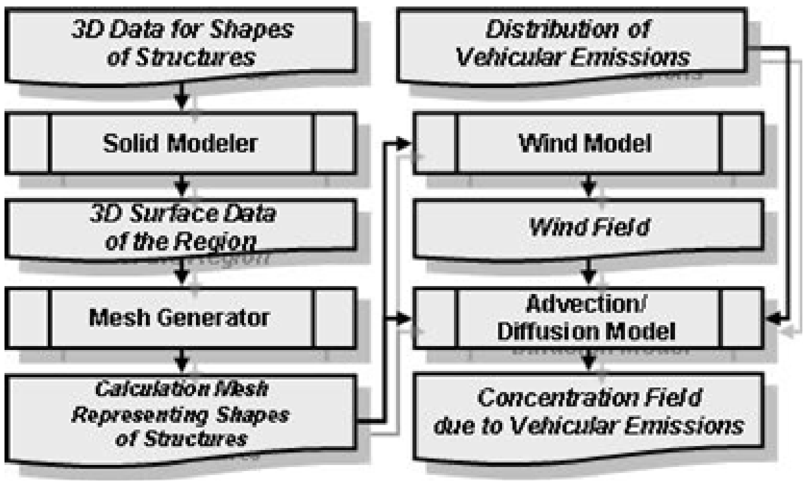

Figure 6 General Structure of CFD Calculation Employed in RsAQSM ***Wind field model and advection/diffusion model use a calculation mesh generated based on 3D map data.***

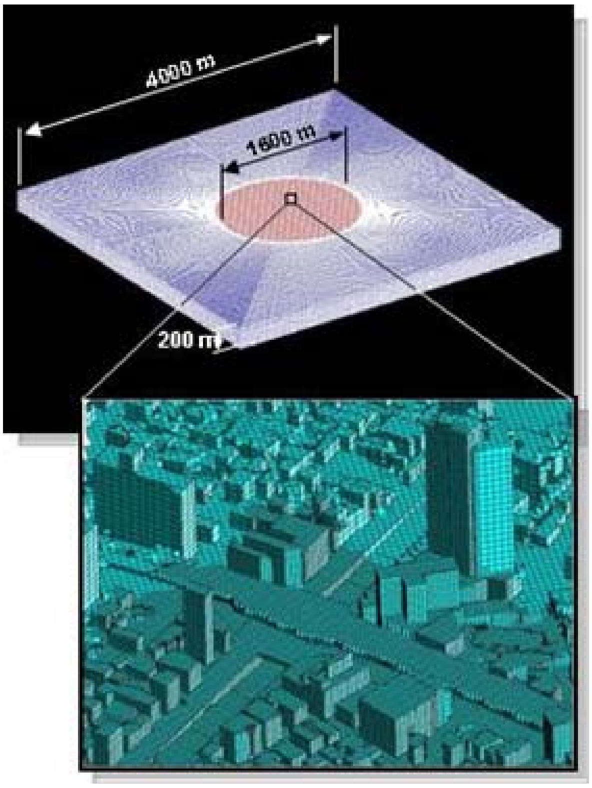

Figure 7 Example of Calculation Mesh used in CFD ***Smallest mesh in the center of the region is 0.75 m in size, while the outer rim is 12 m; total number of meshes is approx. 1.2 million.***

from the traffic simulation model. This comparison shows that the model is capable of representing a transient profile of real emission levels qualitatively and quantitatively.

2.5 Wind Flow and Advection/Diffusion Model

2.5.1 General Features The wind flow field in the target area and the advection/diffusion of vehicular emission gases, obtained with the transient emission estimation model, are calculated in the last step to obtain the air quality along the roads. Figure 6 shows a flowchart of the CFD calculation. Because the target area of the model is relatively small (approximately several hundred meters in diameter around the intersection), the shapes of structures such as surrounding buildings affect the wind field. Therefore, a calculation mesh was created based on a detailed 3-dimensional digital map, so that shapes of structures in the area, such as buildings, houses, elevated roads and underpasses/overpasses would be well represented in the mesh. Star-CD (CD-adapco., 2007) was employed for the CFD model

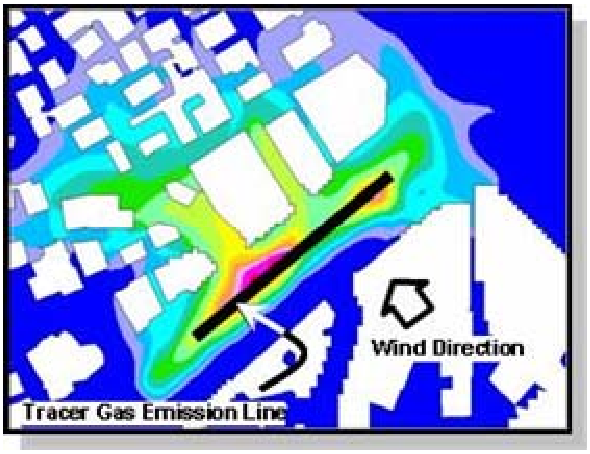

Figure 8 Example of Concentration Contours Calculated by RsAQSM A ***field experiment at Kamiuma intersection involving the release of tracer gas from the center line of the main road was simulated.***

to calculate the wind flow field and transport of emission gases.

The calculation mesh of the area around the Kamiuma intersection is shown in Figure 7. Detail configuration of 1,000 m by 1,000 m square area is represented in a area of circle with a 1600 m diameter , and the smallest mesh size is 0.75 m at the center of the area. The total number of meshes is approximately 1.2 million, including the outer rim for the approaching area. The detailed shapes of the high-rise and medium-height buildings along the roads, residential houses in the background area, and the underpass at the intersection are well represented.

2.5.2 Validation of the Wind Flow and Advection/Diffusion Model Figure 8 shows a typical representation of the tracer gas concentrations found in a tracer gas diffusion field experiment conducted around the Kamiuma intersection in 1999. In the experiment, tracer gas was emitted continuously from the center line of Route 246 as a line source, and transported into the background area by a northwest wind. The diffusion concentration was measured at 41 points on the roads and in the background area. The correlation factor between the measured and calculated tracer concentrations for two wind speed cases, shown in Figure 9, was over 0.9 in each case. These results confirmed the validity of the wind and advection/diffusion model.

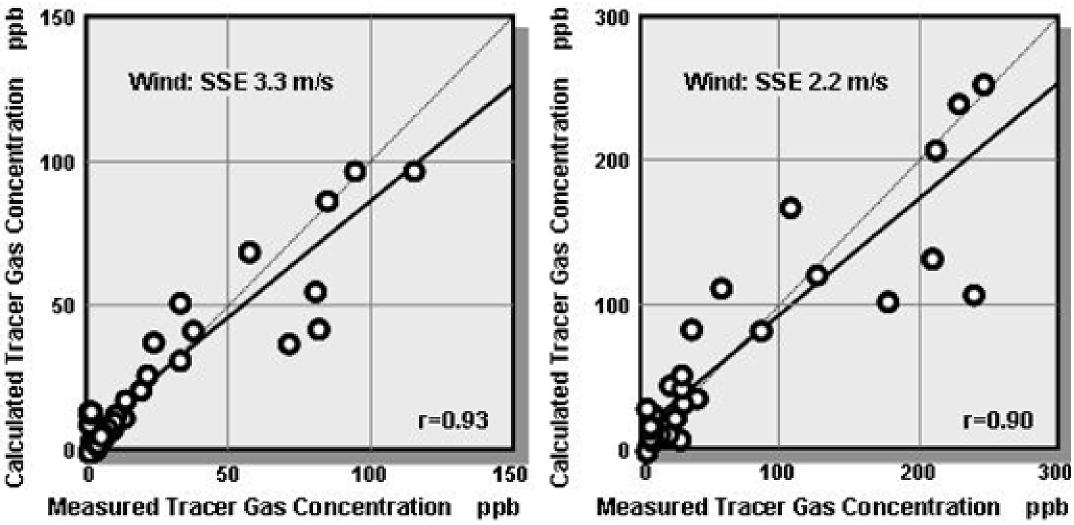

Figure 9 Comparison of Measured and Calculated Tracer Gas Concentrations in Field Experiment
Two cases for different wind speeds were compared.

3. APPLICATION OF RsAQSM TO REAL URBAN ROADS SITUATION

The RsAQSM model described in the preceding section was applied to a real urban road situation to predict the roadside concentration of nitrogen oxides (NOX, representing the sum of nitrogen mono-oxides and dioxides). A strategy for improving roadside air quality was also studied.

3.1 Ikegami Shin-cho Intersection Area

The area around the Ikegami Shin-cho intersection in Kawasaki Ward of Kawasaki city, shown in Figure 10, was chosen as the real urban road situation for application of RsAQSM.

The Ikegami Shin-cho intersection is located in the bayside industrial area between the Tokyo and Yokohama ports. Kanagawa Prefectural Road No. 6 “Tokyo-Daishi-Yokohama Line” (“Industrial Road”) and a Kawasaki municipal road “Satsuki-cho Mizue-cho Line” (“Municipal Road”) intersect here. The Metropolitan Expressway Kanagawa No. 1 Yoko-Hane Line also runs over the Industrial Road. Average traffic volumes on these three roads are approximately 1,600, 850 and 3,500 vehicles/hour, respectively. The Industrial Road goes through the Keihin industrial area where many large plants and small factories are located. As is typical of roads in industrial areas, 40% of the ground level traffic is heavy-duty vehicles. There are no major high-rise buildings in this area; low-rise one- to three-story buildings stand along the two main roads, while behind the roads are residential areas with low-rise houses. A public park is also situated to the southwest of the intersection. The Ikegami Kouen-Mae Roadside Air Quality Monitoring Station (Ikegami Station) is located along the industrial road approximately 160 m in the southwest direction from the intersection.

Figure 10 Map around Ikegami Shin-cho Intersection ***Industrial Road and Municipal Road intersect, while the Met. Expway is build over the Industrial Road.***

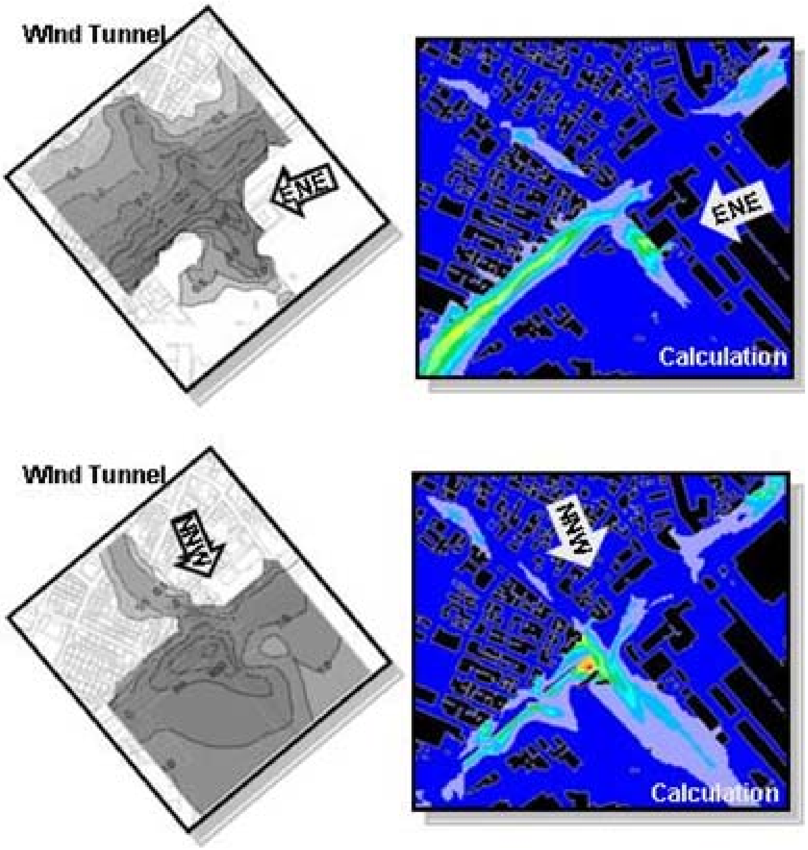

Figure 11 Comparison of NOx Concentration Fields between Wind Tunnel Experiment and Calculation ***Cases for ENE and NNW wind directions; note that contours of the wind tunnel experiment (left) are shown in logarithmic scale, while the calculated contours (right) are shown in linear scale.***

3.2 Validation of Representability of RsAQSM Applied to Ikegami Shin-cho Area

3.2.1 Comparison of NOx Concentration Fields with Wind Tunnel Experiments The calculation results were compared with wind tunnel experiments. The experiments were conducted in the wind tunnel apparatus at the National Institute of Environmental Studies in Japan (Ministry of Environment, et al. 2004). A 1/300 scale miniature model, representing the detailed shapes of the buildings, houses and elevated road in the area, was used in the experiments. Tracer gas was emitted from the roads at a rate distribution representing the vehicular emission distribution.

The concentration contours are compared in Figure 11 for wind directions of ENE and NNW. (Note that the contours are shown in logarithmic scale for the experimental results and in linear scale for the calculation results.) Comparisons of both wind directions show good agreement in terms of the locations of high concentrations and distribution patterns in the area. Other wind directions, not shown here, also showed good agreement.

3.2.2 Comparison of NOx Concentration Profile for One-Day Episode at Ikegami Station A calculated NOx concentration profile for a one-day episode was compared with the monitoring station measurement. Figure 12 show the comparison for the episode on October 3, 2003. The calculated concentration levels agree well with the measured data. Good agreement is also seen for the patterns of the diurnal profile, such as being low at night, increasing in early morning, having a peak at mid-morning, decreasing in the afternoon to reach a bottom in late afternoon, increasing again a little in the evening, and decreasing during the night again. The calculated peak seen at 18:00 , which is markedly different from the measured profile, might be

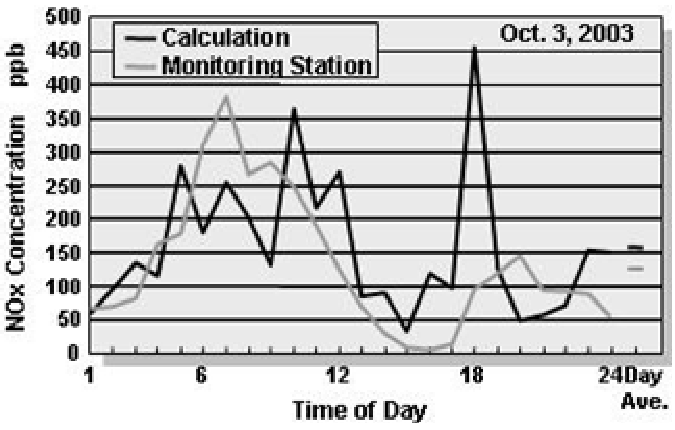

Figure 12 Comparison of NOx Concentration Profile in 1-Day Episode at Ikegami Monitoring Station near Ikegami Shin-cho Intersection ***Concentrations due to vehicular emissions are shown, but the background concentration is not included.***

Figure 13 Green Walls Installed on the Industrial Road ***Divided into three parts, steel panels are installed on the center line of the Industrial Road between the ground level and the bottom of the elevated road.***

attributable to the uncertainty of the wind data used for this time. The one-day average concentrations also show reasonably good agreement.

3.3 Case Study: Effect of "Green Walls", Along the Road

To demonstrate the usefulness of RsAQSM in examining strategies to improve air quality in real-world situations, the model was applied to study the effect of installing "green walls" in the Ikegami Shin-cho area.

3.3.1 Green Walls Green walls refer to large steel panels installed along the center line of the Industrial Road between the ground level and the bottom of the overhead Metropolitan Expressway for a distance of approximately 50 m and divided into three sections, as shown in Figure 13. Wind coming toward the road is disturbed by these walls and flow across the road is separated. The term green comes from the ivy vines growing on the walls.

Although the green walls been installed at the site for years for the purpose of improving air quality around the area, their effect has not been well analyzed so far. The RsAQSM model was used to analyze the effect of the green walls by comparing cases with and without them

3.3.2 Effect of the Green Walls on NOx Concentration Fields Figure 14 on the following page shows the NOx concentration contours for three wind directions for cases with and without the green walls.

The top two figures are for a northwest wind, which blows lateral to the industrial road. With the green walls, the high concentration region occurs in the middle of the road just behind the walls, whereas without the walls, the concentration field shifts leeward. The former case has a relatively narrow concentration field compared with the latter. As a result, the concentration at Ikegami Station is larger with the green walls than without them.

The two figures in the middle are for a southwest wind, which blows parallel to the industrial road. In this wind direction, both the cases with and without the green walls show similar concentration distributions. The concentrations at Ikegami Station are also similar.

The bottom two figures are for an east wind. In these figures, let us look at the buildings and houses along the industrial road in the block northwest of the intersection; this area is exposed to a certain concentration region in both cases. With the green walls, the region is relatively wide with a low concentration, while without the walls, the region is narrower and higher. Even some of the low concentration region sneaks into the background area without the walls.

3.3.3 Effect of the Green Walls on NOx Concentration at Ikegami Station Figure 15 compares the NOx concentration profile at Ikegami Station by wind direction with and without the green walls. When the wind blows laterally from the southeast (i.e., NE-SE-SSW directions), the concentrations are low in both cases. In these wind directions, the station is located windward of the industrial road, which is the main emission source, so the concentration is low. In the other wind directions (i.e., SW-NW-NNE), the concentrations are always larger with the green walls than without them. These results indicate that the green walls are an effective means of reducing roadside NOx concentrations.

3.3.4 Discussion ~ How the Green Walls Works An object that is set in the wind flow field reduces the wind speed around it and stagnation areas often occur behind it. When a scalar source is located near an object, a scalar field may be trapped and a high concentration area tends to occur around the object.

Similar phenomena occur in the case of the green walls. The wind speed decreases around the green walls and a stagnation area occurs leeward behind them, depending on the wind direction. The green walls are installed on the center line of the industrial road, and NOx sources are emitted by the heavy traffic running on both sides of the walls. As a result,

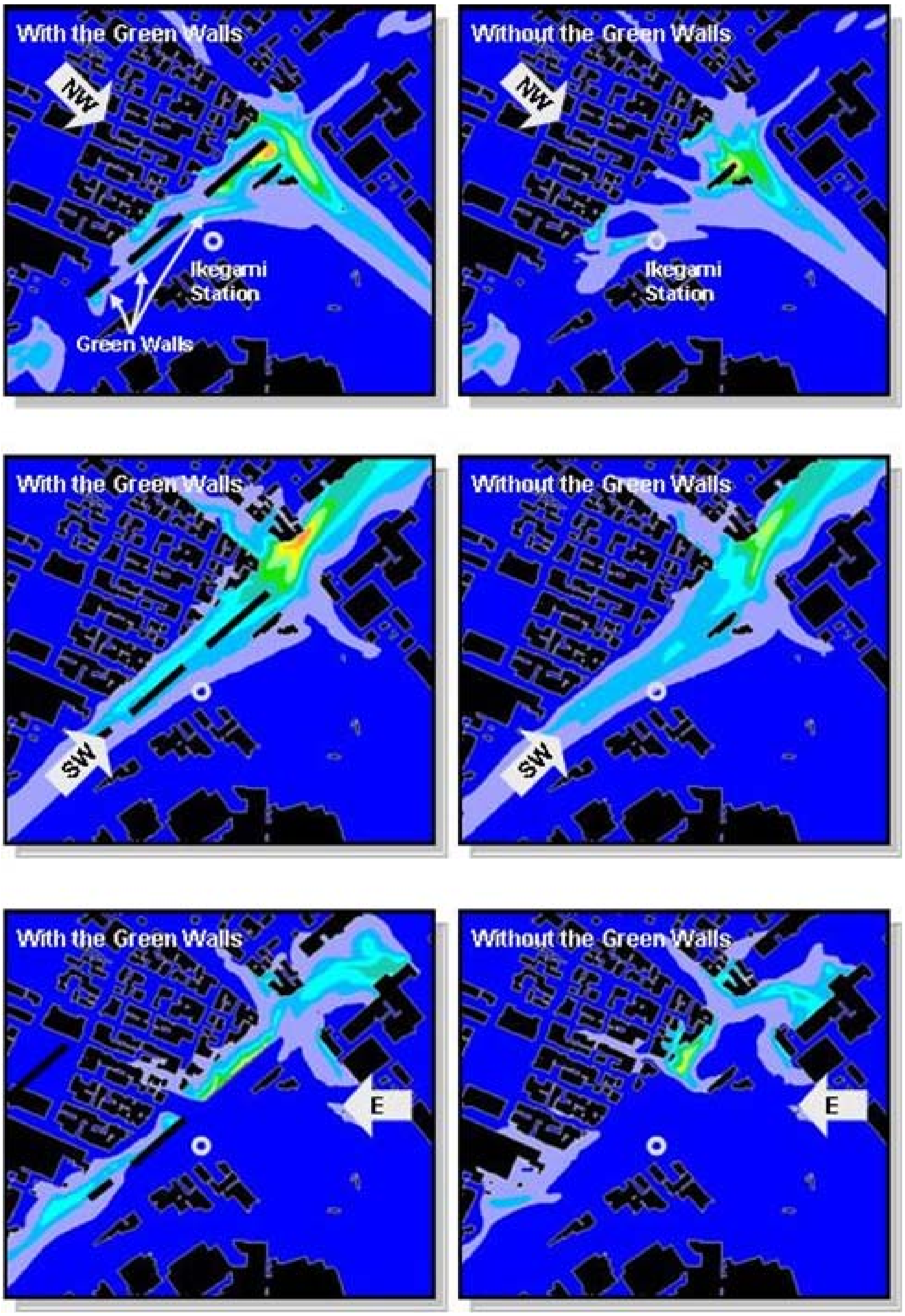

Figure 14 Comparison of NOx Concentration Contours between Cases with and without the Green Walls around Ikegami Shin-cho Intersection Area *Three wind directions, NW, SE, and E, are shown. Concentrations due to vehicular emissions are shown, but the background concentration is not included. Circles in the center of the figures denote the location of the Ikegami Monitoring Station.*

NOx emissions are trapped around the green walls, and a high concentration area occurs around them.

Therefore, in the cases above with the green walls, it is assumed that NOx emissions tend to gather more in the center of the industrial road around the walls, compared with the cases without the walls. When this occurs, NOx concentrations at nearby buildings or houses along the road are lower with the green walls than without them. In other words, the concentration fields have a relatively clear contrast in

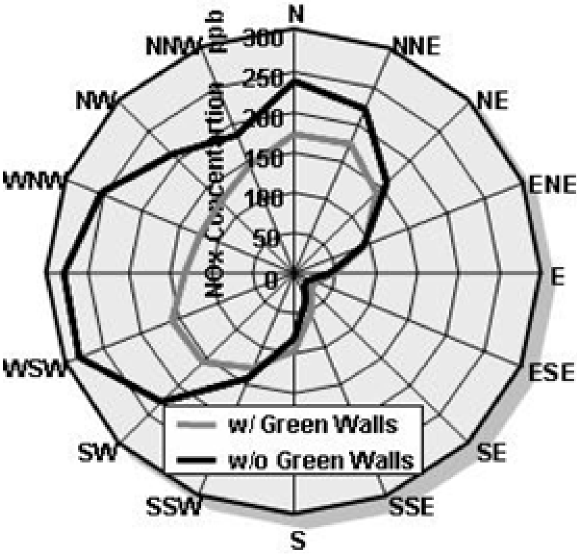

Figure 15 Comparison of NOx Concentration Profile at the Ikegami Station for Cases with and without the Green Walls *Concentrations due to vehicular emissions are shown, but the background concentration is not included.*

the cases with the green walls and a relatively flat distribution in the cases without the walls.

In effect, the green walls work to collect emissions in the center of the road, thus reducing the roadside concentration compared with the cases without the walls.

4. CONCLUSION

A Roadside Air Quality Simulation Model was developed in Phase II of the Japan Clean Air Program (JCAP II) for use in simulating roadside air quality, analyzing the factors causing high concentrations, and studying strategies to solve air quality problems. This model consists of a micro-scale traffic model, a transient emission estimation model, and a wind and advection/diffusion model. Each sub-model was validated by making comparisons in real-world-like situations.

The integrated RsAQSM model was applied to a real urban roadside situation and its usefulness in examining strategies to improve roadside air quality was demonstrated.

RsAQSM is expected to be a powerful tool for use in formulating various strategies to improve micro-scale air quality. The effects of traffic control measures, such as signal timings and route restrictions, can be considered in the micro-scale traffic model. The effects of efforts made at the vehicle level, such as emission controls and an automatic engine stop-start system, can be considered in the transient emission estimation model. The effects of urban construction measures, such as removal or setback of buildings and the construction of new elevated roadways, can be considered in the wind and advection/diffusion model.

After the conclusion of JCAP II, most of the simulation models developed in this project, including RsAQSM, have begun to be released to the public. It is hoped that the models will be used by many users in improving ambient air quality everywhere.

ACKNOWLEDGMENTS

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