Precise Evaluation of Vehicles Emission in Urban Traffic Using Multi-agent-based Traffic Simulator MATES

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Abstract: Recently, global warming issues have been discussed all over the world. Of the total amount of CO_2 emitted in Japan, a transportation sector is responsible for 20%. In the transportation sector, 90% of the emission is due to road traffic. This amount must be reduced drastically to realize a low-carbon society. To do so, various measures have been discussed, and the effects of the measures must be estimated quantitatively. In conventional measurement methods, the amount of vehicle emission is simply calculated by multiplying travel distance or gasoline consumption by a specified emission coefficient. Such an approach neglects the effects of the interactions among many vehicles. In this study, we estimate the amount of CO_2 vehicles emission by using a microscopic traffic simulator integrated with a precise database of exhaust gases emitted from various types of cars. The interactions among various types of cars are precisely considered through traffic simulation using a microscopic traffic simulator based on the intelligent multi-agent approach. By matching the input data of the database with the output information of the traffic simulator, the amount of momentary emission from each car can be estimated. The total amount of vehicles emission in a particular region or the emission history of a particular car is calculated from the momentary emission. Through some simulations, we clearly demonstrate the effectiveness of the developed system, compared with a conventional estimation method. Especially, it was found that the conventional method underestimates CO_2 emission by 20-30 percents in traffic congestion situations.

Keywords: Traffic Simulation, multi-agent model, vehicle emission database

1 Introduction

Road traffic is a key part of the infrastructure supporting mobility through the transportation of humans and goods. At the same time, road traffic causes various types of urban and environmental problems such as traffic congestion, acci-

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dents, energy consumption and CO_2 emission. To solve such traffic-related problems, various countermeasures have been taken, including the improvement of gas mileage and traffic signal controls, the construction of new roads, and the development and installation of ITS (Intelligent Transport Systems) technology. Because it is very difficult to recover previous road environments once they have been changed, it is strongly desirable to estimate the effects of the abovementioned countermeasures quantitatively to improve traffic environments. Therefore, simulations have been playing an important role in the field of traffic engineering, and various types of traffic simulators have been developed and utilized so far [Barceló and Casas (2002); JSTE (2004); Gomes, May, and Horowitz (2007)]. We have also been developing an advanced traffic simulator based on the multi-agent approach named MATES (Multi-agent Based Traffic and Environment Simulator) [Yoshimura (2006); Fujii, Yoshimura, and Seki (2010), Fujii, Sakurai, and Yoshimura (2011)].

This paper describes the quantitative estimation of vehicle exhaust gases from urban traffic by using MATES integrated with a precise database of exhaust gases emitted from various types of cars. A similar approach is proposed by Hülsmann et al. [Hülsmann, Gerike, Kickhöfer, Nagel, and Luz (2011)]. They utilize a queue-based microscopic simulator, MATSim [Charypar, Axhausen, and Nagel (2007)], for their estimation. Their method is applicable to large-scale simulation, but car behaviors are rather simplified. We consider that precisely calculating acceleration or deceleration of cars is indispensable to estimate the amount of CO_2 emission in various traffic conditions.

2   Modeling of Traffic Flow in MATES

Traffic simulators are generally classified into the following three categories: macroscopic models based on continuum fluid dynamics, microscopic models that consider each vehicle as a kind of particle, and mesoscopic models that consider a group of cars as a unit. However, many simulators model cars as inorganic matter. Such inorganic modeling cannot express the behaviors of human drivers who have different levels of knowledge, attitudes, and driving logic. This becomes a strong constraint when dealing with the diversity of drivers' behaviors.

In our research, we regard traffic events as complex systems produced by many human beings who have intelligence as well as individuality. Based on such a natural concept, we construct the traffic simulator MATES (Multi-Agent based Traffic and Environment Simulator). We model each individual element appearing in traffic systems as an intelligent agent [Russel and Norvig (1995)] and then model the whole traffic phenomenon through the interaction among the many intelligent agents in a virtual road environment.

2.1 Multi-intelligent Agent Model

In the process of driving cars, the drivers acquire various kinds of information about the traffic environment, such as the road situation, traffic signs and signals, and cars in their vicinity, through their own senses of sight and hearing. The drivers make decisions about, for example acceleration, deceleration, stopping, turning right or left, passing, changing lanes, and so on. Furthermore, they utilize global information through road maps and car navigation systems. Today, various types of local as well as global information are available for drivers through the installation of ITS technology, and drivers can make their decisions based on such integrated information.

Considering the real world situation, it is essential that a car (driver) model in traffic simulators is able to make decisions autonomously. It is also indispensable for advanced traffic simulators to precisely model the situations in which drivers utilize various types of local as well as global traffic information to make their own decisions. In addition, depending on their individuality, drivers select the necessary information from various types of traffic information they acquire and sometimes they continue processing the information. In other words, traffic simulators must take into account the individual characteristics of each driver.

The multi-agent approach is a well-known method to simulate complex systems. In this approach, a number of agents work in an environment. Each agent acquires information from the environment, judges it autonomously by referring to its own knowledge and preference, and acts in the environment. Such behavior results in interaction with other agents, and as a result, global complex and nonlinear phenomena emerge. Fig. 1 illustrates a conceptual image of an intelligent agent. Fig. 2 shows an image of the interaction between a car agent and an environment in MATES.

In the traffic simulator developed in this research, human beings are directly modeled as intelligent agents and they interact with others. The intelligent agents can imitate human drivers with high accuracy.

2.2 Intelligent Agent

In MATES, each driver is modeled as an intelligent agent. The agent can behave autonomously. The autonomy that the car agent needs is listed below.

Autonomy regarding global movement in a road network:

- Planning (confirmation of the origin and the destination)

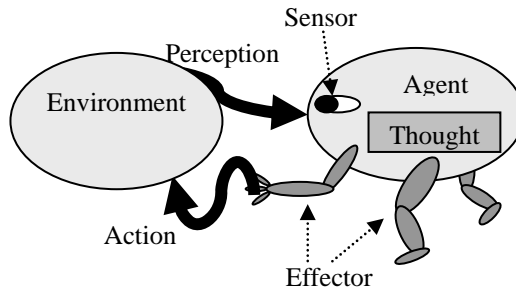- Global search of a route in the road network

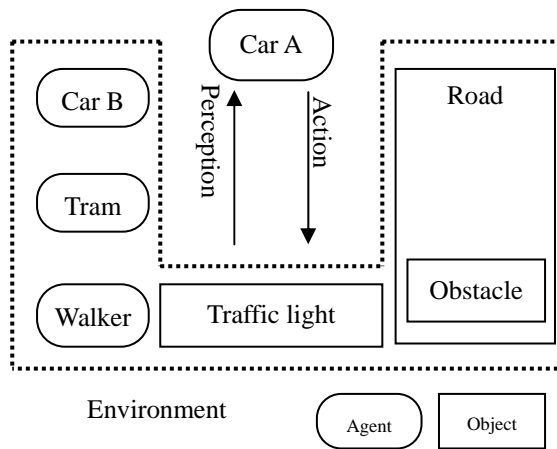Figure 1: Conceptual image of an intelligent agent

Figure 2: An agent and an environment in MATES

- Route selection based on preference

Capability of autonomous driving on a road:

- Knowledge of traffic rules and the capability of following the rules while driving

- Decision on the driving speed

- Changing lanes

- Turning right and left at intersections while considering the behaviors of other cars

- Deciding a lane on the road.

2.2.1 Route search algorithms

After planning the driving route, a route search algorithm is applied. It should be noted here that the current version of MATES does not include a planning process in which the origin and the destination points are decided. Users input the origin and the destination (OD) traffic volume data a priori. As the first step of this research, a route search based on the A* algorithm [Hart, Nilsson, and Raphael (1968)] is implemented. The utility function is defined as a weighted sum of the following multiple factors:

- Distance between the starting (origin) and the destination points

- Trip period from the starting point to the destination point

- The number of times of going straight at intersections

- The number of times of turning right at intersections

- The number of times of turning left at intersections

- The width of the road

The route that maximizes the utility function is then selected. Each car is capable of having a different utility function for route selection.

2.2.2   *Autonomy of microscopic traffic behaviors*

After determining the global route on a road network, each car follows the selected route and drives from the starting point to the destination. While driving, the car agent needs the following autonomy:

- Autonomy to follow the traffic rules

  The most fundamental traffic rule in a virtual road environment is that each car must drive in the virtual lanes. Other traffic rules such as no passing and the speed limit are attached to the road environment. We define the communication protocol such that each car can ask for any information on the road environment.

- Autonomy to determine the driving speed considering slope follow the traffic rules

  MATES employs the generalized force model [Helbing and Tilch (1998)] to determine the speed. This model is shown below:

$$\frac{dv_i(t)}{dt} = f_i^0(t) + \sum_{j \neq i} f_{ij}(t) + \xi_i(t) \tag{1}$$

  where $v_i(t)$ is the velocity of car agent i at time t. The first term on the right-hand side represents the acceleration toward the driver's desired velocity. The second term represents the repulsive force from interactions with other car agents. The third term is a fraction term.

  The generalized force model is the model in which a driver determines his/her driving speeds based only the distance and the velocity difference from the preceding car. In urban traffic, speed determinants are not only the preceding car but also the traffic signals, the situation of the forward intersection, and so on. Therefore, we expanded the model so that the virtual preceding cars reflect the forward road conditions and apply Eq. 1.

  To estimate the amount of emission correctly, we added a slope term to Eq. 1, since the effect of slopes causes significant differences. The new equation to determine the driving speed of the car agent is given below:

$$\frac{dv_i(t)}{dt} = f_i^0(t) + \sum_{j \neq i} f_{ij}(t) - \beta g (\sin \theta - \sin \theta_u) + \xi_i'(t) \tag{2}$$

  where β is the sensitivity of the slope effect ($0 \leq \beta \leq 1$) and is described later, θ is the road gradient that the car is now on, θ_u is the road gradient that the driver has already recognized, and $\xi_i'(t)$ is the new fraction term.

Then we defined the time-dependent change of the parameter β. If β is always 0, the car is not affected by the slope, and then the driver can always keep the desired speed. If β is always more than 0, the driver cannot achieve his/her desired speed. Thus it is natural to assume that β is 1 at first and becomes 0 later. It is not until the driver recognizes the road gradient that he/she tries to recover the speed. Therefore, we modeled the change of β by the following two processes: the recognition process and the adjustment one.

In the recognition process, β is always 1. The difference between the actual speed and the desired one is evaluated. Here, the desired speed is calculated by excluding the slope effect. When the difference becomes more than the threshold v_d, the adjustment process is initiated. In the adjustment process, β approaches to 0 linearly (see Fig. 3). The rate of change is proportional to v_d.

• Autonomy of deciding the lane to drive in

   In MATES, each car agent can decide autonomously which lane it should drive in. A simple linear search algorithm is implemented for this purpose.

• Autonomy of a lane change

   When changing lanes, the car agent must consider both the cars in its current lane and in the next lane simultaneously. To do so, a dummy of the car agent that is going to change lanes is virtually created in the next lane, appropriate speeds are evaluated for both lanes, and finally the speed is computed from both speeds.

2.3   Road environment

In MATES, the environment means the generalized physical as well as conceptual field surrounding the agents. Thus, the environment includes the road network and accompanying information. In this research, a three-layered road network model is invented and employed. The model resembles a directive graph. Here, a virtual lane is the smallest unit for modeling an actual road. In the modeling, we restrict the maneuvering of the car agent only along the lane. Each lane has various kinds of information on length, connection with other lanes, and other accompanying attributes. The environment provides such information to the agent if the agent requests it.

To model an actual road network, lane bundle objects are implemented. A lane bundle object consists of the following two kinds of objects: a single road section and an intersection. Each object consists of virtual lanes and their connectors, as shown in Fig. 4. A number of lane bundle objects are organized as a global road
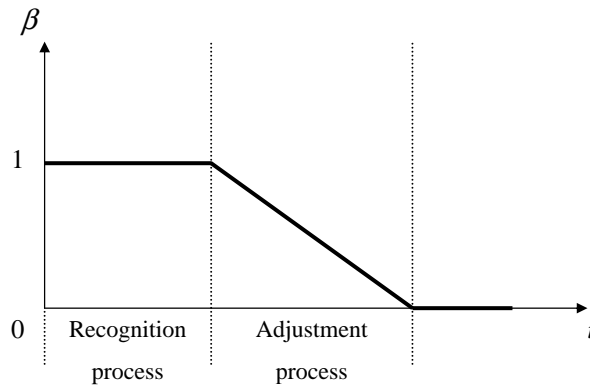
Figure 3: Time-dependent change of parameter β

network. Each connector is placed at either the initial point or the end point and has the following two directions, inflow or outflow. Fig. 5 shows the hierarchical structure of the road.

3   Integration of MATES with the Database of Vehicle Emission

We employ the emission map files of the JCAP2 (Japan Clean Air Project 2) developed by JPEC (Japan Petroleum Energy Center) as vehicle emission data. This database indicates the measured correspondence between car driving data (speed, acceleration, vehicle family, engine type and road gradient) and the amount of exhaust gases (CO, CO_2, HC, NOx and SPM) [JPEC] (see Fig. 6). By matching the output of MATES (speed and acceleration data of each car agent and the road gradient) to the abovementioned database, the amount of momentary emission from each car can be estimated. In addition, the total amount of emission in a particular region can also be calculated from the momentary emission. The overview of the system is shown in Fig. 7.

4   Simulation Results

4.1   Emission at a slope section

To demonstrate the practical performance of the estimation system, we simulated a car driving on a simple road section with a slope and confirmed the changes in the amount of momentary CO_2 emission.

The road set was 2 km long. The first half was flat, while the last half had a specific gradient (0%, 1%, 2%, 4%, 8%) (see Fig. 8). The speed limit was set as 60 km/h
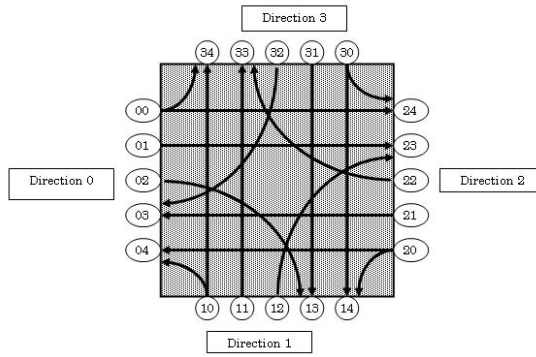
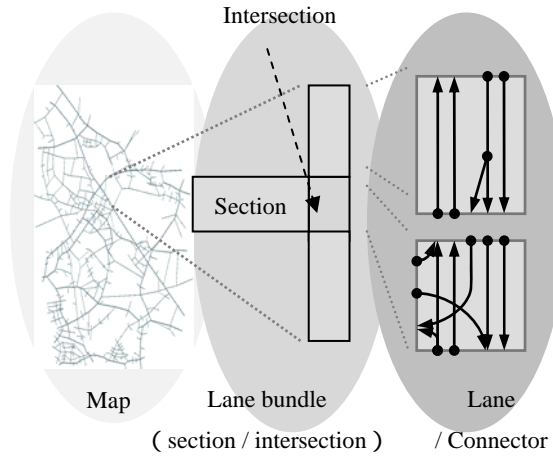Figure 4: A lane bundle object
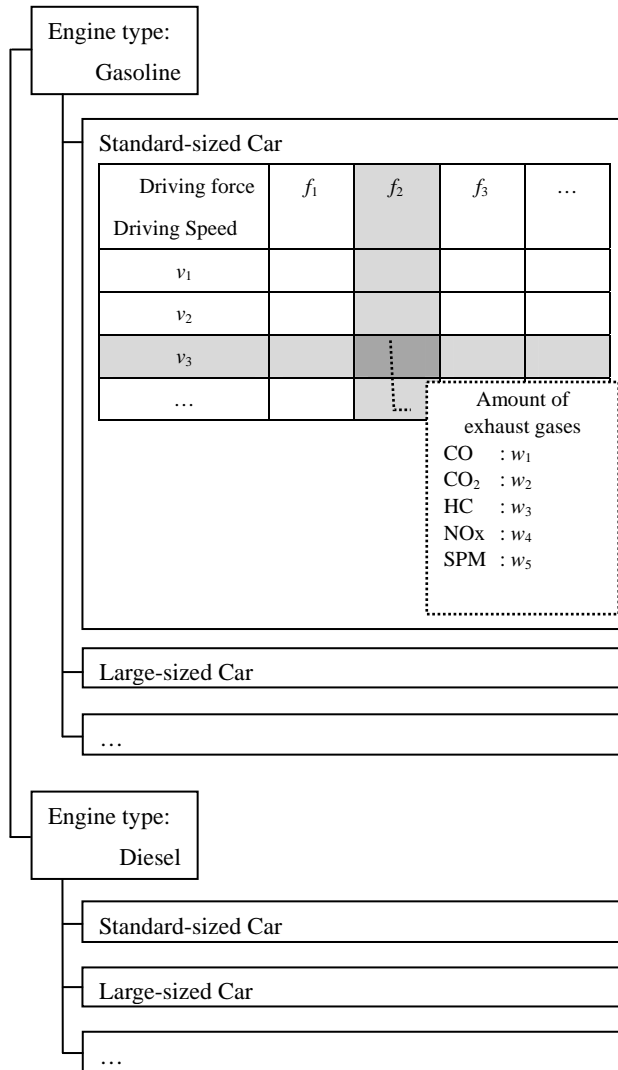

Figure 5: A hierarchical road network

Figure 6: Database of Vehicle Emission

- Vehicle family

- Engine type

Execution of MATES

- Speed and acceleration

   of each car

- Road gradient

JCAP2

map file

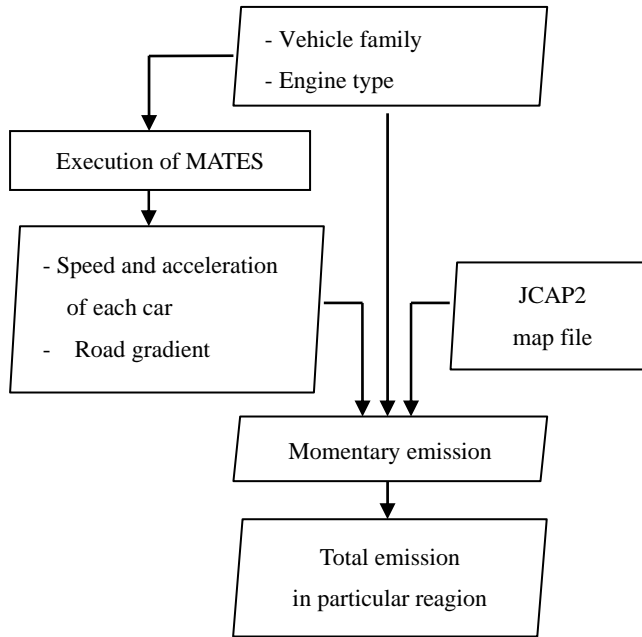Momentary emission

Total emission

in particular reagion

Figure 7: Overview of estimation system

and the threshold v_d was set at 15 km/h. The results are shown in Fig. 9.

4.2 Emission in traffic congestion

Next we performed the simulation in a simple road section with a bottleneck, and estimated the total amount of CO_2 emission in the whole section.

The road was 2 km long. The speed limit of the first half was 60 km/h and that of the last half was 30 km/h (see Fig. 10). The number of car agents was set to 500, 600, ..., or 1500 per hour. By inputting sufficient traffic volume to this road, traffic became congested from approximately the midpoint to the upstream area of the section.

The results are shown in Fig. 11. The line in the graph shows the estimation according to the assumption that the total amount is proportional only to the number of cars.

In Japan, the coefficient value of 267.06 (g-CO2/km/car) is employed [Yonezawa and Matsuhashi (2009)]. This is the conventional estimation method, but sometimes it underestimates. In the worst case, the disparity between the two methods reaches to approximately 30%. It is important to consider the effect of traffic con-
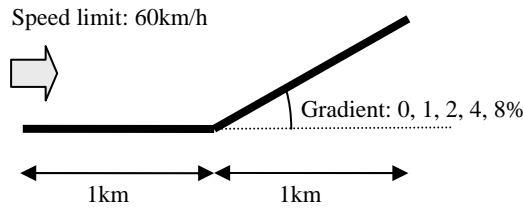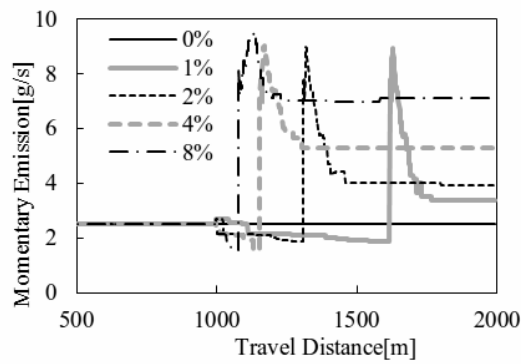
Speed limit: 60km/h

Gradient: 0, 1, 2, 4, 8%

1km   1km

Figure 8: Simulation condition

Figure 9: Estimation of CO_2 emission at slope section

Traffic generation volume:

500, 600, ..., 1500 /hour

1km   1km

Speed limit: Speed limit:
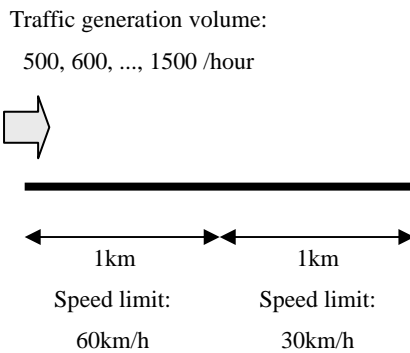
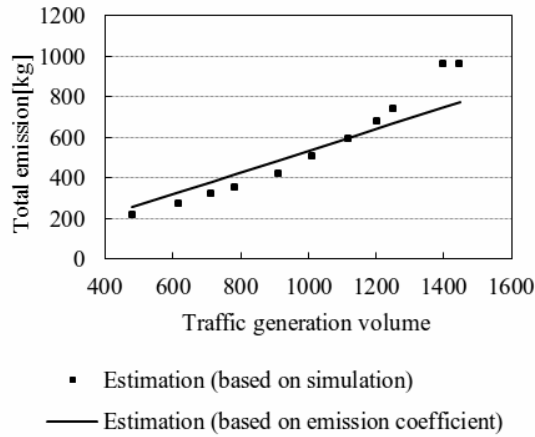60km/h   30km/h

Figure 10: Simulation condition

Figure 11: Estimation of CO_2 emission in traffic congestion

gestion to obtain a correct estimation.

4.3 Emission in an urban road network

Next, we estimated the CO_2 emission in an urban road network. The road map is shown in Fig. 12. It is the northwest area in Kashiwa City, Chiba, Japan. The width of the area from east to west is 9.2 km, and the length from north to south is 7.3 km. The map has 172 nodes and 229 links, and 10,715 cars were generated in a 1-hour simulation.

The amount of CO_2 emission of each car is shown in Fig. 13. In this graph, each "x" represents one car. The line in the graph is the estimation by the conventional method. In this complex network having many intersections and signals, the amount of emission is not always proportional to the driving distance. The total amount of emission in this area is 17005.93 kg-CO_2 by the developed estimation method, while 14453.59 kg-CO_2 by the conventional method. The disparity between the results is approximately 20%.

5   Conclusions

To estimate the amount of CO_2 vehicle emission precisely, we constructed a new estimation system, which is an integration of the multi-agent based traffic simulator MATES and a precise database of measured vehicle emissions. In the traffic simulator, we considered the effect of the attributes of the road and the interactions
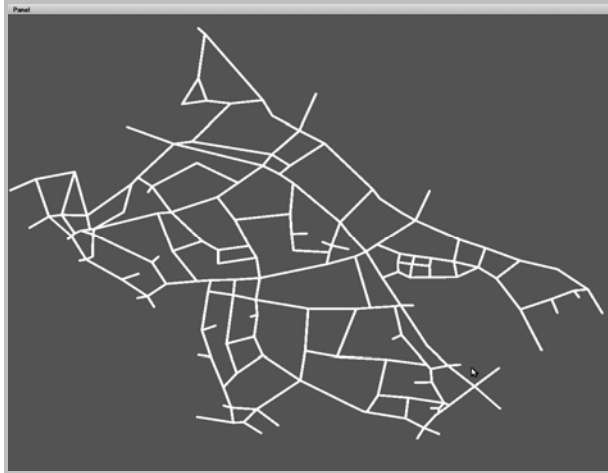
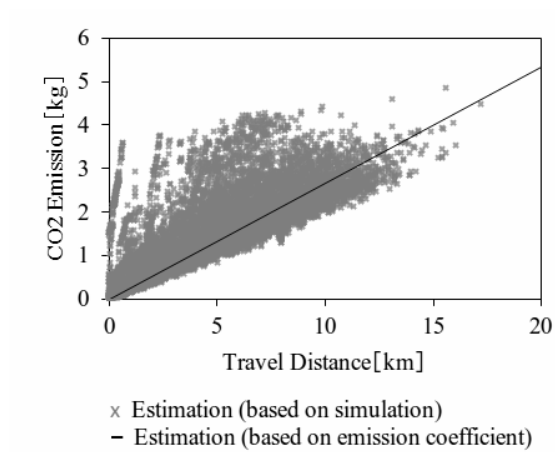Figure 12: Road map of the northwest area in Kashiwa City

× Estimation (based on simulation)
− Estimation (based on emission coefficient)

Figure 13: Estimation of CO_2 emission in Kashiwa City

among numerous cars, such as in traffic congestion.

We performed some simulations to demonstrate the practical performance of the developed system, compared with the conventional method based on the emission coefficient. The conventional method underestimates CO_2 emission by 20%–30% in traffic congestion situations in which vehicles interaction plays a major role in vehicles behaviors.

The Kyoto Protocol requests industrialized nations to reduce greenhouse gas emissions by 6% to 8% of the 1990 levels by 2012, and we have been investigating how to achieve this goal. Under such circumstances, the underestimate of CO2 emission by 20%–30% shown in this study is not acceptable. If we can collect realistic input data, the developed simulation-based method is very useful for precisely estimating the amount of emission gases under actual traffic conditions.

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