 CMES, vol.11, no.1, pp.17-25, 2006

MATES : Multi-Agent based Traffic and Environment Simulator – Theory, Implementation and Practical Application -

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Abstract: This paper describes a development of an advanced traffic simulator based on a multi-agent approach which is named MATES (Multi-Agent based Traffic and Environment Simulator). City traffic phenomena are essentially regarded as complex systems consisting of a number of human beings. Each element creating traffic phenomena such as car (driver), traffic signal, pedestrian and others is modeled as an intelligent agent that possesses its own logic of behavior and preference. The environment surrounding each agent consists of other cars, road network, traffic signals, pedestrian and others. Interaction among numerous agents simulates nonlinear behaviors of city traffic phenomena. First we describe details of the theory and implementation of MATES, and then its fundamental features are examined. Finally MATES is applied to simulate city traffic in Kashiwa city in Japan, employing various real world data as input. Through the simulations, it is clearly demonstrated that MATES is a powerful tool to study complex city traffic problems precisely.

keyword: Intelligent agent, Multi-agent model, Complex system, Traffic simulator, Layered road network, Virtual social experiment.

1 Introduction

Road traffic is nowadays a part of infrastructure to support mobility and transportation of human beings and goods. At the same time, it causes various types of city and environmental problems including regional ones such as traffic congestion, noise, air pollution, as well as global ones such as energy consumption and CO_2 emission. To solve such traffic-related problems, various counter-measures have been taken, including improvement of car performance in energy consumption rate, traffic signal control, construction of new roads, road pricing policy, development and installation of ITS (Intelligent Transport Systems) technology [JSTE (1997)], change of life style such as car sharing and installing LRT (Light Rail Transit). It is very difficult to recover road environments as they were, once they have been changed. It is strongly desired to quantitatively estimate effects of the above-mentioned counter-measures for improving traffic environments. Simulations have been playing important roles in the field of traffic engineering, and various types of traffic simulators have been developed and utilized [JSTE (2000)]. They are roughly classified into the following three categories, macroscopic models based on continuum fluid dynamics, microscopic models [Van Aerde, M. and Yagr, S. (1988), FHWA (1995), KLD Associates (1996), Quadstone Ltd (2003), Barcelo, J., Codina, E., Casas, J., Ferrer, J. L. and Garcia, D. (in Print)], mesoscopic models in which a group of cars are dealt as unit. However, those simulators have dealt cars as inorganic matter. Due to such inorganic modeling, they can not express behaviors of human drivers who have different knowledge and logic for driving. This becomes strong constraint when dealing with diversity of drivers' behaviors and installation of various types of ITS technology into conventional traffic simulators.

In our research, we essentially regard traffic phenomena as complex systems produced by numerous human beings who have intelligence as well as individuality. Based on such a natural concept, we construct a new traffic simulator named MATES (Multi-Agent based Traffic and Environment Simulator). Here, we model any individual element appearing in traffic phenomena as an intelligent agent [Russel, S. G. and Norvig, P. (1995)], and then model the whole traffic phenomena through the interaction among numerous intelligent agents on a virtual road environment. Microscopic traffic simulator named AIMSUN (Barcelo, J., Codina, E., Casas, J., Ferrer, J. L. and Garcia, D. (in Print)) employing detailed modeling of the behaviors of individual vehicles is somewhat similar to MATES in function. However, the concept of MATES and its implementation are very different from those of AIMSUN and have a high potential to model other elements than vehicles.

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In this paper, we first describe the theory of the present multi-agents approach and its implementation. Next, we describe the implementation of multi-layered road network. Then MATES is applied to simulate an actual city of Kashiwa city in Chiba prefecture, Japan. Finally some conclusions are given in the last section.

2 Theory and Implementation

2.1 *Multi-Intelligent Agent Model*

During driving cars, drivers acquire various kinds of information on traffic environment such as road situation, traffic signs and signals, cars in the vicinity of them through their own senses of sight and hearing. The drivers make their own decision for driving attitudes, for example acceleration, deceleration, stop, turning right or left, passing, changing lanes and others. In addition they utilize global information through road maps and car navigation systems. In near future, various types of local as well as global information are expected to be available for drivers through the installation of ITS (Intelligent Transport Technology) [JSTE (1997)], and they will make their decision based on such integrated information. Considering real world's situation, it is essential that a car (driver) model in traffic simulators can make its own decision autonomously. It is also indispensable for next generation traffic simulators to precisely model such situation that drivers utilize various types of local as well as global traffic information for their own decision. In addition, depending on their individuality, the drivers select their necessary information out of various types of traffic information they acquire, and sometimes they process the information. It is strongly needed to take into account such individual character of each driver in next-generation traffic simulators.

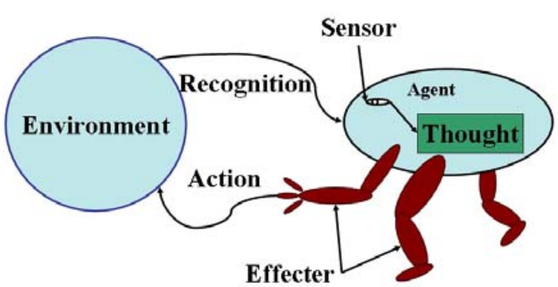


Figure 1 : Conceptual image of intelligent agent

Multi-agents approach is a well-known method to simulate complex systems. In the complex systems, a number of agents are working in an environment. Each agent acquires information from the environment, judges it autonomously referring to agent's own knowledge and preference, and acts for the environment. Such processes interact among others, and as a result, global complex and nonlinear behaviors are emerged. Cell automata [Wolfram, S. (1986)] are often employed to simulate such complex systems. Several researches have been done on cell-automata based traffic simulations [Nishinari, K. (2001)]. In the traffic simulator developed in this research, human beings are directly modeled as intelligent agents, and they interact among others. The intelligent agents are more suitable to imitate drivers, pedestrians, LRT highly accurately. To distinguish the present approach from the cell automata-based approach, we could call this as the multi-intelligent agents approach. However, if not causing any confusion, we call this simply the multi-agents approach in this paper.

2.1.1 *Construction of intelligent agent*

In MATES, each driver is modeled as an intelligent agent [Russel, S. J. and Norvig, P. (1995)]. The agent can behave himself autonomously. Autonomy which the car agent needs is listed bellow :

Type A : Autonomy regarding global movement in road network

- Planning (Confirmation of start (origin) and destination points)
- Global search of route in road network
- Route selection based on preference

Type B : Capability of autonomous driving on road

- Knowledge on traffic rules and capability of driving following the rules
- Decision on driving speed
- Changing lane, merging, division
- Turning right and left at intersections, considering behaviors of confronting cars
- Deciding lane on the road

The car agent is modeled as a utility-lead agent. Fig. 1 illustrates a conceptual image of the intelligent agent. Fig. 2 shows an image of interaction between a car agent and an environment. The agent has a sensor to acquire information out of the environment as well as has an ef-

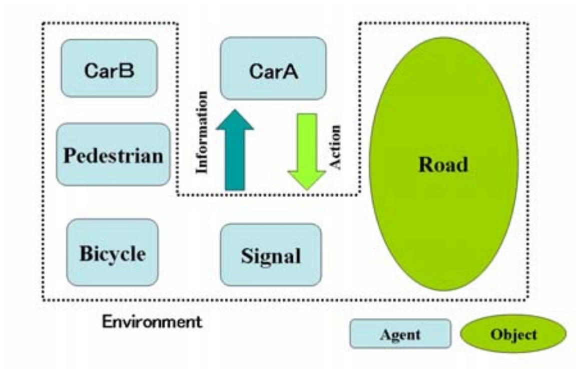


Figure 2 : Car agent vs. environment

fecter to act for the environment. Such sensors and effecters are modeled depending on its application field. The agent has a utility function which is a measure to judge the degree of happiness. The agent decides its behavior so as to maximize his utility function. The utility function is not always a form of equation, but also a collection of rules. It should be noted here that various types of specific agents to be needed for simulating actual traffic phenomena can be easily created based on the present general agent model. Some actual rules implemented in the car agent are described next.

2.1.2 Route search and selection algorithms

Route search algorithm which should be invoked after a planning phase of driving route is implemented. It should be noted here that the present version of MATES doesn't include a planning process in which starting (origin) and destination points should be decided. The origin and destination (OD) data are specified by a user *a priori*. As the first step of the research, the route search based on A* algorithm [Russel, S. J. and Norvig, P. (1995)] is implemented. The utility function is defined as a weighted sum of the following multiple factors :

(a) Distance between starting (origin) and destination points

(b) Trip period from the starting point to destination one

(c) The number of times of going straight at intersections

(d) The number of times of turning right at intersections

(e) The number of times of turning left at intersections

(f) Width of road

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

2.1.3 Autonomy of microscopic traffic behaviors

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

(a) Autonomy to follow traffic rules

The most fundamental traffic rule on a virtual road environment which will be described in section 2.2 is that each car must drive on virtual lanes. In addition, rolling behavior is expressed by means of a concept of lane width. Owing to this concept, the car agent can drive avoiding an obstacle on a road such as illegally parked cars. Other traffic rules such as prohibit of passing are attached on a road environment. We define communication protocol such that each car asks any information to the road environment.

(b) Autonomy to determine driving speed

The MATES employs a fundamental Car Following model [JSTE (1984)] as a basic driving mode to determine speed. Various types of other situations often occur in reality, for example, including free driving mode when no other car drives and mode of other car's changing lane to your lane with twinkling winker. In MATES, various possible situations are stored, and then one is selected out of them. Priority is attached onto the rules. Those rules related to an identical event are modularized.

The function of calculating speed with the fundamental equation of Car Following mode is prepared as default, and other situations are listed. The function of determining driving speed based on each situation is implemented as Object class. The class has not only the function of determining speed, but also its accompanied processes. This is called the Object of Defining Behaviors, and has common interface. New Objects of Defining Behaviors can be easily added into a car agent.

(c) Autonomy of deciding lane to drive

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

(d) Object of defining lane change

The object of defining lane change is the most complicated object among all Objects of Defining Behaviors implemented in the present version of MATES. In a lane change event, the car agent that is going to squeeze itself into the next lane must pay attention to any car driving in the next lane. At the same time, any car agent driving in the relevant lane must consider the car which is coming to squeeze from the next lane. Judging whether to change lane or not is performed based on a certain defined function. After judging that lane change is necessary, the following processes are accompanied immediately.

Step 1 : Confirm the next lane into which the car agent wishes to squeeze

Step 2 : Turn on winker to the relevant direction, and demonstrate his wish to other car agents

Step 3a : If the situation in the next lane is judged to be no good from a viewpoint of safe lane change, the car agent changes speed, i.e. accelerates or decelerates in order to prepare for the condition for safe lane change.

Step 3b : If the situation in the next lane is judged to be well prepared for safe lane change, the car agent starts changing lane. At this time, the agent informs the environment that he is changing lane. This agent is then registered in the special list in which any cars of showing special behaviors are registered. Owing to this mechanism, other cars easily notice the relevant car agent without time consuming search.

Step 3c : Hang out a flag during the period of lane change, and go to the next step.

Step 4 : During the lane change, determine driving speed considering both cars in the former lane and the relevant lane.

Step 5 : When displacement in the lateral direction exceeds a certain critical value, inform this fact to the environment, and change its existing lane from the former one to the new one.

Step 6 : After the car agent enters to the new lane and the lateral displacement gets smaller than the critical value, end the mode of lane change. Then cancel the registration in the environment, put the winker back and clear all flags and go back to the normal driving mode.

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

2.2 Environment

In MATES, the environment means the generalized physical as well as conceptual field surrounding agents, which includes road network and accompanied information. In the research, the three-layered road network model is invented and employed. Here virtual lane is the smallest unit to model an actual road. This is a kind of directive graph. In the modeling, we restrict the maneuver of car agent only that along the lane. Each lane has various kinds of information on length, connection with other lanes, and accompanied attributes. The environment provides such information into the intelligent agent if requested. In order to precisely model an actual road network, the following two key concepts, Lane Bundle Objects and Lane Width, are implemented.

2.2.1 Lane bundle object

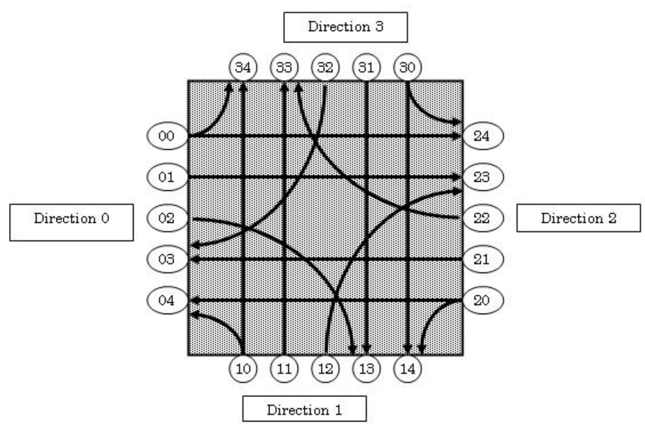


Figure 3 : Lane bundle object

Lane Bundle object consists of the following two kinds of objects : Single Road Section and Intersection. Each of them consists of virtual lanes and their connectors as shown in Fig. 3. A number of Lane Bundle objects are organized as a global road network, i.e. node-link network. Each connector is placed on either the initial point or the end point, and has two kinds of direction either inflow or outflow. Fig. 4 shows layered structure of the road. Typical road structure patterns are modeled as Lane Bundle objects and stored as template. Combing the objects, a complex and realistic road network can be easily constructed.

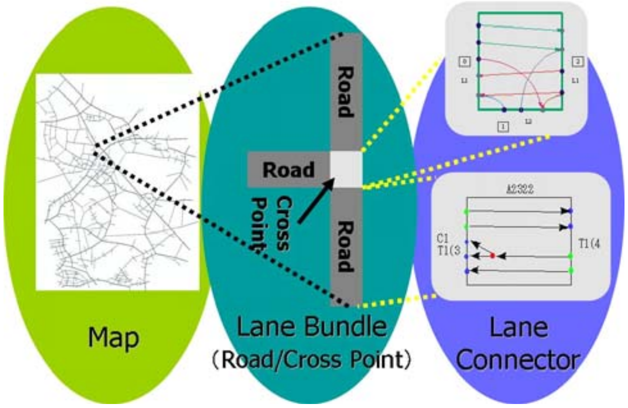


Figure 4 : Three layered road network

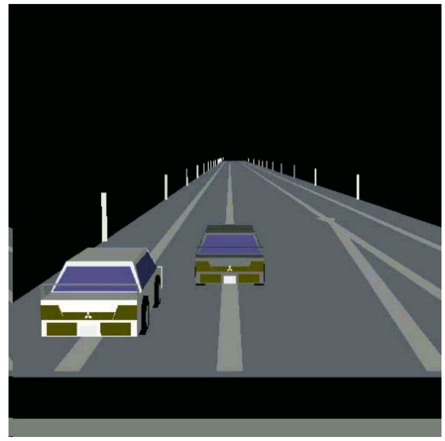


Figure 5 : Visualization image

2.2.2 Lane width

During a normal driving process, lane width of road is not used. Lane width plays an important role when a car agent changes lane. Lane width also affects behaviors of different types of car agents. For example, a big car such as truck and bus must pay more attention to lane width even in a normal driving mode. The definition of Lane width is rather simple. Each road object has a unique lane width value. When lane width of an actual road varies, the road must be modeled by multiple-road models with different lane width values.

2.2.3 Traffic signal

Traffic signal in Japan is controlled in terms of the following three parameters, i.e. cycle length, split time and offset value. These values are directly imported from actual traffic signals.

2.3 Software

Object oriented design and programming techniques are employed to construct MATES. C++ is employed. The MATES runs on Unix like OS such as Linux and BSD. The output data of MATES simulation such as locations of cars and shape of roads are visualized using an open-source visualization tool named ADVENTURE_AutoGL [Yoshimura, S., Shioya, R., Noguchi, H. and Miyamura, T. (2002), Kawai, H. and Yoshimura, S. (2003)]. Fig. 5 shows an example of visualization, a front view from a car driver, which is a part of animation.

3 Fundamental Verification of Car Behaviors

To verify fundamental behaviors of car agents implemented in MATES, some simple but essential simulations are performed.

3.1 Density Wave Behavior of Congested Traffic

Density wave is a typical phenomenon in steady-state traffic congestion. In order to evaluate the density wave quantitatively, progressive wave and stopping wave in arrears of traffic at a traffic signal are simulated. At red light, a row of cars is formed on the road. The propagation of the end of the row is named Stopping wave. On the other hand, the row of cars diminishes gradually at blue light. The value such that the propagation speed of the last end of the row is subtracted from that of the first end of the row is named Progressive wave speed.

In this simulation, we assume a straight road with two lanes on one hand, and set one intersection in the middle of the road. We observe the formation of row of cars in front of the intersection. The split value of the signal, i.e. the ratio of red signal period to blue one is set to be 1 as a standard case. It is known that basic traffic capacity at an intersection is about 2,000 [pcu/hour·lane]. Here pcu means Passenger Car Unit. Taking this value, the traffic capacity at the intersection in this simulation is estimated to be around 2,000, because of 2,000 [pcu/hour·lane] x 2 [lanes] x (1/2). Considering this, the simulation is performed, providing 1,800 [pcu/hour·lane] into the initial end of the road. Counting the number of cars passing this intersection, the saturated traffic flow rate is evaluated as 2,130 [pcu/hour]. Fig. 6 shows equi-contours

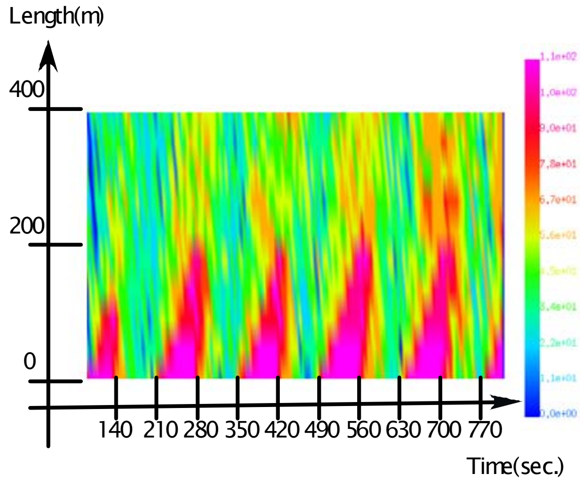


Figure 6 : Arrear state map at cross point

of traffic flow density, i.e. arrear state map. Using the map, the propagation speed of stopping wave and that of progressive wave are evaluated as 10.3 [km/hour] and 39.1 [km/hour], respectively. The propagation speed of stopping wave and that of progressive wave monitored at Tokyo metropolitan high-way in 1981 were 14.8 [km/hour] and 44.4 [km/hour], respectively. The simulated values and the monitored one agree with each other qualitatively well. However, quantitative comparison shows that the simulated values are about 10-20% smaller than the monitored ones. Such difference might be caused due to the fact that the averaged driving speeds of cars in high-way (speed limit of high-way in Japan is 80 [km/hour]) were higher than those of the present simulation (speed limit of nomal road is 60 [km/hour]).

4 Application to Actual City

4.1 Selection of Application Area

Next, MATES is applied to simulate traffic in an actual city. Here, some sensitivity analyses are performed, and the simulated results are compared with observed values quantitatively. The actual city selected is Kashiwa-city area in Chiba Prefecture, Japan. This area involves the following characteristics from a viewpoint of traffic engineering :

(a) Transit traffic of long distance driving is evenly mixed with city traffic.

(b) Heavy traffic congestion is a serious problem.

(c) The University of Tokyo is now constructing a new campus.

(d) A new station of the new railway named Tsukuba Express is to be open in near feature.

It is anticipated from the facts of (c) and (d) that traffic situation in this area will be drastically changed in a few years. It is useful to simulate traffic situations before and after such big changes. The modeled area is 10km long in North-South direction and 7km wide in East-West direction. Precise shapes of intersections are obtained by courtesy of Traffic Control Section of Chiba Prefecture Police Agency. Actual one-day-history data of the traffic signals which are subjected to systematic control are provided from the Traffic Control Section as well, and given to the MATES as input data. Signals at 98 intersections out of 398 ones in the simulated area are subjected to systematic control. The other signals are independent-controlled ones, for which random control is assumed.

4.2 Analysis Conditions

Both ordinary passenger cars and big cars such as trucks are generated as car agents with different attributes. The difference of both cars is expressed in terms of size parameter as well as acceleration and deceleration performance. The performance of the big cars is set to be lower than that of the passenger cars. Car agents are generated at each end of road. The input number of cars per an hour is assumed as follows :

- 1,800 [pcu/hour·lane] for wider road with three lanes on one hand such as National Route Nos.16 and 6,

- 600 [pcu/h·lane] for wider road with two lanes on one hand, and

- 100 [pcu/h·lane] for small road with one lane on one hand.

Table 1 : Conditions for sensitivity analyses

Case	Systematic Signal Control	Agent	Route Selection Preference
1	Yes	Passenger Car	Distance
2	Yes	Passenger Car	Distance Trip Time
3	No	Passenger Car	Distance

Tab. 1 shows conditions for sensitivity analyses. As for route selection, all car agents prefer shortest distant route in cases 1 and 3. In case 2, a half of car agents prefer shortest distant route, while the other half prefer shortest trip time.

4.3 Over-Loaded Test

As one of preliminary tests, an over-loaded simulation is performed. The number of car agents generated is about 170,000 in total. The maximum number of car agents existing at the same time is about 90,000. Six hours simulation in an actual phenomenon takes about 13 hours using a PC of Athlon2000+ with Memory of 1GBytes. The size of data file storing results of the 6 hours simulation is about 18GBytes. It is confirmed in this simulation that each car agent drives in the road network following traffic rules without collision to other cars and reaches to its goal destination successfully. In order to shorten computation time drastically, we are developing the parallel version of MATES.

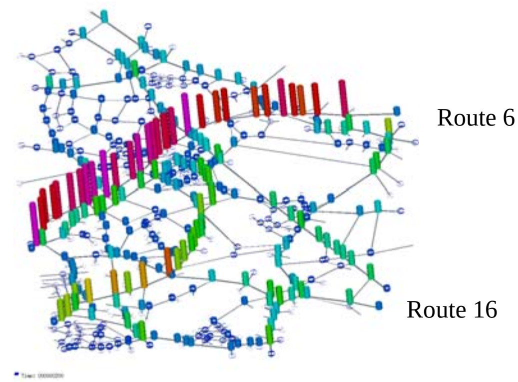
4.4 Results and Discussions

Tab. 1 shows conditions of sensitivity analyses. Fig. 7 shows the simulated results of an amount of accumulated traffic during 30 minutes observed at all intersections of cases 1 to 3. Comparing case 1 (Fig. 7(a)) and case 3 (Fig. 7(c)) shows that traffic along National route No.6 in case 1 is heavier than that of case 3. This is because in case 1, signals are subjected to systematic control, so that traffic is smoothed. On the other hand, no significant change is observed in traffic along National Route No. 16. This is because the amount of traffic is not so heavy that the method of signal control does not influence the traffic so much.

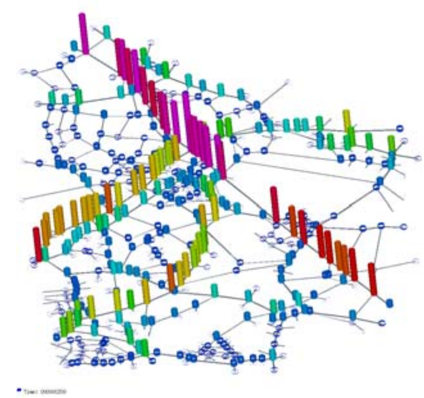
Table 2 : Comparison between simulated and observed results of traffic demand during 7-8AM at 21 intersections

Case	1	2	3
Mean Error	0.57	0.54	0.61
Dispersion	0.056	0.067	0.070

Comparing case 1 (Fig. 7(a)) and case 2 (Fig. 7(b)) shows the amount of traffic along National Route No.16 increases in case 2. This is because in case 2, the car agents that prefer shortest trip time tend to select National Route No.16 on which there are a smaller amount of cars. Next, the observed amount of cars during



(a)



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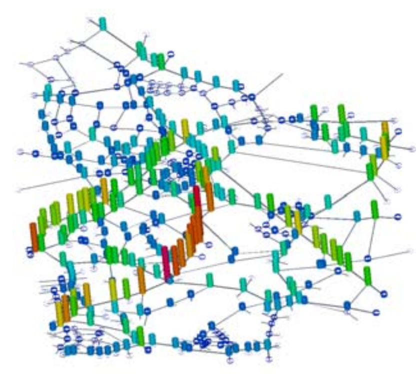

(c)

Figure 7 : (a) Accumulated traffic demand for 30 min (Case 1); (b) Accumulated traffic demand for 30 min (Case 2); (c) : Accumulated traffic demand for 30 min (Case 3)

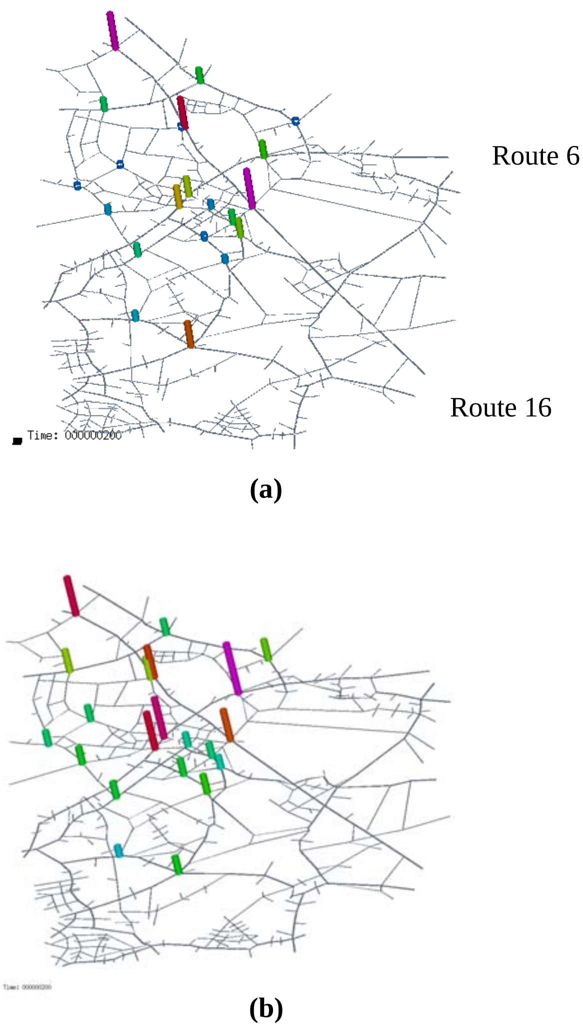

Figure 8 : (a) Simulated result of traffic demand during 7-8AM at 21 intersections (b) Observed result of traffic demand during 7-8AM at 21 intersections

7:00AM to 8:00AM is compared with the simulated one. The traffic data were observed at 21 intersections in the area. Tab. 2 shows relative difference and dispersion between observed and simulated values at the 21 intersections. In case 2, the relative errors are smallest. Fig. 8 shows the comparison between the simulated result in case 2 and the observed one. We can say from the comparison that qualitative agreement is reasonably well. However, as for an absolute value, the error is still large. As the result it is still difficult to make quantitative discussion. This is because we could not get an actual mount of traffic in Kashiwa-city area as input data. This will be further issues to be improved.

5 Conclusions

In this research, we have developed a new traffic simulator named MATES, in which a number of intelligent agents interact among others on a virtual road network. Each agent behaves autonomously, based on its acquiring information from the environment. The basic performances of the MATES are evaluated through some basic but essential simulation problems. Next, MATES is applied to simulate an actual traffic situation in an actual city, Kashiwa-city in Chiba Prefecture, Japan. Based on some sensitivity analyses and comparison with monitored data, it is clearly shown that MATES can reproduce an actual traffic situation qualitatively well. To improve quantitative accuracy, it is necessary to obtain actual data especially on actual traffic demand. In the current version of MATES, each agent behaves quite rationally. This means that no traffic accidents might occur in the simulation. To model traffic accidents, we are going to develop new agents with irrational behaviors.

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