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DEVELOPMENT OF MATDYMO (MULTI-AGENT FOR TRAFFIC SIMULATION WITH VEHICLE DYNAMICS MODEL) I: DEVELOPMENT OF TRAFFIC ENVIRONMENT

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ABSTRACT−For decades, simulation technique has been well validated in areas such as computer and communication systems. Recently, the technique has been much used in the area of transportation and traffic forecasting. Several methods have been proposed for investigating complex traffic flows. However, the dynamics of vehicles and diversities of driver characteristics have never been considered sufficiently in these methods, although they are considered important factors in traffic flow analysis. In this paper, we propose a traffic simulation tool called Multi-Agent for Traffic Simulation with Vehicle Dynamics Model (MATDYMO). Road transport consultants, traffic engineers and urban traffic control center managers are expected to use MATDYMO to efficiently simulate traffic flow. MATDYMO has four sub systems: the road management system, the vehicle motion control system, the driver management system, and the integration control system. The road management system simulates traffic flow for various traffic environments (e.g., multi-lane roads, nodes, virtual lanes, and signals); the vehicle motion control system constructs the vehicle agent by using various vehicle dynamic models; the driver management system constructs the driver agent capable of having different driving styles; and lastly, the integrated control system regulates the MATDYMO as a whole and observes the agents running in the system. The vehicle motion control system and driver management system are described in the companion paper. An interrupted and uninterrupted flow model were simulated, and the simulation results were verified by comparing them with the results from a commercial software, TRANSYT-7F. The simulation result of the uninterrupted flow model showed that the driver agent displayed human-like behavior ranging from slow and careful driving to fast and aggressive driving. The simulation of the interrupted flow model was implemented as two cases. The first case analyzed traffic flow as the traffic signals changed at different intervals and as the turning traffic volume changed. Second case analyzed the traffic flow as the traffic signals changed at different intervals and as the road length changed. The simulation results of the interrupted flow model showed that the close relationship between traffic state change and traffic signal interval.

KEY WORDS : Vehicle dynamics, Multi-agent, Traffic simulation, Virtual driving lane, Interrupted flow model, Uninterrupted flow model

1. INTRODUCTION

Like economics, transportation of people as well as goods has always been basic. Societies with better-managed transportation have a clear advantage over others that do not, as revealed by early civilizations. Transportation has become increasingly more important in our lives. For example, the public expense due to the traffic congestion in US is estimated to be around one hundred billion dollars in 1992 (Akiva *et al.*, 1998). Urban areas are experiencing increasing travel demands, resulting in traffic congestion. This increase has placed a tremendous burden on the existing highway infrastructure. Due to the latent demand for transportation and growth in population and employment, wider freeways have been built, but they have rarely solved this congestion problem (Noland, 2001). Thus, not only is there a need to improve the infrastructure but also a need to increase operational efficiency to solve this problem. First, traffic flow must be simulated accurately for efficient operation of the road facilities.

Various approaches have been implemented to accurately predict traffic flow. Since the 1950's, traffic characteristics have been investigated intensively in parallel with the increase in the use of automobiles and with the expansion of the highway (Pipes, 1953; Newell, 1961). Earlier studies on traffic flow focused on finding the relations among traffic variables such as density, velocity, and

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flow. However, various measurements showed the limited description of traffic flow based on the simple relations among traffic variables (Drake *et al.*, 1967).

Traffic simulation models are typically classified as micro model and macro model. Micro model treats a system as a large set of small, interacting components (Peter, 1993; García *et al.*, 1995). TRANSIMS (Nagel and Rickert, 2001), PARAMICS (Quadstone Ltd., 1999), INTERGRATION (Aerde and Yager, 1988), DYNASMART (Hu and Mahmassani, 1995), and VISSIM (Fellendorf, 2001) are microscopic traffic simulators that describe urban traffic. Macro model focuses on the observable behavior of a system (Chan, 1974). Salvini *et al.* (2003) used a macro model to simulate a huge area. These two types of models have a commonality: The governing equation is derived from fluid mechanics based on continuum theory. Either a macro model which interested in a gross traffic descriptors such as traffic flow or a micro model which details the movement of individual vehicles can be used according to the purpose of simulation.

Traffic flow can be classified into two types. The first type is the uninterrupted traffic flow, in which the traffic flow is continuous as in highways or motorways (Michalopoulos and Pisharody, 1981). Various simulations to describe uninterrupted traffic flow have been proposed. Since vehicles in uninterrupted traffic flow normally maintain a constant and continuous flow, fluid mechanics based on continuum theory can be applied (Pue, 1982). Although a micro model based on fluid mechanics can express the detailed behavior of vehicles at a local area, it cannot clearly describe a traffic congested flow due to irregular occurrences such as traffic accidents. The second type is the interrupted traffic flow, in which the traffic flow is interrupted by traffic signals as in urban roadways (Michalopoulos *et al.*, 1984). The interrupted traffic flow is derived from a complicated relation among traffic signs, pedestrians, temporary stopped vehicles, traffic accidents, and so on. The most urgent task of urban transportation is the relief of traffic congestion. Increased traffic flow on existing roadways inevitably results in congestion. Congestion leads to delays, decreases in traffic flow rate, and higher fuel consumption and thus, has negative environmental effects. Congestion is caused by irregular occurrences, such as traffic accidents, vehicle disablements, and spilled loads and hazardous materials. The demand for research accounting for the irregular occurrences has increased because the traffic congestion of urban roadways needs to be analyzed accurately. Behaviors of vehicles in urban area are repetitive movement of stop and go, passing, and yielding. Therefore, simple car-following theory cannot accurately describe the behaviors of vehicles in an urban area. To describe various driving conditions and consider the driver diversity, many research have actively used the agent technique.

To understand urban travel behaviors, agents-based approach is increasingly developed and applied in a micro simulation framework to predict the temporal and spatial distributions of trips in an urban area (Arentze and Timmermans, 2005). In agent-based models, each actor within the system of interest are modeled as an autonomous 'agent' in the system, who possesses an identity, attributes, decision-making, and acting capacity. Agent-based modeling is extremely efficient, effective, and natural in both conceptualizing and implementing complex, dynamic, disaggregate models of human decision-making (Polak and Huang, 1999). Roozemond (1999) studied the agent-based traffic control system, Hernández *et al.* (1999) announced the knowledge-based agent framework for real-time traffic management, and Kukla *et al.* (2001) simulated a pedestrian flow by autonomous agents. Although the agent-based approach has many advantages, it has difficulty in sufficiently considering those elements that are thought to greatly affect traffic flow, such as the characteristics of each driver and vehicle, etc.

The purpose of this paper is to establish a traffic simulation system using a multi-agent approach, named as MATDYMO (Multi-Agent for Traffic Simulation with Vehicle Dynamic Model). It can simulate both the interrupted traffic flow model and the uninterrupted one, microscopically and macroscopically. Macroscopically, it analyzes the general parameters of traffic flow such as the average velocity, vehicle density, and total number of passed vehicles. Microscopically, it models a vehicle based on the vehicle's own characteristics such as the vehicle length, width, maximum allowable velocity, yielding index, passing index, and other characteristics, which will be discussed later. Also, it models the vehicle agent using vehicle dynamics (Elmarakbi and Zu, 2004) to describe the behavior of a vehicle more accurately.

2. REQUIREMENTS OF AGENT IN TRAFFIC SIMULATION

Workers involved in agent research have offered a variety of definitions, each hoping to explicate his or her use of the word "agent". An autonomous agent is defined as a system situated within and a part of an environment that senses that environment (Russell and Norvig, 1995) and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future (Maes, 1995). The Table 1 lists several of the properties which may help us further understand agents.

The agent requirements in the traffic simulation, which motivated the development of the system proposed in this paper, are the following. With respect to an agent, the system should be able to express the diversity of the drivers and vehicles. The driver agent should be capable of having different driving styles

Table 1. Properties of agent.

Property	Other names	Meaning
Reactive	Sensing and acting	Responds in a timely fashion to changes in the environment.
Autonomous		Exercises control over its own actions.
Goal-oriented	Pro-active	Purposeful does not simply act in response to the environment.
Temporally		Continuous is a continuously running process.
Communicative	Socially able	Communicates with other agents, perhaps including people.
Learning	Adaptive	Changes its behavior based on its previous experience.
Character		Believable "personality" and emotional state.

ranging from 'slow and careful' to 'fast and aggressive' driving. Similarly, vehicle agents should be capable of having various vehicle dynamic characteristics. In Figure 1, the boxes bound by double lines shows the proposed system that can satisfy the agent requirements of the traffic simulation.

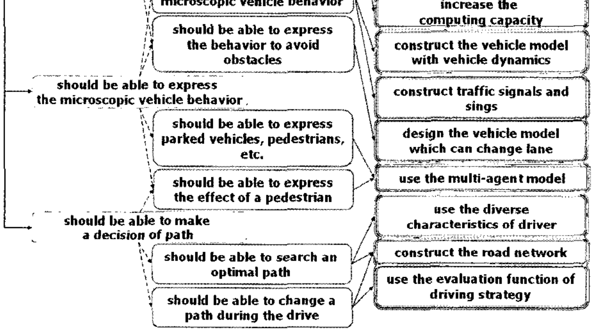

Figure 1. Requirement of the traffic simulation.

3. CONFIGUREATION of MATDYMO

The MATDYMO has four sub systems: road management, vehicle motion control, driver management, and integration control. The road management system constructs the traffic environment by creating modules of the node generation, digital map data importing, road network connection, and lane generation. It sends the road characteristics, such as the radius of curvature, road shape, and locations of vehicles, to the vehicle motion control system and sends the lane information to the driver management system. The vehicle motion control system, which constructs the vehicle agent, consists of the PID (Proportional-Integral-Derivative) velocity control module, and the throttle and brake control module. The vehicle agent is an 8 DOF (Degrees-Of-Freedom) mathematical model consisting of six sub components, the engine, torque converter, transmission, drive train, throttle, and brake actuator. The vehicle motion control system sends the vehicle velocity and location information to the road management system.

The driver management system, which builds driver agent, uses the A* algorithm (Kuri *et al.*, 2002; Nakamiti and Freitas, 2002) to find the travel path. It has the lane changing module that controls the dynamic and static lane changes. The integrated control system regulates the MATDYMO as a whole, observes the agent movements in the system. It provides a GUIs (Graphic User Interface). User can modify the map database and vehicle characteristic database, update parameter sets such as the simulation time step, and control the visibility of vehicle ID (identification) and intersection ID by the GUIs. Also the integrated control system defines the rules of driver behavior and communication frameworks. The vehicle motion control system and driver management system

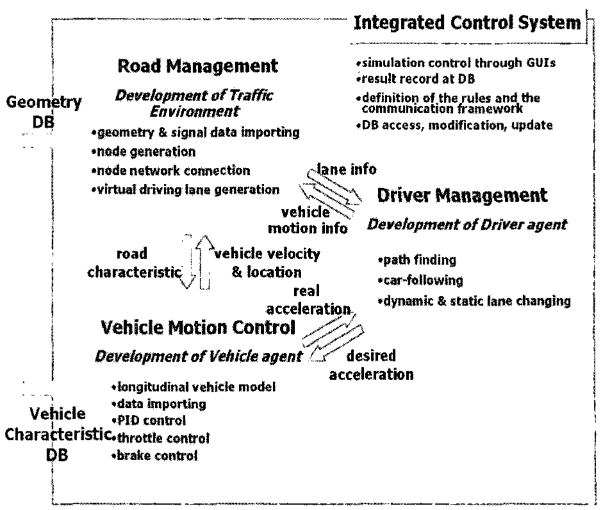

Figure 2. Configuration of the MATDYMO.

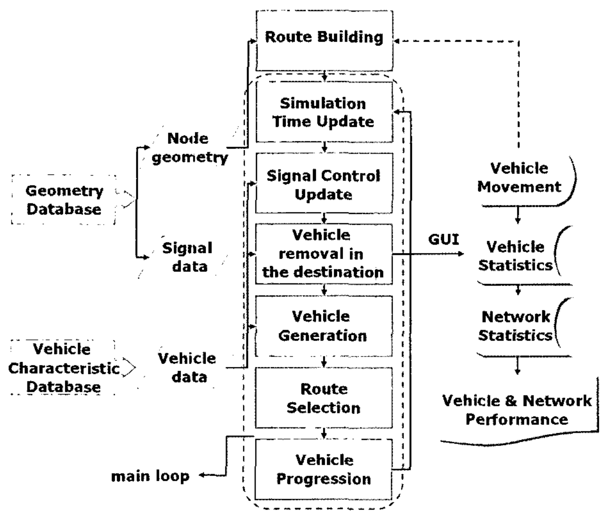

Figure 3. Simulation flow of the MATDYMO.

are described in the companion paper (Cho *et al.*, 2005). The Figure 2 shows the configuration of the MATDYMO. The overall simulation flow of the MATDYMO is presented in Figure 3.

4. ROAD MANAGEMENT SYSTEM

In this chapter, we will discuss the road management system, which constructs the traffic environment. The road management system consists 4 modules: node generation, road network connection, lane generation, and traffic signals control. It sends road characteristics, such as the radius of curvature, road shape, and locations of vehicles, to the vehicle motion control system, and lane information to the driver management system. The elements of traffic environment in MATDYMO are the node, road, virtual driving lane, and traffic signals.

4.1. Node Generation Module

The node, which represents the intersection in real traffic environment, is the basic element used in traffic environment construction, in which road, virtual driving lane, and traffic signals are generated. The node has coordinate information, node relation information, and intersection identification information. In MATDYMO, the coordinates are specified either as latitude-longitude pairs or as x and y coordinates in arbitrary coordinate axes. The shape of intersection is defined by the number and coordinates of the neighboring nodes. The node is classified into 3 types: intersection node, T-Junction node, and connecting node. Intersection node and T-Junction node has 4 and 3 neighboring nodes, respectively. Connecting node is used to express the round road shape.

4.2. Road Network Connection Module

Roads can be defined as the physical space where vehicles move. However, this concept is somewhat difficult to actualize in computer simulation, since the physical space has too many DOFs. In this study, we treated roads as networks between nodes, called a road network. Therefore, roads are composed of sets of linear segments. Each set describes the geometry of the road between two nodes as a sequence of connected line segments called the virtual driving lane.

4.3. Lane Generation Module

When a driver drives a car, the actions of the driver can be categorized as follows: steering, speeding up and down, and changing lanes, and operating blinkers. Steering can be excluded, if the road is a railroad. For fast and accurate computing, the virtual driving lane, which is very similar to a railroad line, is proposed in this study. The lane generation module, which generates the virtual driving lane, has the several advantages; easy implementation, direction recognition, and clear path selection.

4.4. Traffic Signals Control Module

The traffic signal control (Huddart, 1969) means the management of the traffic flow by use of traffic signals. The discontinuity of traffic flow by the traffic signals often increases total travel time in a signalized traffic system. The interval of the traffic signals between intersections must be carefully controlled. The effect of changing the traffic signal' interval between intersections is simulated in chapter 6.

5. INTEGRATED CONTROL SYSTEM

The structure of the integrated control system is shown in Figure 4. The system performs three roles: vehicle position sensing, DB interfacing, and agents and environment rule implementation. The integrated control system provides GUIs, which can be used to modify and update the map database and vehicle parameter database.

The integrated control system collects vehicle information, such as, velocity, node's ID, road's ID, lane ID and so on, and broadcasts it to vehicles. Also, it updates data renewed by the GUIs' parameters such as simulation step time, total simulation time, view control, type of saving data, and etc. during the simulation. It saves the simulation result data on the vehicle velocities, mean velocities, number of delay vehicles, total travel times, etc. in the DB.

A rule is defined as the conditions that lead an agent to a conclusion in the process of its thinking (Patrick *et al.*, 1988). A vehicle can expect certain changes to occur in its environment and makes decisions according to rules. A vehicle looks at other vehicles on the road continuously and moves to reach its destination safely in an optimized

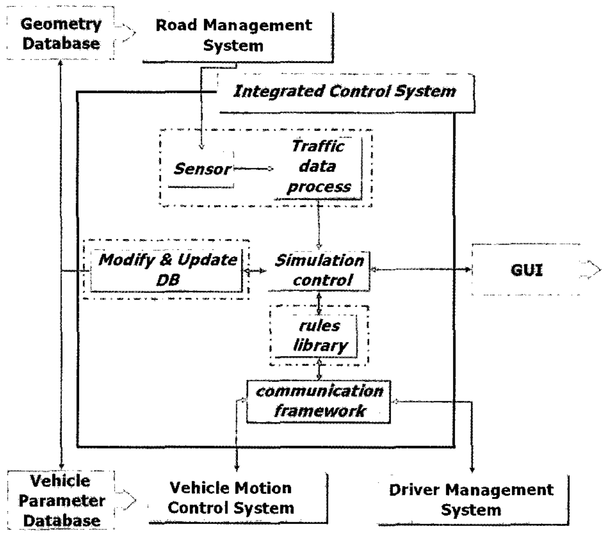

Figure 4. Structure of the integration control system.

Table 2. Rules among vehicles.

Case	Rules
In process	A vehicle yields to cars with the right of way.
	A vehicle having the higher yielding index has priority of passing the lane over one having the low yielding index.
	According to the passing index, a vehicle tries to pass the vehicle going slowly.
Decelerating	A brake lamp should be turned on.
Lane changing	A vehicle should secure an enough space.
	A signal light should be turned on.
Parking on the shoulder	An emergency light should be turned on.

way. The rules among vehicles are shown in Table 2.

To represent a real traffic flow, an agent should express a driver's decision making process when it is faced with certain conflicting situations. In this paper, "yielding index" and "passing index" are used as the parameters representing psychological state. An agent decides its action such as, passing, yielding, and following according to these indices. The yielding index can be defined as the tendency to yield during lane changing. A higher yielding index means that the vehicle is more likely to yield. The passing index can be defined as the tendency to pass. An aggressive driver has a low passing index, whereas a cautious driver has a high passing index.

In real life, a driver recognizes another vehicle and estimates its velocity by using his/her sense organs. In the agent paradigm, this process was actualized by selective information transmission. That is, the integrated control system sends only the information of vehicles that are in the visibility range.

6. ROAD NETWORK SYMULATION

MATDYMO is evaluated via simulation to identify its properties and possible weaknesses for a variety of scenarios and cases. First, the vehicle agent behaviors in the microscopic aspect according to the different acceleration/deceleration rates and different speed limits have been analyzed in the uninterrupted flow model. Second, traffic flow was analyzed by considering the interval of the traffic signals and turning traffic volume in the interrupted flow model. Third, traffic flow considering the interval of the traffic signals and road length in the interrupted flow model was analyzed.

6.1. Analysis of Agent Behavior in the Uninterrupted Flow Model

The uninterrupted flow model represents the road in the state of continuous traffic flow as in a highway or

Table 3. Characteristics of vehicles.

ID	Type	Color	Acceleration rate (m/s^2)	Speed limit (km/h)
1	Bus	White	-3 m/s^2~1.5 m/s^2	90 km/h
2, 3	Car	Yellow	-3 m/s^2~2.0 m/s^2	110 km/h

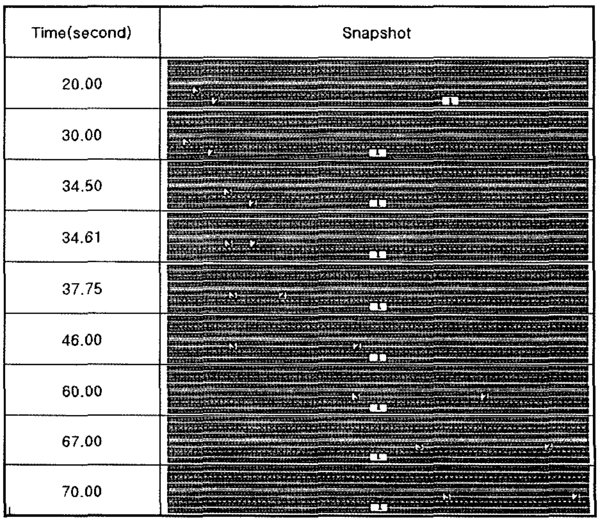

Figure 5. Continuous images of simulation at various times.

motorway. Two types of vehicles are appropriated to simulate the passing conditions, and the characteristics of vehicles are shown in Table 3. The vehicle-color pairs were as follows: car-yellow and the bus-white. In this simulation, behaviors of vehicle such as changing lane, speeding up/down, and passing were actualized to analyze their interactive effect on adjacent vehicles. The various vehicle movements are presented as continuous images at various times in Figure 5.

Vehicle 2, V2, follows another vehicle 1, V1, at the initial time, and V1 is stationary. The speed limit of V1 is lower than that of V2, and there is enough passing space, so V2 can pass V1. At the same time, vehicle 3, V3, speeds down until desired relative distance when V2 breaks into V3's lane. The passing space and desired relative distance depends on the relative velocity and relative acceleration. From Figure 7, we can see that the relative distance of V3 to V2 is smaller than the desired relative distance when V2 breaks into V3's lane. For this reason, V3 decelerates suddenly, as shown in Figure 6. The detailed car-following theory is discussed in the companion paper. The Figure 8 shows the current lane of vehicles according to the simulation time. Velocities,

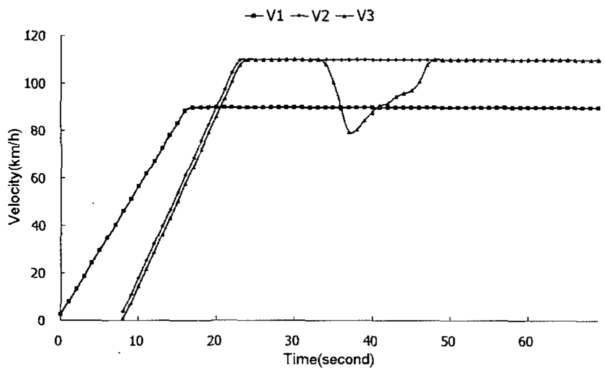

Figure 6. Velocity variations based on the simulation time.

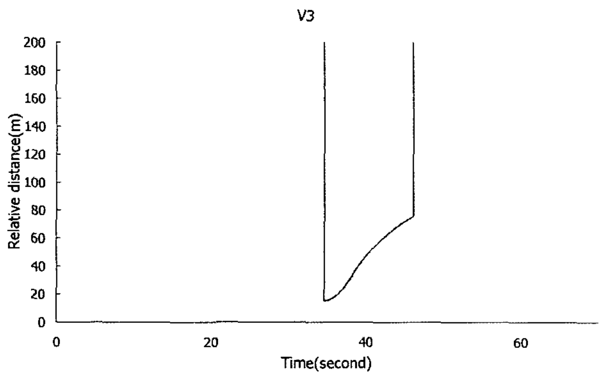

Figure 7. Relative distance variation based on the simulation time.

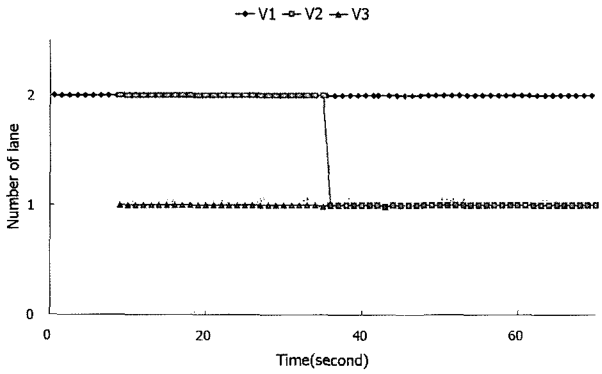

Figure 8. Current lane variations based on the simulation time.

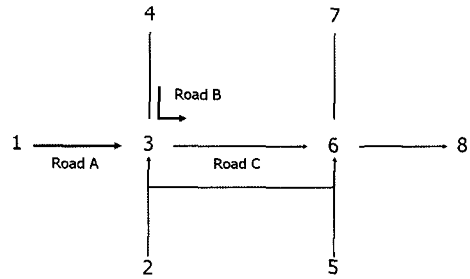

Figure 9. An interrupted flow model.

relative distances, and current lane are shown in Figures 6, 7, and 8, respectively.

Because there is no leading vehicle in front of V1, the relative distance of V1 is infinity. In this simulation, we set the front visual field as 76 m because if the relative distance between two vehicles is larger than 76 in uninterrupted flow, the car-following is not influenced by the leading vehicle's behavior (Aycin and Benekohal, 1998). The simulation result showed that the driving conditions of each vehicle were substantially affected by adjacent vehicles and, in turn, affected the velocity of the traffic as a whole.

6.2. The Effects of the Interval of the Traffic Signals and Turning Traffic Volume

In this simulation, a simple intersection model was constructed as shown in Figure 9. The traffic flow was simulated using this model according to the interval of the traffic signals and turning traffic volume at node 3. That is, the ratio of turning traffic volume, the traffic volume of road B against the one of road A, was changed to 50%, 25%, and 17% at node 3. Vehicles were generated at nodes 1 and 4, and terminated at node 8. The traffic signals were located at nodes 3 and 6. The conditions of the traffic signals are shown in Table 4.

The length of road C was 600 m. The simulation was carried out for 1 hour at a time step of 10 ms. The applied congestion density was 120 vehicles/km. In this simulation, the average delay of road C between nodes 3 and 6 was observed. The average generated traffic volume was 0.71. The simulation result was compared with those from the commercial software, TRANSYT-7F (T7F, Lin and Gan, 1999), as shown in Figures 10, 11, 12, and 13.

The MATDYMO gave results very similar to those of T7F for the case in which the turning traffic volume was varied. The maximum delay was about 15 seconds, and the minimum delay about 50 seconds, as shown in Figures 10, 11, and 12. The larger the straight traffic volume was, the larger the variation in the average delay was, as shown in Figure 13. That is, when the straight traffic volume increased, the average delay became more

Table 4. Conditions of the traffic signals.

Node \ Signal (sec.)	Green	Orange	Red	Period
3, 6	35	2	38	75

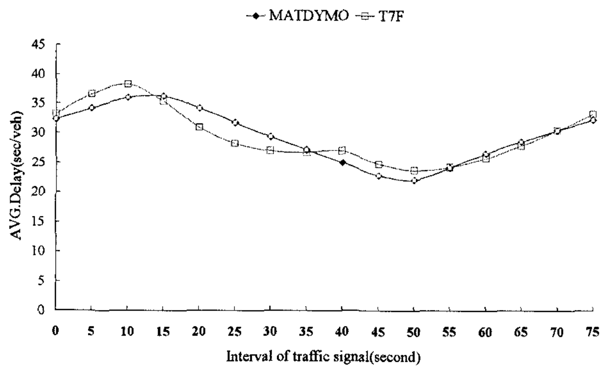

Figure 10. Variation of the average delay versus the interval of the traffic signals at 50% turning traffic volume.

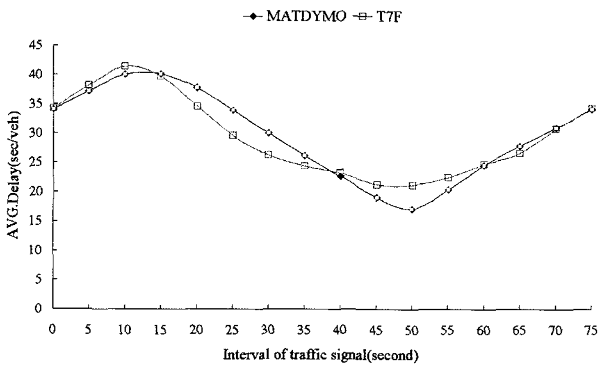

Figure 11. Variation of the average delay versus the interval of the traffic signals at 25% turning traffic volume.

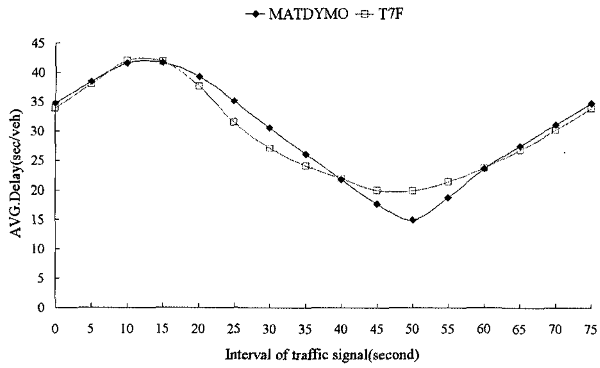

Figure 12. Variation of the average delay versus the interval of the traffic signals at 17% turning traffic volume.

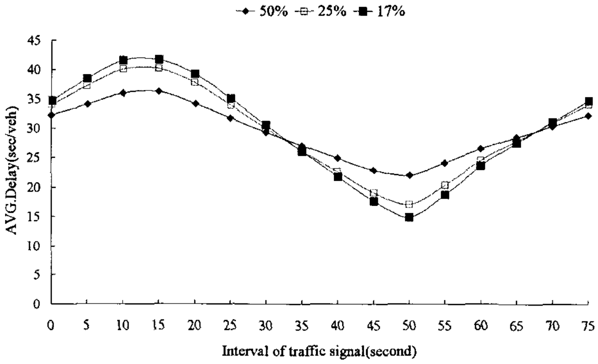

Figure 13. Comparison of the variation of the average delay versus the interval of the traffic signals at different ratios of turning traffic volume.

sensitive to the changing interval of the traffic signals. Because the total traffic volume was constant, the increase in the straight traffic volume means the increase in the passing traffic volume per unit time. For this reason, if the straight traffic volume is increased, to maintain a continuous traffic flow, it is necessary to control the traffic signals of the road network.

6.3. The Effects of the Interval of the Traffic Signals and Road Length

The shape and traffic signal conditions same as those in section 6.2 were used to analyze the traffic flow according to the interval of the traffic signals and length of road C in Figure 9. Nodes in which vehicles were generated and terminated were the same as those in the above simulation. Simulation was carried out for 1 hour at a time step of 1 ms. A speed limit was 80 km/h, and a congestion density of 120 vehicles/km was applied. Also, the saturation traffic volume was 2400 vehicles/h.

The ratio of turning traffic volume to the straight traffic volume was 25% at node 3. The average delay of node C was the same as that in the preceding simulation. The average traffic volume of road C was 0.71 in this simulation. Simulation was executed for the shifting intervals of the traffic signals between nodes 3 and 6. The intervals varied from 0 to 75 seconds by 5s, and road C lengths were set to 400 m, 600 m, and 800 m. The simulation results were compared with those from TRANSYT-7F, as shown in Figures 14, 15, and 16.

As in the previous case, the MATDYMO gave very similar result to those of T7F for different road lengths.

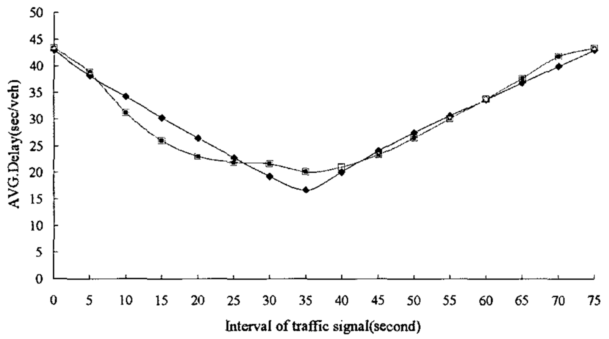

Figure 14. Variation of the average delay versus the interval of the traffic signals at 400 m.

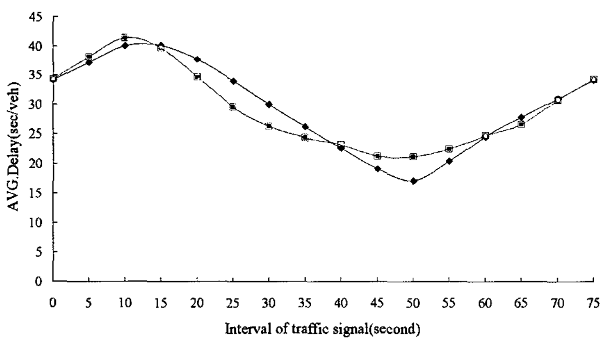

Figure 15. Variation of the average delay versus the interval of the traffic signals at 600 m.

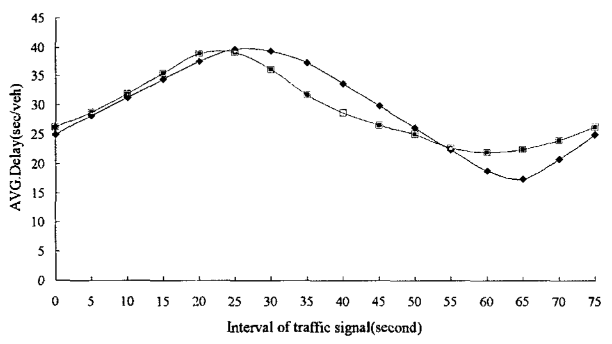

Figure 16. Variation of the average delay versus the interval of the traffic signals at 800 m.

The maximum delays were 0 second, 15 seconds, and 30 seconds shown in Figures 14, 15, and 16, respectively. The maximum delays shifted by 15 seconds from 0 second to 30 seconds according to the road length. Also, the minimum delay showed a similar tendency; that is, the minimum delays shifted 15 seconds from 35 seconds to 65 seconds. The maximum and minimum delays have the same 35 second time shifting for each case. The shorter the road length is, the more sensitive the traffic flow is to the interval of traffic signals. The decrease in the road length means the increase in the passing traffic volume per unit length. Therefore, if the road length is short, traffic signal control is needed to avoid discontinuity of traffic flow.

7. CONCLUSIONS

The MATDYMO (Multi-Agent for Traffic Simulation with Vehicle Dynamic Model) system is a multi-agent system for traffic simulation. The MAT DYMO consists of four sub systems with an object oriented flavor: the road management system, the vehicle motion control system, the driver management system, and the integration control system.

MATDYMO was used to simulate traffic flow of the interrupted and uninterrupted flow model. The simulation for the uninterrupted flow model confirmed that the agent's behavior could characterize the diversity of human behavior and vehicle well by using rules and communication frameworks. It was shown that the driving conditions of each vehicle are substantially affected by its adjacent agents. The change of traffic flow according to the interval of the traffic signals was simulated for the interrupted flow model, and the results of this simulation were compared with those from the commercial software, TRANSYT-7F. When the straight traffic volume increased, the average delay became more sensitive to the interval of the traffic signals. Because the total traffic volume was constant, the increase in the straight traffic volume meant the increase in the passing traffic volume per unit time. Therefore, if straight traffic volume is increased, the traffic signals for the road network must be controlled to maintain a continuous traffic flow. Also, the shorter the road length was, the more sensitive the traffic flow was to the interval of traffic signals. If the road length is shorter, the passing traffic volume per unit length is increased according to the condition of the constant traffic volume. The simulation results of the interrupted flow model showed that the change of the traffic state was closely related with the interval of the traffic signals. For the interrupted flow model, the interval of the traffic signals between intersections must be adequately controlled to relieve the traffic congestion.

The simulations confirmed that the proposed system represented the driving conditions of each vehicle and road network practically. With MATDYMO, users can evaluate the traffic equipment and policy of an actual traffic environment.

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