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Multi-agent based traffic simulation and integrated control of freeway corridors: Part 1 simulation and control model †

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Abstract

Freeway corridors consist of urban freeways and parallel arterials for alternative use. Ramp metering in freeways and signal control in arterials are contemporary traffic control methods that have been developed and applied in order to improve the traffic conditions of freeway corridors. However, most existing studies have focused on either optimal ramp metering in freeways or progressive signal strategies between arterial intersections. For efficient control of freeway corridors, ramp metering and signal control must be considered simultaneously, as otherwise the control strategies for freeway operation may disturb arterial traffic. On the other hand, traffic congestion and arterial bottlenecks that arise with increasing traffic volume at peak hours and ineffective signal operation may cause problems with accessibility to freeway ramps and degrade the urban freeway's ability to act as a through-traffic process. This research dynamically estimates the traffic stream between an urban freeway and its ramps according to changes in the freeway structure, traffic passing demand, and control methods due to restricted valid information. The results are then compared with those from other methods. Finally, the integrated control in the urban freeway traffic axis is optimized based on the expected traffic stream, by using design of experiment (DOE), neural network (NN), and a simulated annealing algorithm.

Keywords: Vehicle dynamics; Multi-agent; Traffic simulation; Integrated control; Ramp metering; Signal strategy; Freeway corridor; Agent simulation

1. Introduction

An urban freeway is generally defined as a motorway located in an urban area with the purpose of providing high-speed and uninterrupted traffic flow through a restricted entrance-exit system. Urban freeways are typically very different from regional freeways because of the functional characteristics resulting from the urban location. The differences are caused by various characteristic factors of urban freeways such as heavy traffic demands, frequent entrance-exit, incessant change of traffic capacity, and geometrical structure with restraint.

A freeway corridor is defined as a general freeway network consisting of urban freeways and parallel arterials. Ramp metering in freeways and traffic signal control in arterials are contemporary traffic control methods that have been developed and applied in order to improve the traffic conditions of freeway corridors. However, most existing studies have focused on either optimal ramp metering in freeways, or progression signal strategies between arterial intersections. The effective control strategies for freeway operations may impair arterial traffic. On the other hand, traffic congestion and arterial bottlenecks that arise with increasing peak-hour traffic volume and ineffective signal operation may hinder freeway ramp

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accessibility. These obstacles have restricted the main function of the freeway, which is the provision of a through-traffic process.

To understand urban traffic behavior and manage urban freeways efficiently, agent-based approaches have been developed and applied in a simulation framework to predict the temporal and spatial distributions of trips in an urban area [1]. In such agent-based models, each actor within the system of interest is modeled as an autonomous 'agent' in the system, which 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 [2]. Roozemond [3] studied an agent-based, traffic control system, Hernandez et al. [4] announced a knowledge-based, agent framework for real-time traffic management, and Kukla et al. [5] simulated a pedestrian flow by autonomous agents. Although the agent-based approach has many advantages, it lacks the capability to consider fully those elements that are thought to greatly affect traffic flow such as the characteristics of each driver and vehicle.

This research is composed of two papers: 'Simulation and Control Model' and 'Integrated Control using Optimization Technique'. The purpose of this paper (Part 1: Simulation and Control Model) is to establish a traffic simulation system using a newly proposed, multi-agent approach, which we have termed Multi-Agent for Traffic Simulation with Vehicle Dynamic Model (MATDYMO). In this paper, the traffic stream between an urban freeway and its ramps is dynamically estimated according to changes in the freeway structure, traffic passing demand and control methods due to restricted valid information. The traffic stream is validated by comparing to commercial software, TRANSYT-7F, for an interrupted flow model, and to Urban Freeway Traffic Simulation Model (URFSIM) for an uninterrupted flow model. In the related paper (Part 2: Integrated Control using Optimization Technique), the integrated control in the urban freeway traffic axis is optimized based on the expected traffic stream. We extract 80 sampling points from the design of experiment (DOE) and derive each response from MATDYMO. A neural network (NN) is then adopted to approximate the objective function and a simulated annealing algorithm is used as an optimization method. The objective is processed according to three criteria: maximizing the freeway traffic volume, minimizing the delay at ramps and arterials, and satisfying both cases.

2. Development of traffic simulation system

The traffic simulation model developed in the present research contains four sub-categories: the freeway formation system, control system in vehicle movement, driver control system, and integrated control system. The freeway formation system determines the traffic condition based on various modules to deal with topographical data, form intersections, and create freeways or traffic lanes. It provides information about the degree of curve in the road, the road shape, the current vehicle position and other data on the control system in vehicle movement. It also provides traffic lane information with the drive control system. The control system in vehicle movement governs the so-called vehicle agent which consists of a PID speed control module and the throttle and brake control module. By employing a vehicle dynamics model with 8 degrees of freedom (DOF), including engine, torque converter, transmission, gear, throttle, and brake actuator, the vehicle control system gives the vehicle speed and position to the freeway formation system. The driver control system creates the driver agent and sets its path by using A* algorithm. Using a dynamic and static lane change module, the driver control system also determines the traffic lane to drive. The integrated control system manages all the agent information related with operating traffic simulations and controls those simulations. Using the graphic user interface (GUI) provided by this integrated control system, the system users can revise a variety of vehicle information and simulation parameters. The system also defines almost all of the regulations and communication protocols on agents. Fig. 1 exhibits the structure of the traffic simulation models developed by this research and Fig. 2 the simulation stream.

2.1 Freeway formation system

This chapter discusses the freeway formation system, consisting of modules for the formation of intersections, freeways and traffic lanes, which creates the traffic simulation condition. Intersection is one of the most important factors in the creation of traffic conditions, and the system provides information on the coordinates and connections. Coordinates are determined

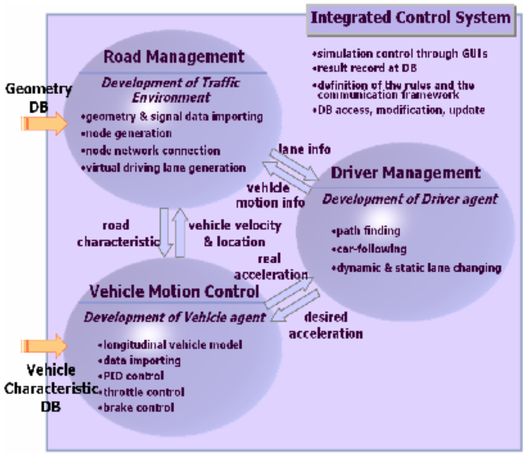

Fig. 1. System configuration.

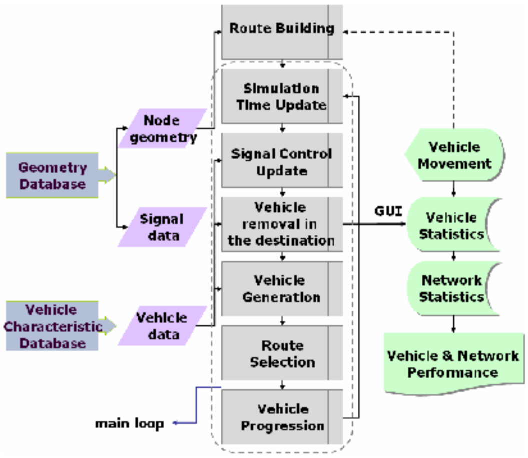

Fig. 2. Simulation flow of the system.

either by the latitude and longitude or by X and Y values for the particular position coordinates. The intersection shape depends on the number and location of nearby intersections. Roads are made on the basis of previously created intersections by the lanes. However, roads can be distinguished between virtual traveling lanes, where vehicles actually run, and normal lanes

2.2 Vehicle control system

The control system in vehicle movement produces the vehicle agent which represents the physical shape of the vehicle and moves according to the dynamic characteristics of the vehicle. The characteristics are the reaction of the actual vehicle to the target speed set by the driver agents. Vehicles cannot gain or

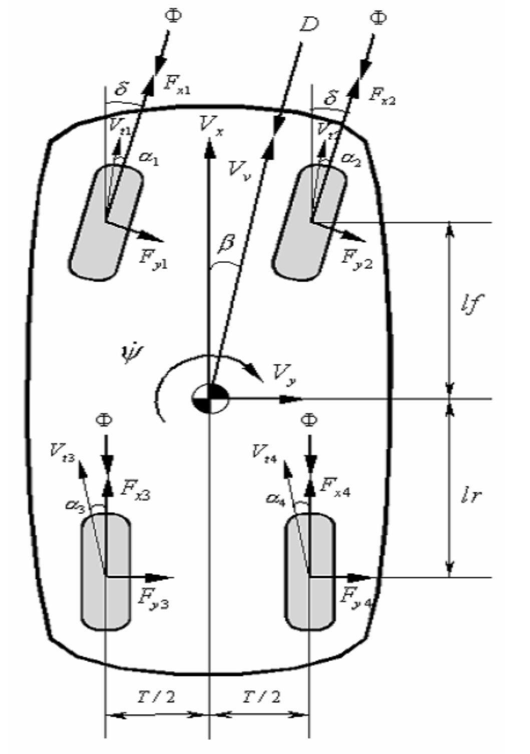

Fig. 3. Vehicle dynamics model for the system.

reduce speed properly and ideally due to their limited acceleration and deceleration capabilities. Therefore, vehicles with dynamics are introduced for the vehicle agent. Vehicle dynamics in this research refers to the vehicle dynamics model with 8 DOF, which was developed by Suh et al. [6]. In addition, the dynamic conveyance model is included [7]. As shown in Fig. 3, vehicle model forms the 8 DOF model for the rotation movement on the vertical and horizontal axis directions, for the vehicle's center of gravity toward the vertical or horizontal direction, and for the rotation movement of each wheel [8]. The dynamic conveyance model supplies early achieved data for the target vehicle, while the remaining unachieved data are replaced with a revised model which was used in SVPG (Sungkyunkwan Univ. Virtual Proving Ground) performed by our laboratory [9]. The dynamic conveyance model is composed of engine, torque converter, and transmission.

- The longitudinal motion

$$M(\dot{V}_x - V_y\dot{\theta}) = F_{x1}\cdot\cos\delta - F_{y1}\cdot\sin\delta + F_{x2}\cdot\cos\delta - F_{y2}\cdot\sin\delta + F_{x3} + F_{x4} \tag{1}$$

where, V_x is the longitudinal velocity, V_y and $\dot{\theta}$ are the lateral and the yawing velocities, respectively, and M and δ are the mass and angular displacement, respectively. Subscripts x and y denote x and y directions, respectively. F_{x_i} and F_{y_i} are the applied forces calculated in the tire i-th in the longitudinal direction.

- The lateral motion

$$M(\dot{V}_y + V_x\dot{\theta}) = F_{x1}\cdot\sin\delta + F_{y1}\cdot\cos\delta + F_{x2}\cdot\sin\delta + F_{y2}\cdot\cos\delta + F_{y3} + F_{y4} \tag{2}$$

- The yawing motion

$$I_z\ddot{\theta} = F_{T1} + F_{T2} + F_{T3} + F_{T4} \tag{3}$$

where, I_z is the mass moment of inertia in the z direction, F_T the body's yawing moment due to the applied force in the tires, and moments $F_{T1}, F_{T2}, F_{T3}, F_{T4}$ are defined as follows:

$$\begin{aligned}
F_{T1} &= a\cdot(F_{x1}\cdot\sin\delta + F_{y1}\cdot\cos\delta) + \frac{T}{2}(F_{x1}\cdot\cos\delta - F_{y1}\cdot\sin\delta)\\
F_{T2} &= a\cdot(F_{x2}\cdot\sin\delta + F_{y2}\cdot\cos\delta) + \frac{T}{2}(-F_{x2}\cdot\cos\delta + F_{y2}\cdot\sin\delta)\\
F_{T3} &= -b\cdot F_{y3} + \frac{T}{2}\cdot F_{x3}\\
F_{T4} &= -b\cdot F_{y4} + \frac{T}{2}\cdot F_{x4}
\end{aligned} \tag{4}$$

where, T is the width of the vehicle, a is the length between the front wheel and the center of gravity and b that between the real wheel and the center of gravity.

2.3 Driver control module

The driver control module creates the drive agent which governs the driving. The application of simple driving regulations for traffic simulation could be improper for the drive agent as it requires the entering of various capabilities such as autonomy and characteristics. The most remarkable characteristic of the driver agent is the autonomy on the drive course: many different courses can be followed from the starting point to the destination. Drivers will not always choose the shortest course and efficiency or experience may be involved in the choice of course.

The driver control system is composed of modules to choose courses, follow vehicles and change lanes. The driver agent conveys the target accelerated speed which is produced by the vehicle following module to the control system in vehicle movement and provides information about the current position and driving lane with the freeway formation and integrated control systems.

The autonomy to choose the path is the most important aspect. Using A* algorithm, we determine the comprehensive path and choose the detailed microscopic path according to the driver agent's choice toward the traffic condition change. The vehicle following module is composed of speed limit control and following control. Speed limit control works when there is no car ahead to follow or when there is a car to follow while maintaining a safe distance. Simultaneously, the driver agent sets the limited speed as the target speed and conveys the target acceleration to the control system in vehicle movement after measuring it. The following control works to set and maintain a safe distance from the proceeding car. The safe distance is calculated by the following quadratic for the velocity:

$$D_i = \alpha v_i^4 + \beta \quad \text{Eq.} \tag{5}$$

where, v denotes the velocity of vehicle i, and α

and β are constants for each value: 0.000161 and 1.0, respectively. Changing lanes is categorized as either static or dynamical change. Static lane change is that required to follow the path, i.e., the change necessary to follow the virtual driving lane for the right or left turn. On the contrary, dynamic change is the choice of a path toward the near lane which minimizes the congestion of the driving path. The static lane is changed when the driving lane is chosen, while the dynamical lane change is determined by the traffic condition and the characteristic of the driver agent. The relationship between the driver control system and the control system in vehicle movement is exhibited in Fig. 4.

2.4 Integrated control module

The integrated control system performs three functions in the simulation: vehicle position detection, DB (Database) interface and regulation execution for agents and conditions. The integrated control system

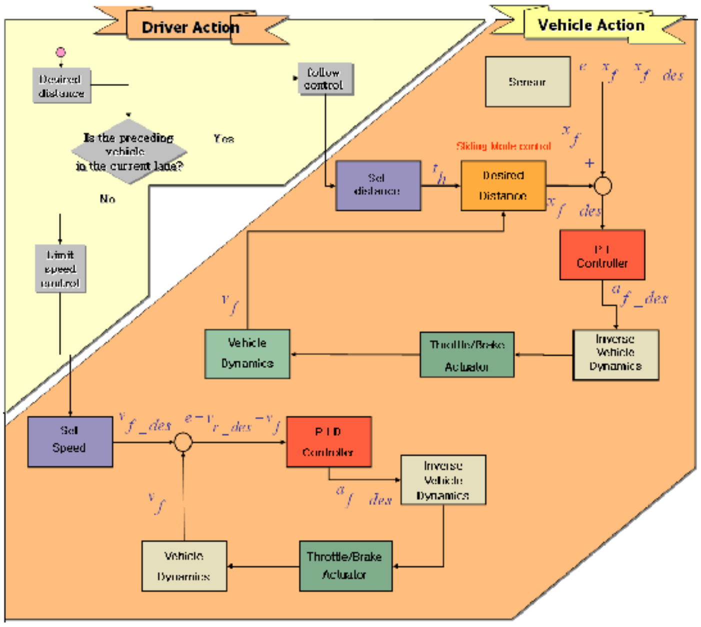

Fig. 4. Relationship between the driver agent and the vehicle agent.

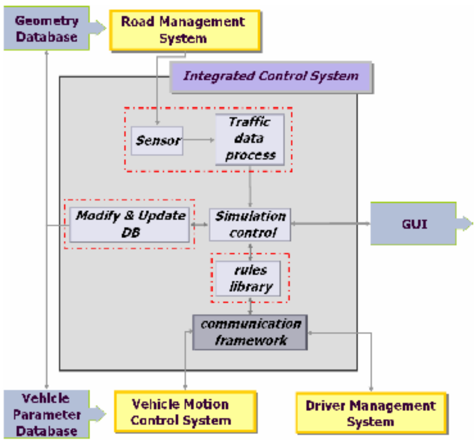

Fig. 5. Structure of the integrated control system.

combines velocity, intersection ID (Identification), road ID and lane ID as vehicle information and distributes to other vehicle agents. In addition, it inputs into the DB various results such as the simulation step time handed by GUI, the total simulation time and the formation of data. Rules are defined as the instruction to produce any Fig. 5 Structure of the integrated control system result from the agent's consideration of condition [10]. The driver agent makes the appropriate decision while communicating with the traffic condition. The integrated control system is shown in Fig. 5.

The drive agent should be able to present the decision-making process when it is confronted with any opposite situation. In order to present the driver's characteristics, two indices are introduced: 'the yield index' and 'the overtake index'. The driver agent decides each action for overtaking, yielding and lane change during driving according to the two indexes. The yield index shows the tendency to yield to changing lanes, with a higher index indicating a greater chance of yielding. The overtake index means how many times the driver overtakes, with a higher index indicating a more aggressive driver.

3. Traffic situation simulation and verification

Using a traffic simulation model based on the previously developed multi-agent, this research forecasts the condition of an urban freeway and the traffic condition of its ramps according to the freeway geometrical structure, passing demand and control method. The study also compares the developed system with URFSIM [9] and then verifies that system. Among the continuous freeway models that are available, the traffic situation simulation uses the simple urban freeway as a sample. The research results are very similar to those of URFSIM and, furthermore, have a capability to show the traffic settlement situation more accurately.

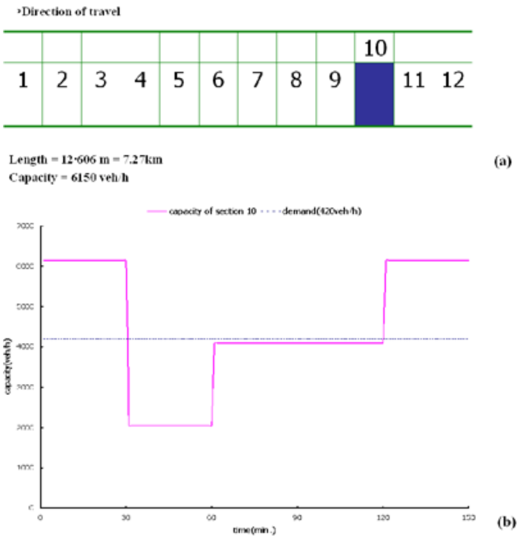

Fig. 6. Configuration of uninterrupted flow model: (a) layout and (b) incoming traffic flows.

3.1 Simulation modeling

Traffic situations arising due to accidents or vehicle breakdowns are so complicated that their simulation is almost impossible. Furthermore, they introduce a capacity change. Fig. 6 exhibits a 7.27 km section of straight lane, without any in/out exits, which is divided into 12 fractions (Δx). Each fraction is 606 m in length and has three lanes. The capacity per lane is 2,050 veh/hr , giving a total capacity for each fraction of 6,150 veh/hr . The total simulation time is 150 minutes and the entrance traffic volume at the beginning part is set as 4,200 vehicles. The traffic situation is set to occur in fraction 10 at 30 minutes after the simulation starts, with two lanes being closed at 60 minutes (the capacity is reduced to 2,150 veh/hr) and one lane between 60 and 120 minutes (the capacity is reduced to 4,300 veh/hr). Based on this situation, the speed limit is 110 km/hr and the degree of confusion is 37.8 $veh/km/lane$. The simulation is continued for 150 minutes and the result is compared with URFSIM.

3.2 Simulation result and verification

After the traffic simulation, based on multi-agents with the sample of a simple urban freeway among the continuous traffic models, confusion is evident at the beginning in fraction 10 in the period between 30 and 60 minutes after the simulation starts, as shown in Figs. 7 and 8. The confusion spreads to the upper stream (change of density in fractions 4 and 8). The traffic density increases in the left confusion part of the traffic-density graph in the upper part of the warned fraction and then stays constant. Meanwhile, the density in fraction 10, where the warning happens, remains constant at k_c = 37.8 $veh/km/lane$, which is the confusion density.

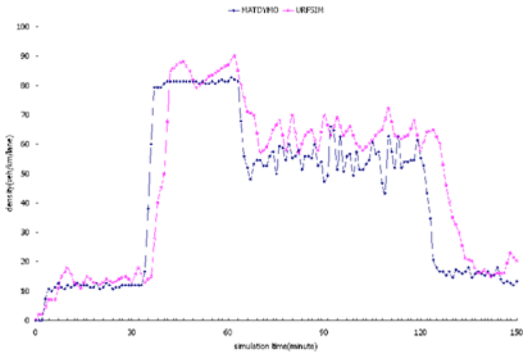

Fig. 7. Traffic state estimation at segment 8.

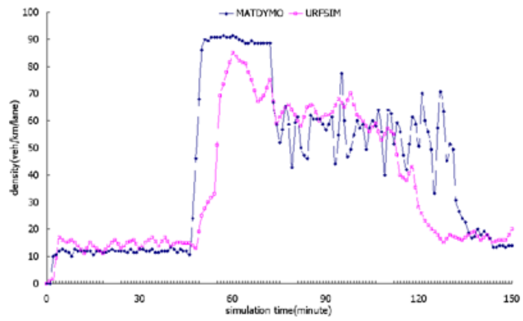

Fig. 8. Traffic state estimation at segment 4.

Fig. 7 displays the traffic-density changes during the simulation in fraction 8 where the warning happens in the upper part. Before the warning, the traffic density is maintained at a low level of 15 $veh/km/lane$ and the traffic volume is 4,200 veh/hr . However, as the warning happens in fraction 10 after 30 minutes, the density tends to increase drastically with a consequent decrease in the traffic volume. In fraction 10, when two lanes are closed, the density remains high at 85 $veh/km/lane$ and the traffic volume decreases to 2,150 veh/hr . As the warning is moderated, the confusion is gradually eased and the volume returns to a normal condition. Regarding the density in fraction 8 shown in Fig. 7, the traffic congestion begins after approximately 34 minutes in this system, compared to 36 minutes in URFSIM; however, the congestion traffic density appears to be similar for both cases. According to Fig. 8, the beginning times of traffic congestion are similar for fraction 4 and URFSIM: 46 and 48 minutes, respectively. Congestion traffic density is also similar for the two systems: 85 $veh/km/lane$ and 91 $veh/km/lane$, respectively. The total spreading time from fraction 8 to fraction 4 is 12 minutes and is identical for two cases. However, the present research gives a longer time for the congestion to recover from the warning situation than URFSIM did, especially an 11-minute gap in fraction 4. This gap is due to the loss of starting or acceleration in the congested situation, which reduces the traffic volume of that situation compared to that of either deceleration or balanced situation with the given density. Therefore, additional research based on the separately observed data is necessary in order to reflect the CFD-based simulation. The traffic estimation system presented here explains the warned recovery situation very well using the vehicle agent provided by vehicle dynamics, thereby confirming the system's ability to forecast the traffic stream in continuous condition. These results validate the application of this system to a complicated warned situation process.

4. Integrated control model

Regarding the inclusion of ramp metering and signal cycle control in integrated control, this research introduces another optimization method, which is different from the previous integrated control model. In detail, a design point is extracted by the DOE and the response of traffic volume and delayed vehicle density for each design point is obtained by MATDYMO. Data from MATDYMO are adapted to approximate the objective function and constraints according to the NN theory [11] and are then used to normalize the optimization design. This optimization design is accomplished by using a simulated annealing algorithm [12] for the approximated formulation. The subject freeway model is shown as Fig. 9. FTT denotes the number of delayed vehicles in the freeway, ATT/ATT' the number of delayed vehicles in the arterial freeway, RD the number of delayed vehicles at the ramp, S_j the traffic volume in freeway fraction j, FC_j the total capacity in freeway fraction j, and RC_j the total capacity in ramp fraction j. In addition, Q_0, c_1, and A_0 are the traffic volume of each fraction, as shown in Figs. 10 and 11. The traffic volume from each entrance ramp (E_1) is set at 10% of the arriving traffic volume (A_0). A delayed vehicle is defined as one having a speed of less than 5 km/hr. The traffic inflow to the urban freeway or arterial freeway is shown in Fig. 12 and the detailed data are presented in Table 1.

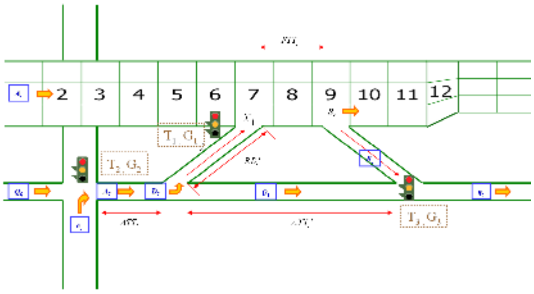

Fig. 9. Test freeway layout.

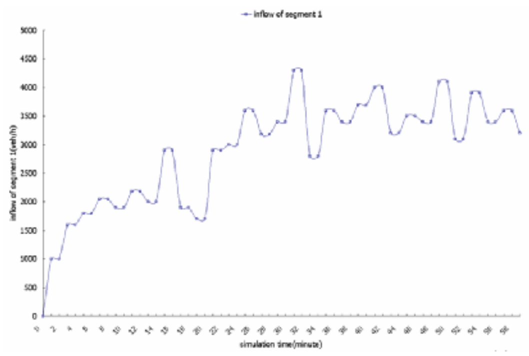

Fig. 10. Incoming traffic flows: inflow of segment 1.

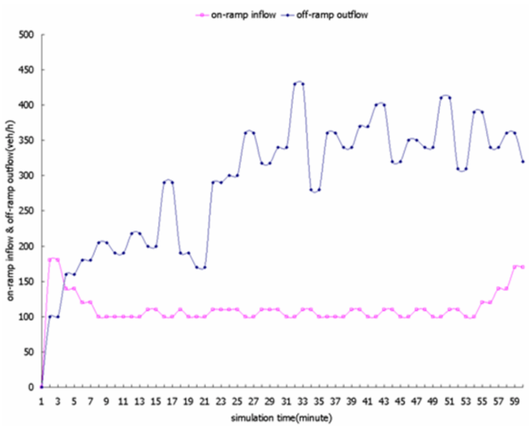

Fig. 11. Incoming traffic flows: on-ramp inflow and off-ramp outflow.

Table 1. Incoming traffic flow.

Time (min.)	A_0	Q_0	c_1	D_1
1	1000	135	45	180
2	1000	135	45	180
3	1600	105	35	140
4	1600	105	35	140
…	…	…	…	…
60	3200	128	43	171

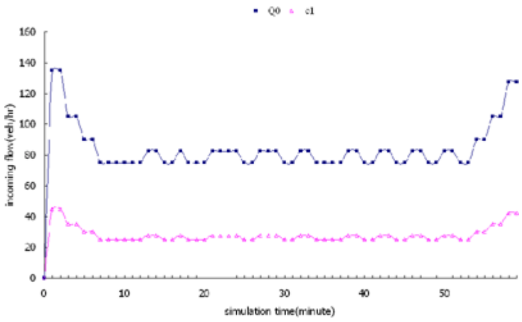

Fig. 12. Incoming traffic flows from arterials.

5. Conclusion

The purpose of this research was to achieve the integrated control of an urban freeway axis by using the forecasting results of the urban freeway traffic stream estimated by a newly proposed, multi-agent approach for traffic simulation, termed Multi-Agent for Traffic Simulation with Vehicle Dynamic Model (MATDYMO). This paper developed a dynamic traffic simulation system capable of incorporating different agents and situations based on MATDYMO. Situations were composed of the roads and signals, while agents consisted of the driver agent and vehicle agent. In addition, the traffic forecasting simulation was compared with the results obtained from using URFSIM in order to verify the developed simulation program. The virtual geometric structure and passing pattern of a warned situation were also investigated. The results of URFSIM and the proposed system demonstrated very similar analysis results for the traffic congestion situation. However, the proposed system generated more realistic results for easing the traffic congestion situation. Finally, this paper defined an optimization model and tried to find a method to optimize the integrated control. Optimization targets were defined to minimize the delay incurred by the ramp metering and signal cycle control in the arterial freeway, to maximize traffic volume in the urban freeway, and to optimize both of them. Subjects for all three targets were also defined. Meanwhile, integrated control optimization is performed in the related paper (Part 2: Integrated Control using Optimization Technique).

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