SOUND: A Traffic Simulation Model for Oversaturated Traffic Flow on Urban Expressways

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1. INTRODUCTION

This study develops a dynamic traffic simulation model SOUND (a Simulation model On Urban Networks with Dynamic route choice) which reproduces dynamic traffic condition such as length of traffic congestion and travel time for an oversaturated expressway network in urban areas. Importantly, we are frequently required to understand how traffic condition changes if we, for instance, construct a new route and/or alter traffic regulations. Especially, for a congested urban expressway network, we must estimate time-dependent changes of traffic to evaluate impacts of new policies and development of infrastructures.

In developing the SOUND model, special attentions are paid so that it incorporates drivers' route choice behavior and controls traffic density as a function of the flow to simulate the shockwave propagation.

2. REVIEW OF EXISTING MODELS

Since late 1970's, several traffic simulations models applicable to areawide networks incorporating drivers' route choices have been developed. SATURN (Vliet and Hall, 1991), CONTRAM (Leonard *et al.*, 1989), DYTAN (Kido *et al.*, 1978), the BOX model (Iida *et al.*, 1991), and the Block-Density model (Ueda *et al.*, 1991, Kuwahara *et al.*, 1993) are all belonging to this category. A common problem in these model is that traffic density on a link has not been controlled in relation to the traffic flow. More specifically, let's consider highway sections with large and small bottleneck capacities as shown in Fig's 1 and 2. When the capacity is large as in Fig.1, the traffic density in the upstream section is normally low compared to that with small capacity as in Fig.2. Therefore, in Fig.1, a vehicle from an on-ramp can enter in the middle of the congestion, while it must join the queue at the tail in Fig.2. Thus, depending upon the density, priorities of vehicles change. In general, on- and off- ramps on an urban expressway locate closely each other, and hence, the control of traffic density is important to maintain priorities of vehicles especially at merging points.

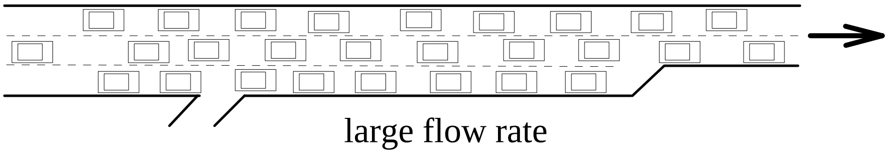

Fig.1 Large Bottleneck Capacity

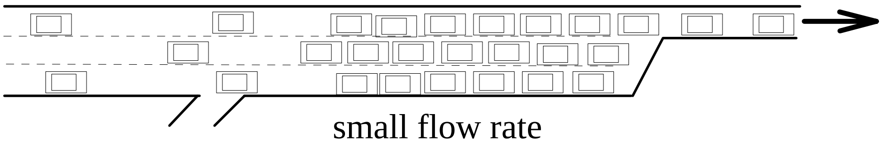

Fig.2 Small Bottleneck Capacity

The Block-Density model previously developed by us can control traffic density as in the manner described above. However, it consumes huge computer memories, since traffic density of each block of 50~60 meters must be stored by destinations of vehicles in the block. Also, these block densities must be updated at every scan interval of a few seconds, which requires substantial amount of computation time.

3. OUTLINE OF THE SOUND MODEL

As presented in Fig. 3, SOUND consists of two parts: the vehicle simulation module and route choice module. In the vehicle simulation module, travel time in each link is evaluated by moving vehicles forward along routes determined by the route choice module, whereas the route choice module evaluates every driver's route at a regular interval based on travel times estimated by the vehicle simulation module. These two modules are repeatedly implemented to reproduce dynamic evolution of traffic flow on a network. This model, therefore, does not reproduce an exact user equilibrium flow but approximately describes the equilibrium flow dynamically.

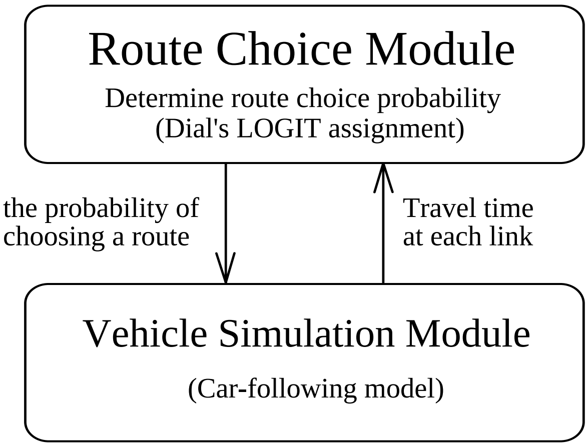

Fig.3 Model Structure

3.1. Vehicle Simulation Module

(1) Car-following Model

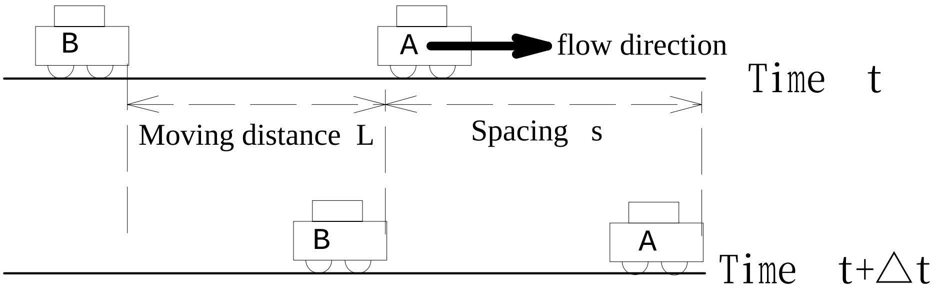

Fig.4 The Car-Following Method

In the vehicle simulation module, at every scanning intervals (△t), each vehicle (or each group of several vehicles) on the network moves discretely in the order from downstream of each link based on the pre-specified flow-density relationship (q-k curve). Suppose two vehicles A and B run on a link at time t as shown in the upper picture of Fig.4. At time t+△t, the front vehicle A first moves by some distance as in the lower figure. In this situation, if vehicle B moves by L, the spacing between A and B becomes s at time t+△t. Since each vehicle memorizes its current position which means that the distance s+L can be known in the module, moving distance of vehicle B during scanning interval △t is calculated so that spacing s and velocity L/△t agree with the flow-density relationship pre-specified.

First of all, the volume-density relationship,

$$q = f(k), \tag{1}$$

where q = traffic flow [veh/unit time],
k = traffic density [veh/unit length],

is converted to the speed-spacing relationship as below:

$$q = k \cdot v = k \cdot 1/s = f(1/s),$$

$$\therefore \quad v = s \cdot f(1/s) \tag{2}$$

where v = vehicle speed [unit length/unit time],
s = vehicle spacing = 1/density [unit length/vehicle].

Also, since the vehicle speed is written as L/△t, Eq.(2) becomes

$$L/\triangle t = s \cdot f(1/s). \tag{3}$$

Since s + L is known, the L and s can be determined from Eq.(3).

(2) Motions at Merging and Diverging Nodes

At a merging section, we consider following two situations depending on the degree of traffic congestion:

1. No congestion
   When traffics on both upstream links are not in the congested region on the q-k curve, vehicles on each merging link can be treated independently just as on a simple section.
2. Congested
   When traffic is congested in either or both upstream link(s), vehicles on these links merge so as to maintain the prespecified merging ratio. The merging ration is here defined as a ratio of traffic when both upstream links are congested, and the ration can be determined in advance according to the geometric design at the section. For example in Fig.5, when both upstream links i and j are congested, capacities of these links are calculated as the capacity of link k multiplied by the merging-ratio. However, note that when traffic demand on either one of the links is less than the above capacity (which means the link is not congested), the surplus capacity of the link should be transferred to the another congested upstream link.

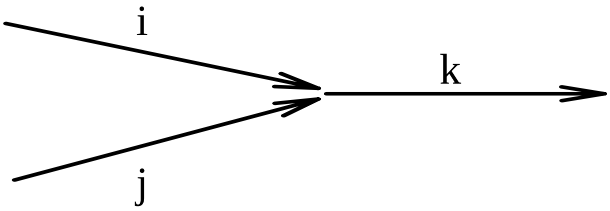

Fig.5 Illustration at a Merging Section

At a diverging section, the diverging ratios by vehicle destinations are updated based on the route choice module mentioned later. The number of vehicles to each of two downstream links are monitored by their destinations. And, when one vehicle arrives at the diverging node, it chooses one of the downstream links which has the least count for a destination of that vehicle.

(3) Evaluating Travel Time of Each Link

Each vehicle memorizes entrance and exit times of every link on the way to its destination. When a vehicle exit from a link, travel time of the link is updated as the time difference between the entrance and exit times. Consequently, travel time of a link carrying large traffic demand is more frequently updated than a link with less traffic.

3.2. Verification of Shockwave Propagation

In this section, we compare shockwave propagation estimated by the vehicle simulation module with that by the kinetic theory using a simple highway section with one bottleneck. A length of the highway section is 3000 [m] and the entire section has the same q-k relationship shown in Fig.6. However, the most downstream section has traffic capacity of only 1400 [veh/h], which becomes a bottleneck.

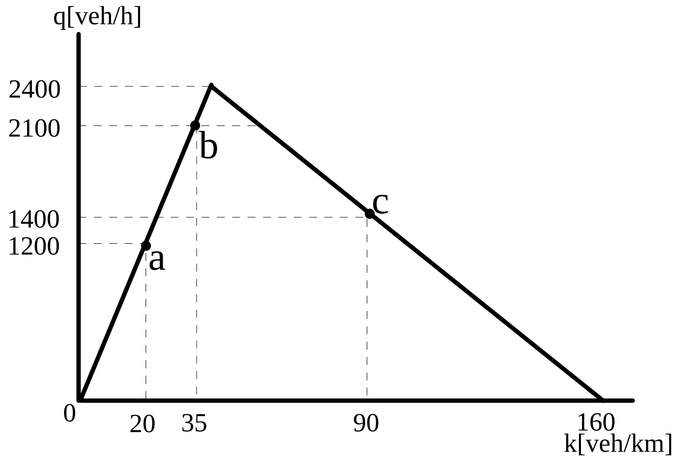

Fig.6 Flow-Density Relationship used in Verification

pattern 1 : A heavy traffic comes from upstream, arrives at the bottleneck, and then congestion occurs from the most downstream bottleneck which propagates upstream.

Assume that traffic flow is initially 1200 [veh/h] denoted as point a in Fig.7 for the entire highway section, and then traffic flow of 2100 [veh/h] denoted as point b start entering the highway at time 0. The forward shockwave 1 propagates and traffic condition of the upstream section of the shockwave shifts from a to b. After the shockwave reaches the bottleneck, the backward shockwave 2 is generated and propagate to the opposite direction. Traffic condition of the downstream section of the backward shockwave changes from b to c, since the bottleneck capacity is limited to 1400 [veh/h] less than the traffic demand of 2100 [veh/h]. Speeds of these propagation by the theory are 60 [km/h] for wave 1 and 700/55 [km/h] for wave 2, with which the simulated wave speeds well agree.

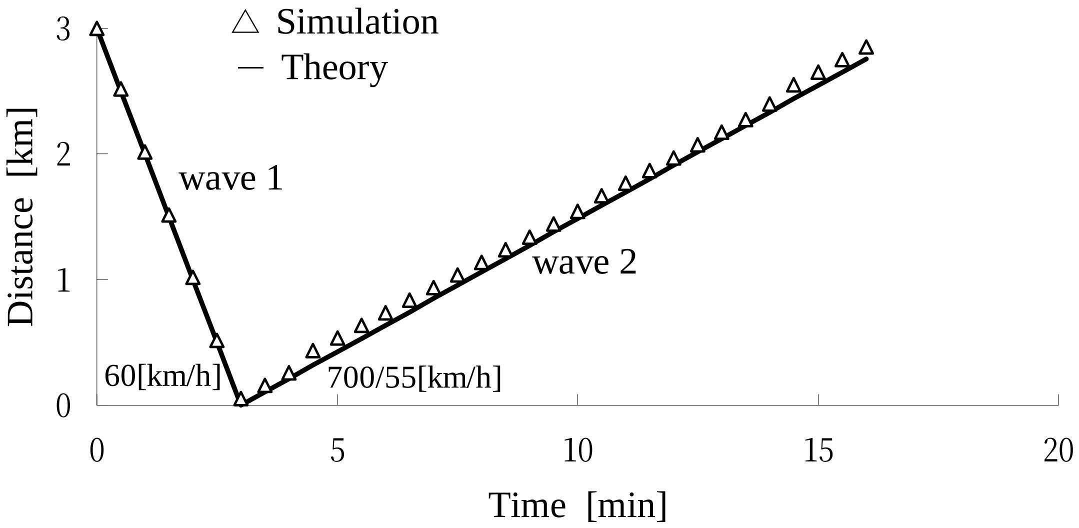

Fig.7 Result of Verification (pattern 1)

pattern 2 : Traffic congestion disappears due to the reduction of traffic demand.

Starting from condition c for the entire highway section, when traffic demand returns from

2100 [veh/h] to 1200 [veh/h], the forward shockwave 3 starts as shown in Fig.8. Traffic condition of the upstream section of the wave changes from c to a. The simulated shockwave speed exactly fits the theoretical one, 200/70 [km/h] .

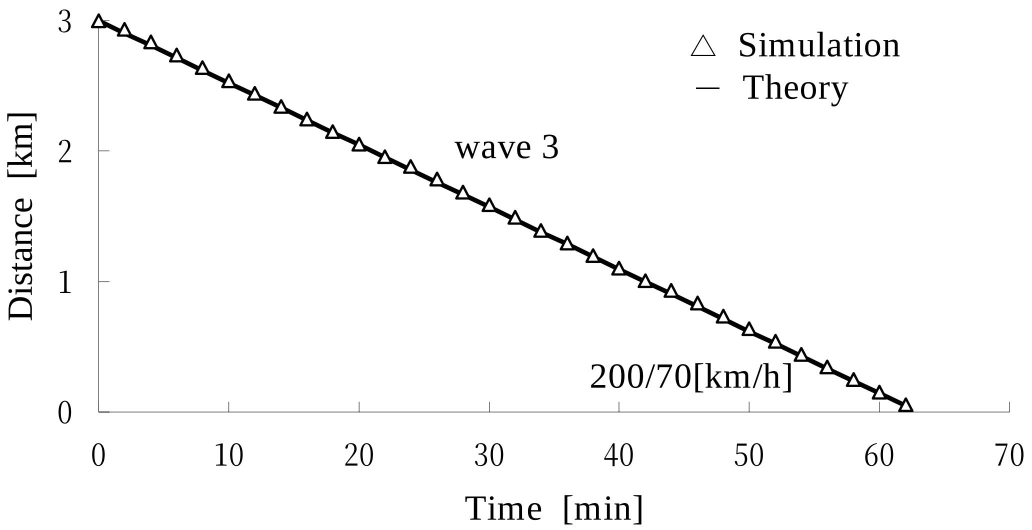

Fig.8 Result of Verification (pattern 2)

From these results, it is confirmed that the vehicle simulation module can reproduce the shockwave propagation reasonably although the time is dealt with discretely to simplify the model.

3.3. Route Choice Module

We first divide users into two groups: Route Choice Group sharing the fraction of a (0 < a < 1) who selects routes based upon time varying travel times on a network, and Fixed Route Group with fraction 1-a who does not change routes regardless of travel times.

For Route Choice Group, the route choice probabilities are updated at every ΔT ($\geq \Delta t$) interval by the Dial's Logit assignment with parameter θ shown blow based on link travel times obtained from the vehicle simulation module. On the other hand, for Fixed Route Group, the fixed probabilities are calculated similarly by the Dial assignment with the same parameter value of θ based on the free flow link travel times at speed of 60 [km/h].

$$\mathrm{Prob}(r) = \frac{\exp(-\theta \cdot T_r)}{\sum_i \exp(-\theta \cdot T_i)} \tag{4}$$

where Prob(r) = route choice probability of route r,
T_r = travel time of route r,
θ = non-negative parameter

Then, based on the determined route choice probabilities, the diverging ratio at every diverging node by destinations is reevaluated. Hence, in the vehicle simulation module, a vehicle chooses a next link to go based on the above diverging ratio. Consequently, a vehicle in Route Choice Group on the network may change the route at every ΔT.

As in the above, this model does not strictly follow the dynamic stochastic user equilibrium principle. To strictly reproduce the equilibrium, the iterative calculation of the whole study time period may the required as in CONTRAM (Leonard *et al.*, 1989) and SATURN (Vliet and Hall, 1991), which however needs a substantial amount of computer memories and computation time. For this reason, we decide to employ the above non-iterative procedure to reproduce the equilibrium flow approximately.

3.4 Validation of the SOUND Model

To examine how simulated traffic condition differs from the strict stochastic user equilibrium flow, several test runs are made using a simple network as shown in Fig.9 with scan interval Δt of 1 second and ΔT of 10 seconds. The flow-density relationships are assumed as in Fig.10 in which the free flow travel speed is 60 [km/h] and the slope in the congested region are 20 [km/h] for every link. However, since the capacity of link 4 is 2400 [veh/h] which is smaller than those of other links (= 4200 [veh/h]), the merging node C becomes bottleneck, where the merging ratio of link 1 to 2 is assumed 1:1.

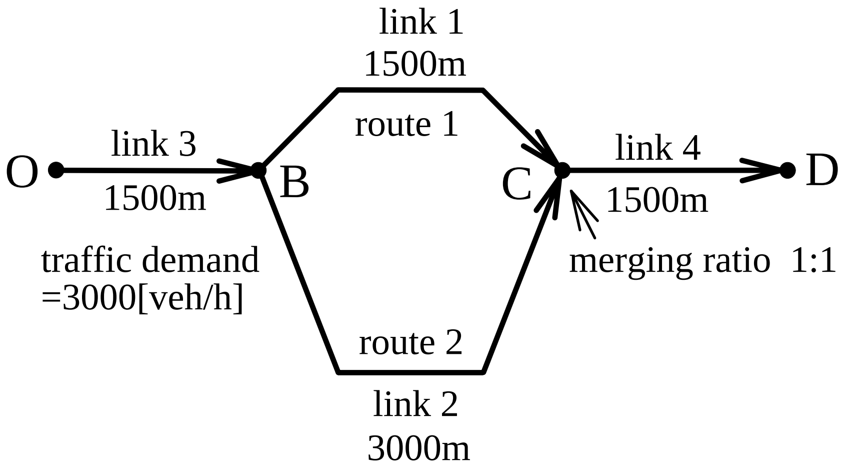

Fig.9 A Simple Network used to Validation

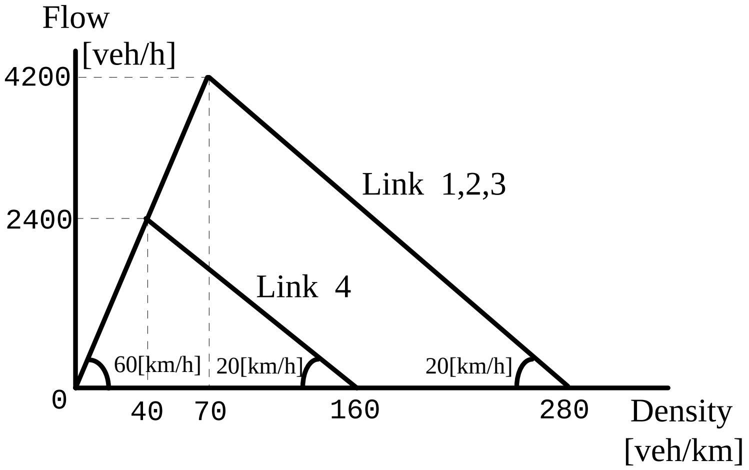

Fig.10 Flow-Density Relationship used to Validation

The parameter θ is set as the following two values:

1. $\theta = \infty$ (a vehicle in the choice group chooses the shortest route to its destination),
2. $\theta = 0.011$ [1/sec].

Fig.11 shows how the choice probability generally sensitive to the parameter value. Also, all vehicles are assumed to belong to the choice group; that is, α=1.

For θ=∞, if the demand of 3000 [veh/h] is loaded from the origin, at first every vehicle chooses route 1 because of the shorter travel distance of 1500 [m] on link 1. However, mean while, traffic congestion starts from C on link 1 and at some time, travel time on route 1 becomes equal to that on route 2. From that time, the same amount of demands are assigned on the both routes so as to maintain the equilibrium.

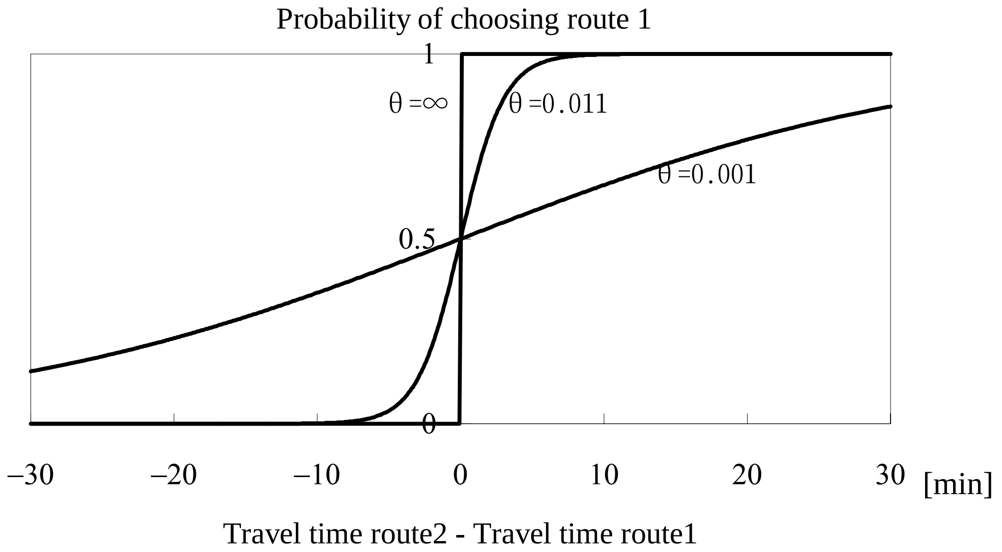

Fig.11 Sensitivity of Route Choice Probability to Dial's Parameter θ

Fig.12 shows the cumulative departure curves from node B on routes in the above situation. The simulated values is oscillating compared to the strict equilibrium for the following reason. In the strict equilibrium, a vehicle chooses its route based upon the actually experienced travel time; on the other hand, in the simulation, the assignment is made based on the current instantaneous travel times when a vehicle passes B. For example, if travel time on one route is smaller than the another and the demand is assigned on the shorter route, actually the travel time gets longer due to the newly loaded demand. In the strict equilibrium, the diverging ratio at B is determined by taking the above effect into consideration. However, in the simulation, the effect is not fully incorporated and hence more demand tends to be assigned on the shorter route which causes the oscillation.

[veh]

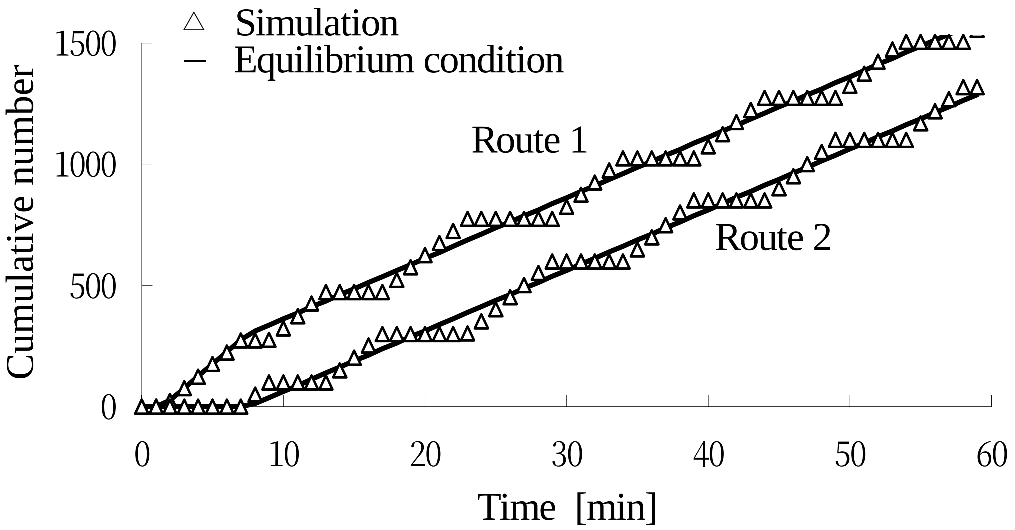

Fig.12 Comparison of the Cumulative Number of Vehicles entering each Route at Merging Node B ($\theta = \infty$)

Fig.13 shows the same cumulative vehicles for θ=0.011. Although the oscillation also appears in this case, the amplitude is much smaller. This is because the amount of demand more than necessary assigned on the shorter route is smaller under the stochastic equilibrium than under the user equilibrium ($\theta = \infty$). In spite of the local oscillation, the simulated values seem to globally follow the strict equilibrium in both cases. For a more precise reproduction, we should improve the evaluation of travel times not just based on the instantaneous travel times but predicted travel times in near future.

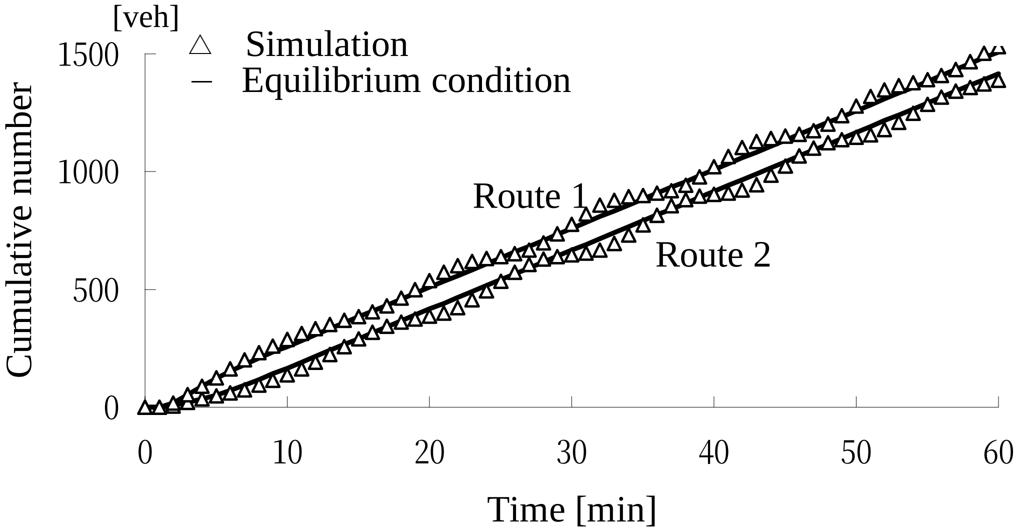

Fig.13 Comparison of the Cumulative Number of Vehicles entering each Route at Merging Node B (θ = 0.011)

4. APPLICATIONS TO METROPOLITAN EXPRESSWAY

4.1 A Case without Route Choices

In the previous section, we learn that the model can reasonably reproduce the shockwave propagation as well as the route choice behavior. Here, we first apply the model to the 12-km highway section from Yoga to Tanimachi on Route 3 as a case without route choices.

As the input data, the model requires the time-dependent OD demand between every on and off ramps along Route 3, the flow-density relationship of every link, and the merging ratio at every merging node. The OD demand can be obtained in every one-hour period from the OD survey conducted by the public corporation and the other input data have been observed by traffic detectors.

Fig.14 compares the observed travel time from Yoga to Tanimachi with the simulated time. In this study, the observed travel time is obtained from the average travel time measured by traffic detectors installed about every 300 meters along Route 3. Without route choices, the model seems to well reproduce the observed travel time.

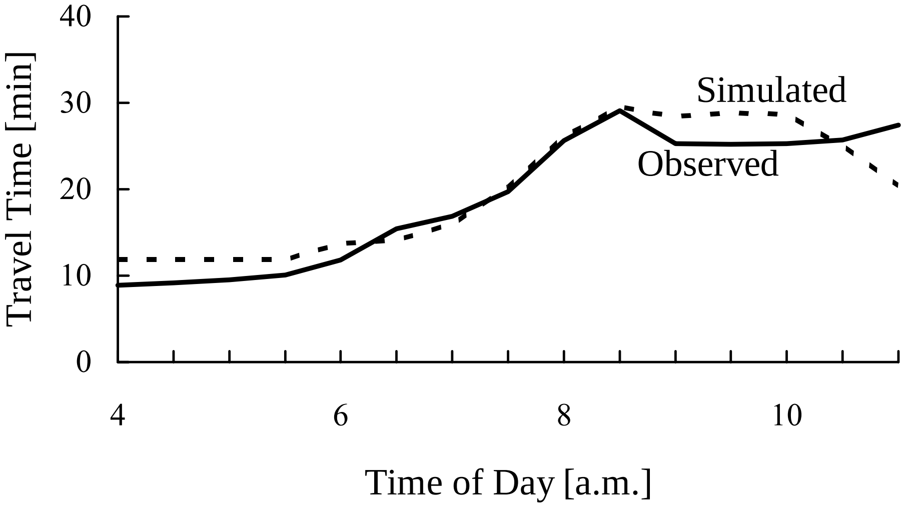

Fig.14 Comparison of Travel Time (from Youga to Tanimachi)

4.2. A Case with Route Choices

Next, the model is applied to a whole network of the Metropolitan expressway where several alternative routes exist for each of the OD pairs. The Metropolitan expressway is an about 200-km length and approximately carries 1 million vehicle trips per day. To include the route choice module, Dial's parameter θ and a fraction of Route Choice Group α must be additionally specified. Figures 15 and 16 show the simulation result with various combination of θ and α, in which the vertical axis shows the total absolute difference in travel times between observed and simulated values. During the simulation period from 4 am. to 11 am, about 350 thousands vehicle trips are generated and they spend the total travel time of 10 million minutes. In the simulation, the total travel time is about 11 million minutes which means 10% larger, but as shown in the figures, the difference in the travel time appears more than 3 million minutes for all the combinations of θ and α because it counts the absolute values of the travel time difference.

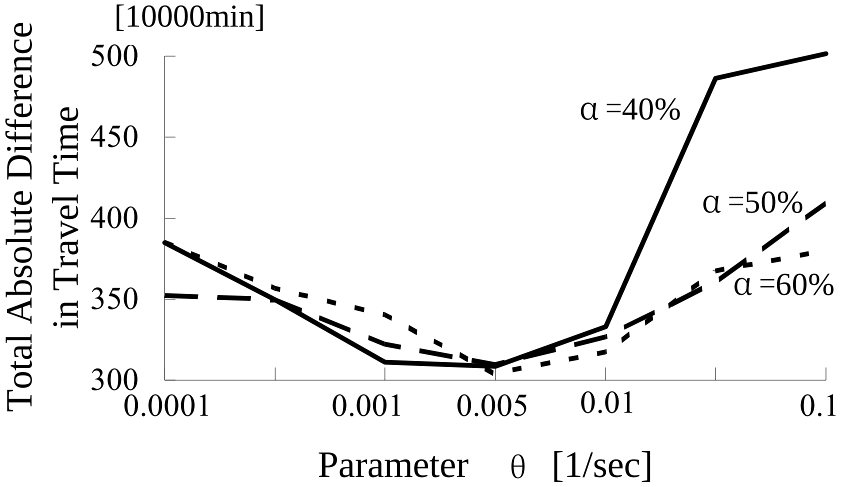

Fig.15 **Changes of Travel Time depending on Dial's Parameters θ**

From Fig.15 and 16, we see that the optimum value of θ is around 0.001 to 0.005 [1/sec] and the optimum fraction of Route Choice Group α seems about 60%, which agrees with the result estimated by a separate research based on an interview survey.

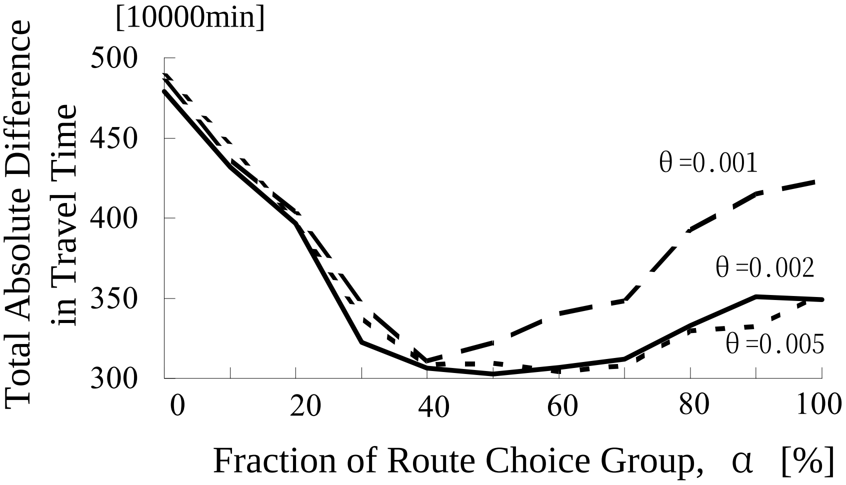

Fig.16 Changes of Travel Time depending upon the Fraction α

Figures 17 and 18 shows the observed and simulated average travel speed by each link during 8 to 10 am. The correlation coefficient is 0.81 and the average difference in the speed is 3.5 [km/h].

5. SUMMARY AND FUTURE RESEARCH NEEDS

This study is briefly summarized as follows:

1) This study develops a dynamic simulation model SOUND which incorporating drivers' route choice behavior.

2) The model consists of the vehicle simulation and route choice modules, which are alternatively implemented in short time intervals to approximately reproduce the dynamic stochastic user equilibrium flow.

3)For the vehicle simulation module, we particularly pay attention to shockwave propagation. According to several examinations on the wave propagation using a simple network, the simulated wave speed well fits with the theory.

4) As a case without route choices, we apply the model to Route 3 of the Metropolitan expressway and see that the simulated traffic condition reasonably agree with the observed one.

5) Finally, the model applications to the entire network of the expressway reveals that the fraction of Route Choice Group is about 60% and the simulated travel time and speed show similar values of observed ones.

For the future research, the followings are required to improve the SOUND model:

1) For the route choice module, the evaluation of travel time should be further analyzed so as to describe drivers' choice behaviors.

2) For the traffic simulation module,
   - capacity reduction at a diverging node due to complex vehicle motions such as lane changing should be investigated,

━━━ above 40km/h

- - - - under 40km/h

Fig.17 Average Speed at each Link (Observed)

━━━ above 40km/h

- - - - under 40km/h

Fig.18 Average Speed at each Link (Simulated)

- the model should consider vehicle types such as trucks, passenger cars, and so on,
- variation in capacity at bottlenecks due to congestion should be included, and
- vehicle motions in surface streets with signalized intersections should be modeled.

ACKNOWLEDGMENTS

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