EVALUATION METHOD OF DYNAMIC TRAFFIC OPERATION AND A CASE STUDY ON VARIABLE CHANNELIZATION FOR MERGING SECTIONS

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ABSTRACT

This paper presents an evaluation method of dynamic traffic operation. The method is to use two traffic simulation models of different scales for analyzing the effect of the operation on the local area and the whole road network systematically. As a case study using the method, variable channelization is tested for Tokyo Metropolitan Expressway, which is an urban expressway network. The result shows that, even if a channelization scenario which seems to be the optimum for a subject local section, it can negatively affect the whole network. Therefore, the method is considered to be effective, and it is expected that the method can be adopted for the evaluation of dynamic channelization, which changes the channelization automatically according to the traffic condition.

Keywords: Dynamic Traffic Operation, Variable Channelization, Merging Section, ITS

1. INTRODUCTION

Traffic demand fluctuates time to time, day to day, and season to season. It makes traffic engineers negotiate with which level of traffic demand should be taken into account for determining necessary traffic capacity when designing a traffic facility. For this, most road design manuals, such as Highway Capacity Manual (2000), use peak-hour factor and k-value. The use of those values is reasonable from economic aspects. However, there are still many hours in a year when traffic demand exceeds the capacity calculated based on the concept of those values. It is also difficult to forecast exactly future traffic demand and its hourly fluctuation. Concerning this problem, variable traffic operation can be a good solution which changes traffic operation as scheduled considering the fluctuation of traffic demand. Furthermore, dynamic traffic operation enables the variation of traffic operation automatically in accordance with the fluctuation of traffic condition. However, even if a scenario of a variable traffic operation strategy is effective for a subject area and a traffic condition, it never guarantees the improvement of overall traffic performance in the whole road network. Therefore, it is essential to check the effect of a variable or dynamic traffic operation strategy on not only the subject local area but also the whole network.

In this paper, we focus on variable channelization for merging sections in an urban expressway network. The variable channelization is a traffic operation strategy which changes the number of lanes of each approach on a merging section as scheduled considering the traffic condition (giving more lanes to an approach of which the traffic demand is more than that of the other approach). This operation has already been adopted in several countries. However, as mentioned above, the best variable channelization strategy for a local area does not always guarantee the improvement of the traffic performance in the whole road network, especially a complicated network with one or more circular routes. Therefore, this paper proposes a performance evaluation method for dynamic traffic operation which takes into account the problem and presents a result of a case study which applied the method to a variable channelization strategy for an urban expressway network. The case study was performed for a pre-scheduled variable channelization. However, the performance evaluation method is applicable to the evaluation of a dynamic channelization which changes the channelization automatically in accordance with the variation of traffic condition and, furthermore, any dynamic traffic operation which requires examination of the effect on the whole road network.

2. METHODOLOGY

2.1 Performance Evaluation Method

The concept of the evaluation method for variable channelization we propose is to use two traffic simulation models of which scales are different for analyzing the effects on the local area and on the whole road network. In details, microscopic traffic simulation is used for the analysis of the traffic performance on merging sections where the variable channelization is to be applied, which is resulted by behavioural changes of individual drivers. Then, macroscopic or mesoscopic simulation is used for the network analysis of which initial parameters or data are modified and applied based on the microscopic simulation result. This concept is easy to apply and simple to understand, since the relationship between the effects of the variable channelization strategy on the local area and the whole network is clear.

Generally, macroscopic or mesoscopic simulation needs initial parameters including link and node data as well as OD volume. Among them, parameters which can reflect the change of scenarios of any dynamic traffic operation strategy might be traffic capacity or maximum discharge rate of the subject local area where the strategy is applied. In case of variable channelization, the parameter should be maximum discharge rate of each approach on a merging section. Therefore, what we need from the microscopic simulation as a result should be maximum discharge rates of each approach on each subject merging section for each channelization scenario. At the same time, the macroscopic or mesoscopic simulator must be able to change the values during the simulation. Figure 1 depicts the evaluation method for variable channelization, and requirements of the two traffic simulators for this method are summarized in Table 1.

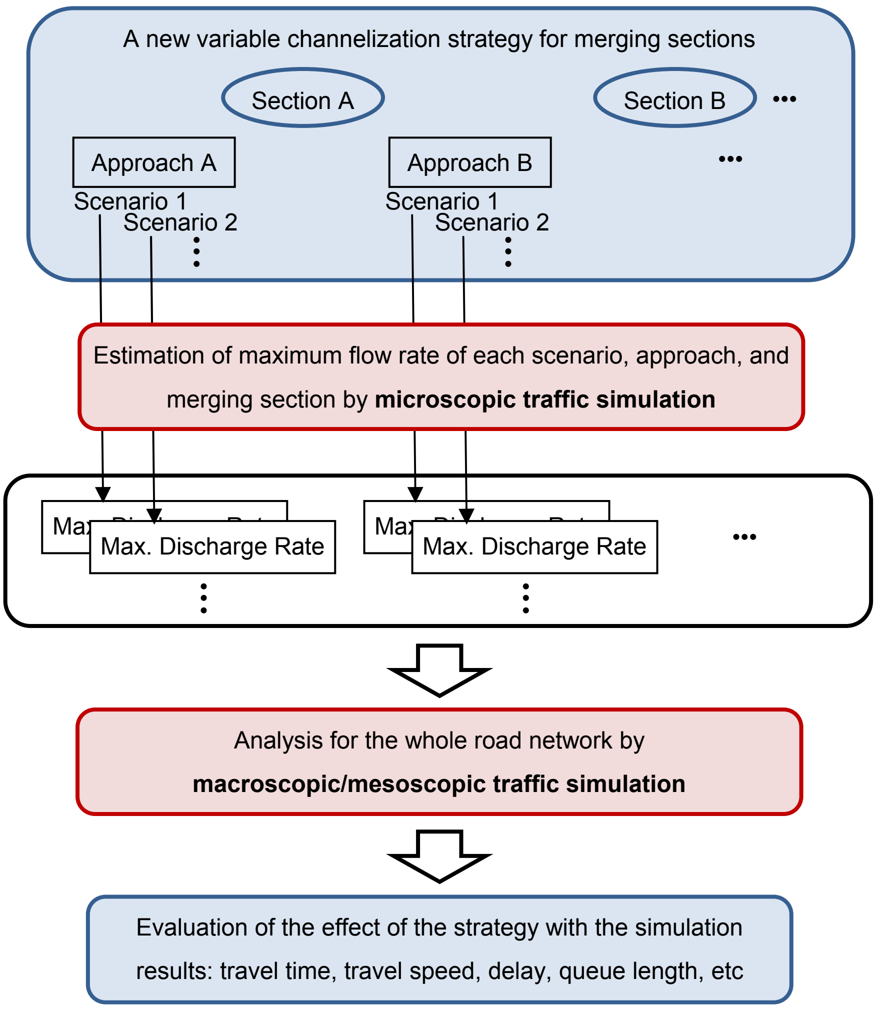


Figure 1 – Concept of the Evaluation Method of Variable Channelization

Table I – Requirements of the Traffic Simulators

Microscopic traffic simulator
· Reproduction of traffic flow condition for any scenario of dynamic traffic operation · Reproduction of lane-change behaviour · Reproduction of car-following behaviour
Macroscopic or mesoscopic traffic simulator
· Coverage of the whole subject road network · Capable for changes of related parameter values during simulation · Capable for changes of route choice

2.2 Case Study

As a case study, variable channelization at three merging sections of Metropolitan Expressway (MEX) is examined in this paper. MEX is an urban toll expressway network of Tokyo, the capital of Japan, and Yokohama of which length in total is 322.5 km. MEX consists of one complete circular route (Route C1, 14.8 km), one incomplete circular route (Route C2, 16.8 km out of 49.9 km under construction), and several radial routes as depicted in Figure 2.

MEX is the busiest urban expressway network in Japan used by 1.15 million vehicles per day in average (in July, 2009). Route C1 is always congested in daytime because of the concentration of the traffic towards downtown Tokyo and the through traffic. In order to minimize traffic congestion and maximize the efficiency of traffic operation, variable channelization at several junctions of Route C1 has been examined so far. With this background, three merging sections of Hamazakibashi, Ichinohashi, and Tanimachi on Route C1 were selected for the case study (see also Figure 2). They are junctions connecting Route C1 with Route 1 (Haneda Line), Route 2 (Meguro Line), and Route 3 (Shibuya Line), respectively. However, only one merging section of each junction is used in this study. Those are depicted in Figure 3.

The number of lanes of Route C1, 1, 2, 3, and almost all the MEX routes is two per direction. The number of lanes on the merging side is one at Tanimachi (left-side merge) and Ichinohashi (right-side merge) and two at Hamazakibashi (left-side merge). The lane widths are all 3.25 m. The length of acceleration lane is 110 m from the physical nose to the end of the taper for the three merging sections. It is worth reminding that vehicles travel on the left side of roads in Japan.

Using the evaluation method proposed in this paper, analysis for the local sections will be carried out, which is to estimate maximum discharge rates of merging side and Route C1 for each merging sections and each channelization scenario by using microscopic simulation for the first step. Then, analysis for the network will be carried out, which is to evaluate the effect of the variable channelization on the whole MEX network by using macroscopic (or mesoscopic) simulation for the second step.

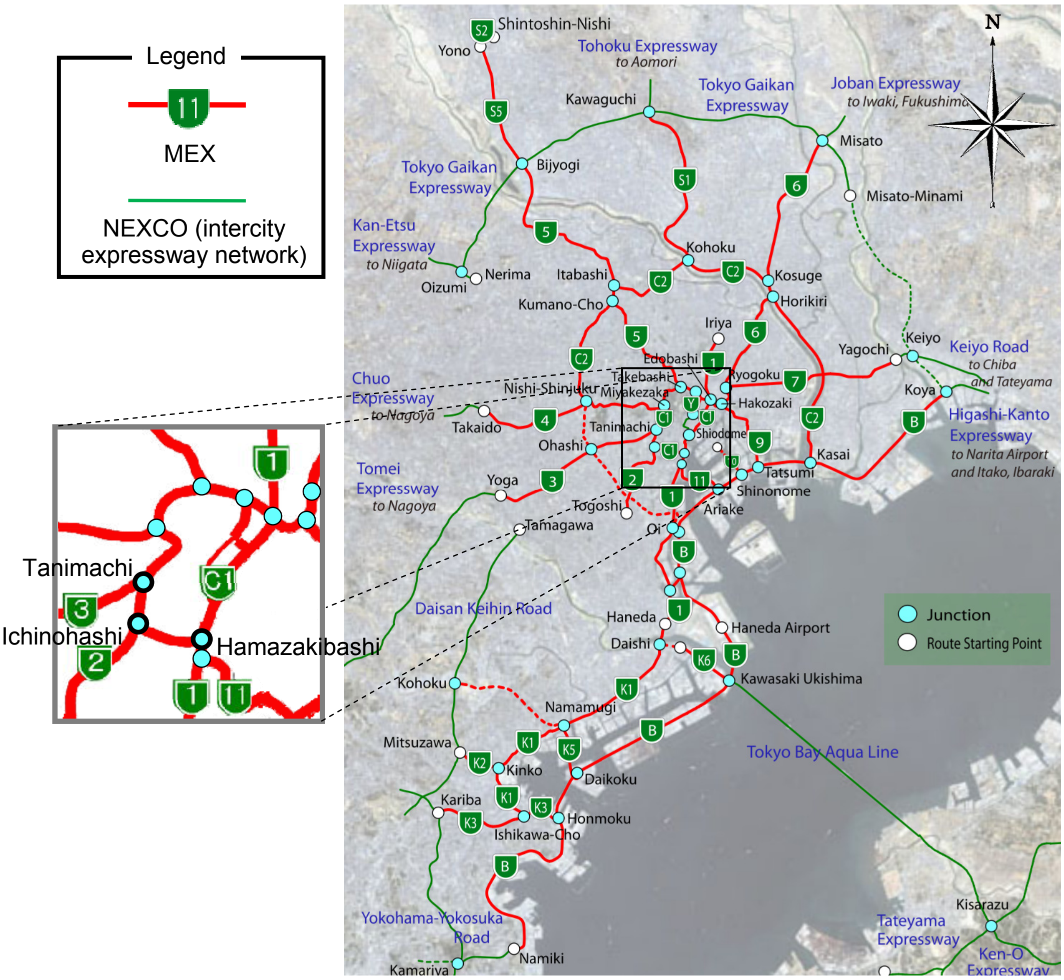
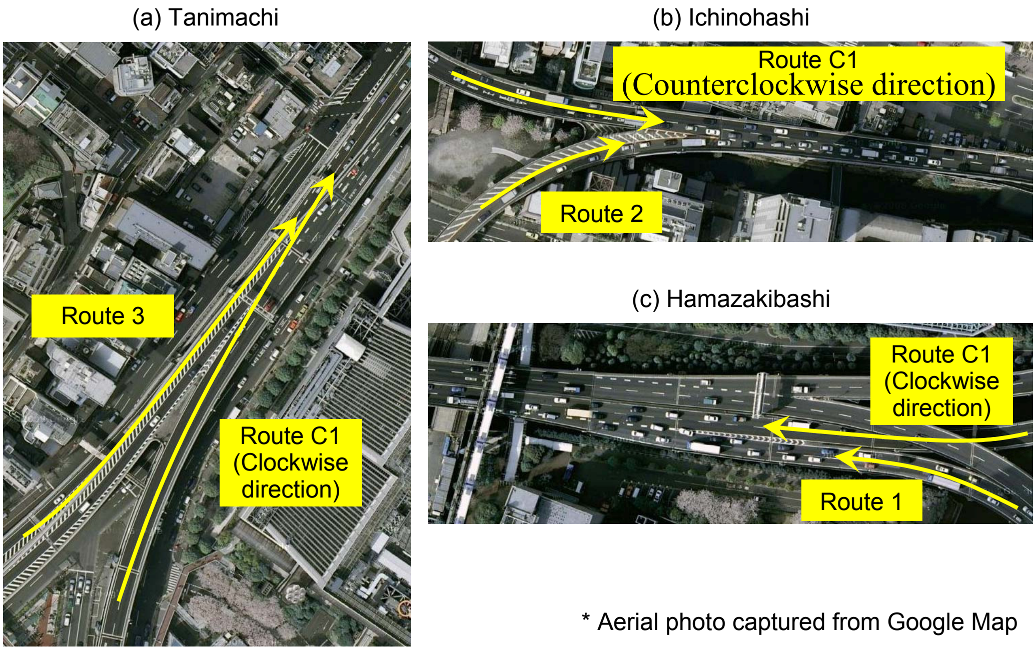


Figure 2 – Tokyo Metropolitan Expressway (MEX) Network in Tokyo and Yokohama, Japan



* Aerial photo captured from Google Map

Figure 3 – Merging Sections Chosen for the Case Study: Tanimachi, Ichinohashi, and Hamazakibashi

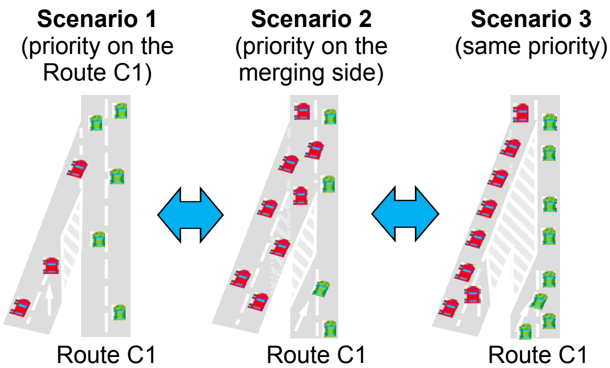
3. ANALYSIS FOR LOCAL SECTION

3.1 Simulation Model

The simulator used for this analysis is KAKUMO, which was developed by Institute of Industrial Science, the University of Tokyo. KAKUMO performs microscopic simulation based on car-following and lane-changing models and reproduces vehicular dynamics including acceleration/deceleration (Kuwahara et al., 2005; Suda et al., 2005). Therefore, it is considered that KAKUMO satisfies the requirements mentioned in Table 1 and is suitable for this analysis.

3.2 Variable Channelization Scenario

The ramps of each merging side of the three merging sections were originally designed and constructed for two-lane structures. However, the approaches merging into Route C1 at Ichinohashi and Tanimachi have been operated as one-lane channelization (two-lane merging into the left lane of Route C1 at Hamazakibashi). The number of lanes of Route C1 is two, as mentioned in section 2.2. These are the current channelization for the traffic operation of the merging sections. Let us define it as scenario 1 of the variable channelization scenarios in this paper (see Figure 4). As Scenario 2, a scenario with two-lane merging and one-lane reduction at Route 1 side is defined. In this scenario, merging vehicles from Route 1, 2, and 3 have priority against vehicles on Route C1. Scenario 3 is a channelization scenario with one lane from each side. For this scenario, it is necessary to reduce one lane at the upstream of each side (Also see Figure 4 for Scenario 2 and 3).



Note. 1. Scenario 1 represents the current channelization.
2. The number of lanes for the merging side for Scenario 1 of Hamazakibashi is two, but the priority is on Route C1.
3. Ichinohashi is right-side merging.

Figure 4 – Variable Channelization Scenario

Intuitively, Scenario 1 would be applied when the traffic demand on Route C1 is more than that on the merging side, Scenario 2 for the opposite case, and Scenario 3 when the traffic demands of both sides are similar, if the traffic condition of only local sections is taken into account for the variable channelization strategy.

3.3 Model Parameter Calibration

The purpose of the microscopic traffic simulation is to estimate the maximum discharge rates for each approach of the merging sections which are used for the macroscopic (or mesoscopic) simulation in the next step. However, because the simulator in this study, KAKUMO, is not specialized for merging sections, it is essential to calibrate parameters of several models of KAKUMO.

The calibration was conducted with two aspects of driving behaviour as same as Sarvi did (Sarvi, 2000). One is the relationship between spacing and speed. For this aspect, parameters of the car-following model were calibrated based on the traffic data observed by Sarvi. The other is aggressive sudden lane change from a lane closer to the merging side to the other lane on Route C1 which is often observed at the upstream of Route C1 just before the merging section in order to avoid more delay caused by merging. It is also observed that merging vehicles change their lane just after completing their merging into Route C1. For this aspect, parameters of the lane-changing model were calibrated based on the same traffic data.

3.4 Simulation Result

By applying the calibrated parameters to KAKUMO, the maximum discharge rates were estimated for each approach, merging section, and scenario by simulation. The vehicle type used in the simulation is only passenger car. Maximum discharge rate may change depending on the traffic condition of merging section. This must be examined and reflected to a macroscopic/mesoscopic simulation for the network analysis, and they are considered in the future works. In this paper, maximum discharge rate is estimated under the condition that traffic demands from both approaches of a merging section are enough to make queues on each approach, which is often observed at the three merging sections. The sum of the maximum discharge rates of both approaches would be traffic capacity of the subject merging section.

The simulation result is shown in Table 2. As mentioned, Scenario 1 represents the current channelization. The maximum discharge rate of the merging side of Hamazakibashi is greater than that of Ichinohashi or Tanimachi, because the number of lanes is two. However, that is less than the double of the maximum discharge rate of merging side of Ichinohashi or Tanimachi, because the vehicles from both lanes of the merging side should merge into the same single lane, the left lane of Route C1. Instead, the maximum discharge rate of the Route C1 side is less than that of Route C1 of Ichinohashi or Tanimachi. The capacity of

Hamazakibashi is approximately 200-300 pcu/h greater than that of Ichinohashi or Tanimachi. Considering safety issue, however, it is difficult to conclude that two-lane merging into Route C1 is better. Also, less maximum discharge rate for Route C1 side and more congestion on the route can possibly reduce the traffic performance of whole Route C1 and, in addition, radial routes connected to Route C1.

Scenario 2 is an opposite channelization pattern of Scenario 1. Therefore, the result shows that the capacity by Scenario 2 is not much different from the capacity by Scenario 1, but the maximum discharge rates of merging side and Route C1 side are exchanged. In Scenario 3, maximum discharge rates of both approaches are almost the same, because the congested traffic condition for both approaches is applied. The maximum discharge rate of one approach is as same as the capacity of the upstream bottleneck where the number of lanes is reduced from two to one. It is considered that a reasonable result is obtained, and the values are applied to a macroscopic simulator for the network analysis.

Table 2 – Maximum Discharge Rate Estimated from a Microscopic Simulation (pcu/h)

	Hamazakibashi		Ichinohashi		Tanimachi	
	Route C1	merging	Route C1	merging	Route C1	Merging
Scenario 1	2,266	1,531	2,609	951	2,540	968
	3,797		3,560		3,508	
Scenario 2	984	2,791	968	2,540	951	2,609
	3,775		3,508		3,560	
Scenario 3	1,953	1,955	1,826	1,813	1,812	1,826
	3,908		3,639		3,638	

4. ANALYSIS FOR NETWORK

4.1 Simulation Model

The simulator used for this analysis is SOUND (a Simulation model On Urban Networks with Dynamic route choice), which was developed by Institute of Industrial Science, the University of Tokyo. SOUND performs a mesoscopic traffic simulation, which treats traffic at individual-vehicle level and reproduces shockwave propagation (Yoshii and Kuwahara, 1995) with a route-choice model using Dial's logit assignment. Despite the relatively detailed simulation, it can cover a road network within a radius of approximately 50 km by ordinary personal computer. It has been already proved that the whole Tokyo metropolitan road network can be simulated by SOUND (Tamamoto et al., 2004). For this study, SOUND has been modified to be capable for changing discharge rates of merging section as scheduled during simulation. Therefore, it is considered that SOUND satisfies the requirements of a simulator for the network analysis mentioned in Table 1.

4.2 Simulation

Since three channelization scenarios are being considered for three merging sections, 27 combinations are possible for one time interval. Therefore, an optimum variable channelization strategy would be the sequence of those combinations which provides the best traffic performance of the network. The method how the optimum channelization was estimated will be described in this section, and the result will be shown in the next section. In addition, simulation results with fixed channelization for the 27 combinations will be shown to discuss about the simulation result of the optimum channelization. In this paper, we define, for example, 'case 312' as a combination of scenario 3, 1, and 2 for Hamazakibashi, Ichinohashi, and Tanimachi, respectively. Therefore, the simulation result with fixed channelization for case 111 will be the reproduction of current traffic condition of MEX.

The simulation time is 24 hours from 04:00 to 04:00 on the next day. The OD table used in the simulation was made from ETC (Electronic Toll Collection) data of MEX collected in March of 2008. The ETC data has information about on-ramp/off-ramp and entrance/exit time of every ETC user, and the ETC users were 79.1% of all the MEX users for the one month in March, 2008. Therefore, it is expected that the OD table applied to the simulation generates vehicles considerably close to the real world during the 24 hours. For link and node data, such as length, free-flow speed, capacity, jam density, number of lanes, etc for each link, dataset which have been calibrated previously are used.

4.2.1 Simulation for Fixed Channelization

Each case was simulated for 24 hours with fixed channelization for the 27 combinations. The performance measure is total queue length (km), which is the sum of queue length values estimated at each link of the MEX network. Here, queue length of a link at time *t* is calculated as follows.

$$Q_{\lambda,t,c} = q_{d,\lambda,t,c} / k_{j,\lambda} \qquad \text{Equation 1}$$

Here, $Q_{\lambda,t,c}$ = queue length of link λ at time t when case is c (km)
$q_{d,\lambda,t,c}$ = number of vehicles on link λ of which speeds are less than the free-flow speed of link λ at time t when case is c (pcu)
$k_{j,\lambda}$ = jam density of link λ (pcu/km)
c = channelization case, 1 to 27 (case 111~case 333)

SOUND calculates movement of vehicles by using simplified fundamental diagram which shows a triangular relationship between flow and density and is given to each link. Therefore, vehicular speeds on a link are all the same as the free-flow speed of the link under the uncongested condition and decreases under the congested condition as the density increases. Therefore, Equation 1 assumes that a vehicle of which speed is less than the free-flow speed on a link forms a queue and calculates the queue length at time *t*. The total queue length of the network at time *t* is calculated by the following equation.

$$Q_{t,c} = \sum_{\lambda} Q_{\lambda,t,c} \qquad \text{Equation 2}$$

Here, $Q_{t,c}$ = total queue length at time *t* when case is *c* (km)

It should be reminded that a traffic condition of a link at time *t* is a result of the variations of traffic demand and the traffic condition. Therefore, a macroscopic simulation should be performed from time 1 to time *t* for the estimation of $Q_{\lambda,t,c}$ and, consequently, $Q_{t,c}$.

4.2.2 Simulation for Variable Channelization

This section describes how an optimum variable channelization is determined. The performance measure for the method is total queue length of the whole network as same as the measure used for the simulation with fixed channelization. The measure is calculated with the following equations.

$$Q_{\lambda,t,s} = q_{d,\lambda,t,s} / k_{j,\lambda} \qquad \text{Equation 3}$$

$$Q_{t,s} = \sum_{\lambda} Q_{\lambda,t,s} \qquad \text{Equation 4}$$

Here, $Q_{\lambda,t,s}$ = queue length of link *λ* at time *t* when case set is *s* (km)
$Q_{t,s}$ = total queue length at time *t* when case set is *s* (km)
$q_{d,\lambda,t,s}$ = number of vehicles on link *λ* of which speeds are less than the free-flow speed of link *λ* during a time interval *t* when case set is *s* (pcu)
s = case set $\{s_1, s_2, ..., s_t\}$ which is a sequence of the channelization cases (case 111~333) applied to the simulation from time 1 to time *t*

Equation 3 and 4 are almost the same as equation 1 and 2. The only difference is that equation 3 and 4 use channelization case set *s* instead of a fixed case *c*. Therefore, identifying case s_{t+1} which minimizes $Q_{t+1,s}$ at time *t*+1 among the 27 cases and updating the channelization case set *s* until *t* reaches the end of simulation are the method determining the optimum variable channelization. The update frequency is 30 minutes in this paper.

4.3 Result

4.3.1 Simulation with Current Channelization

As already mentioned, case 111 represents the current channelization of the three merging sections. Therefore, accuracy of the simulation can be evaluated comparing observation data and the simulation result of fixed channelization with case 111. The observation data used for the comparison is traffic detector data collected at every 300 m on all the links of the MEX network on March 24.

The result shows that the correlation coefficient between observed and estimated traffic volumes on each link is 0.86. Therefore, it is considered that the vehicle generation and the route choice models work well and that SOUND gives us reliable simulation results. However, the correlation coefficient between observed and estimated average speeds on each link is 0.50. It is difficult to say that the reproduction of vehicular speeds on each link is accurate. One reason might be that the simplified flow-density relationship is adopted for calculation of the vehicular movement in the SOUND model, and we should be careful in discussing the result about speeds.

4.3.2 Simulation for Fixed Channelization

Results of the simulation for fixed channelization for 27 cases are shown in Figure 5 (a). It is worth noting that the simulation result during the first one or two hours from the beginning (04:00) should not be reflected to discussion, because it takes time for generated vehicles to travel and fill the empty road network.

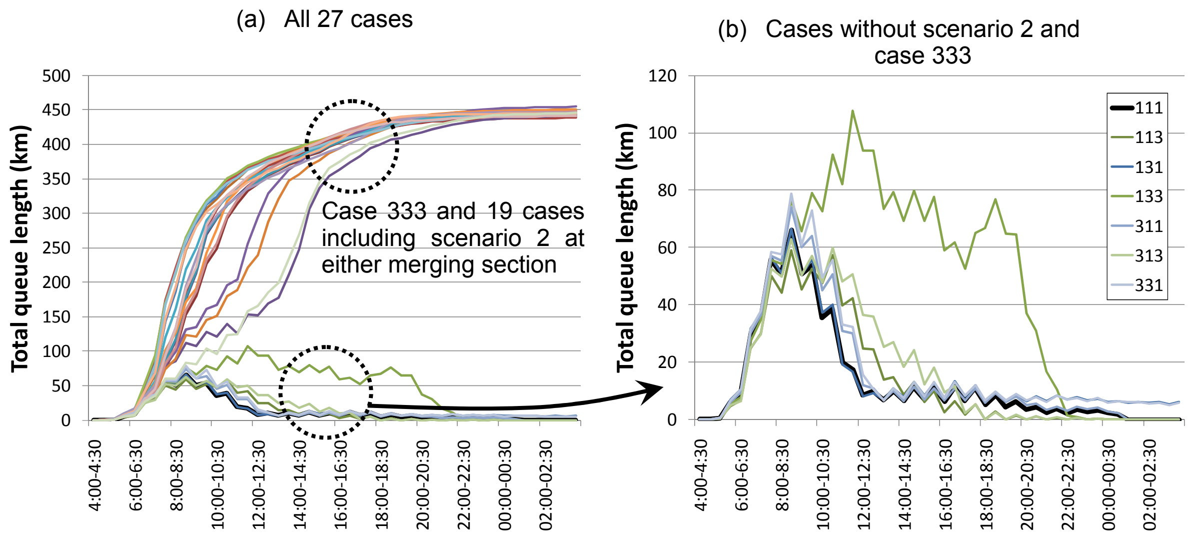
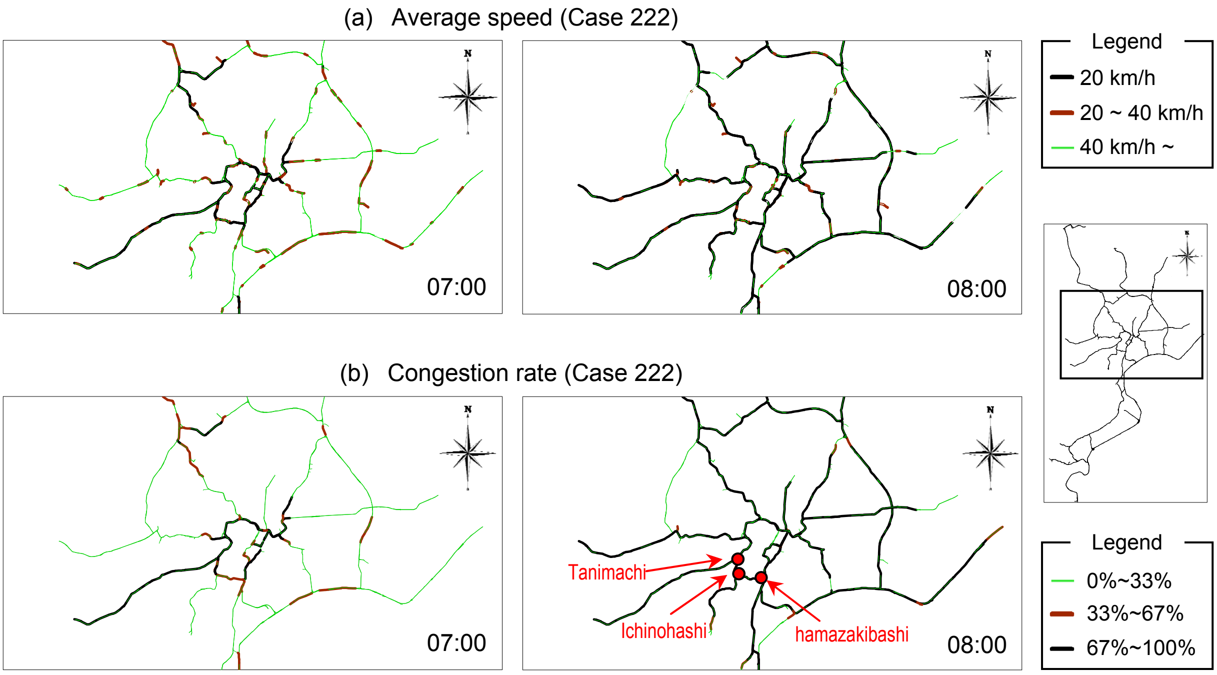


Figure 5 – Temporal Variation of Total Queue Length by Fixed Channelization for 24 Hours (27 cases)

In this figure, there are cases in which total queue length increases abnormally and continuously even after the morning peak and converges on a value around 440 km. The cases include one or more merging sections where scenario 2 is applied. The reason is that the simulation fell into gridlock condition, under which vehicles cannot move on sections of 440 km, and which is unrealistic. However, the point is what causes the gridlock. To clarify the reason, the spatial distributions of average speed and congestion rate were examined by using MapInfo. Congestion rate, in this paper, is defined as the ratio of queue length on a link against the link length. The result is that steep increase of traffic flow on Route C1 causes severe congestion on itself and other radial routes. Here, the reason of the steep increase of traffic flow on Route C1 is scenario 2, which impedes the flow on the circular route, and, consequently, impedes the flow from the radial routes connected to the subject merging sections into Route C1, even though the number of lanes for it increased to two. One example of this analysis for case 222 is shown in figure 6. From this result, it can be concluded that, considering characteristics of an expressway network with circular routes inside, scenario 2 should be applied carefully.

Figure 5 (b) is a rearrangement of Figure 5 (a) without the 20 cases. It shows that case 111 is fairly good as a fixed channelization strategy. However, in the morning time until around 10:00 and in the afternoon, after around 15:00, case 113 and case 313, respectively, show less total queue length than case 111, the current channelization. This is evident that a variable channelization strategy can improve the overall performance of MEX than operated by fixed channelization.



Note. Congestion rate (%) = queue length (km) / link length (km) × 100

Figure 6 – Average Speed (a) and Congestion Rate (b) for Case 222

4.3.3 Variable Channelization Strategy

Using Equation 3 and 4 explained in Chapter 4.3.2, the best strategy of variable channelization was investigated. Whenever one optimum case was chosen for a time interval (30 minutes of the scenario-change frequency), the simulation was repeated from the beginning according to the channelization case set *s* which had been updated until that time to find out another optimum case of the next time interval. The result is shown in figure 7 for the scenario change and in figure 8 for the temporal variation of the total queue length when the optimum variable channelization is applied.

	04:00		08:00		12:00		16:00		20:00		00:00	04:00
Hamazakibashi	1 1 2 2	1 3 1 1	1 1 1 1	1 1 3 1	3 3 1 1	3 1 3 1	1 3 3 1	3 3 3 1	3 1 1 1	3 3 3 1	1 2 3 3	3 3 3 3
Ichinohashi	3 3 1 1	1 1 1 1	1 1 3 1	1 1 1 1	3 1 1 1	3 1 1 1	3 1 3 1	3 1 3 1	3 1 3 1	3 1 1 1	1 3 3 3	3 3 3 3
Tanimachi	3 3 2 2	3 3 3 3	3 3 1 3	1 1 3 1	1 1 3 1	1 1 3 3	1 1 1 1	3 3 3 3	3 3 3 3	3 3 3 3	3 3 3 3	3 3 3 3

Figure 7 – Optimum Schedule of Scenario Change for the Variable Channelization

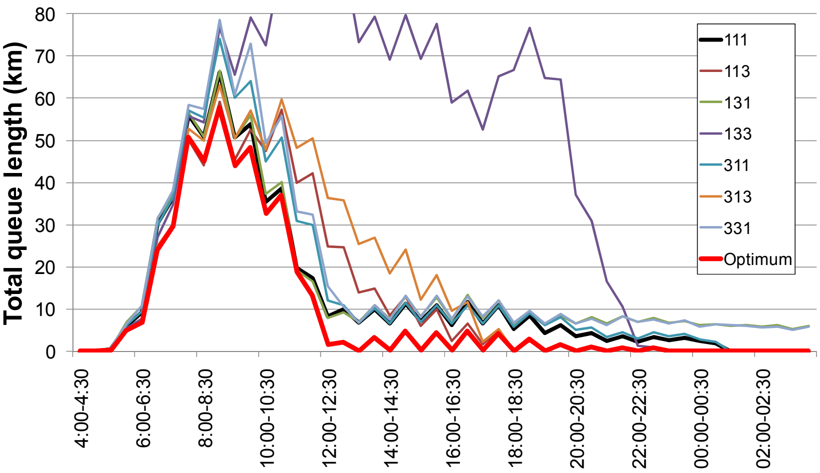


Figure 8 – Total Queue Length of the Variable Channelization and Several Fixed Channelization

Again, the result obtained until 5:00 or 6:00 should not be reflected to the discussion. What is interesting from the result is that channelization scenario 2 is adopted only once at Hamazakibashi during 0:30-1:00. It is clear that scenario 2 is not suitable even at the morning peak hours when the traffic demand from Route 1, 2, and 3 to Route C1 is increasing. The optimum variable channelization strategy shows the least total queue length at any time during the 24-hour simulation. Until around 11:00, there is no considerable difference between the total queue lengths of case 111 and the optimum variable channelization. The reason is the extreme concentration of traffic demand onto Route C1 so that applied scenarios by the optimum strategy are almost scenario 1 at Hamazakibashi and Ichinohashi. Scenario 3 applied to Tanimachi in the morning is considered to make the small difference. However, in the afternoon, the total queue length considerably decreases by using the optimum strategy.

5. CONCLUSION AND FUTURE WORK

In this paper, a performance-evaluation method for dynamic traffic operation was proposed. It is to use two traffic simulators of which scales are different for analyzing the effect of a dynamic traffic operation on not only the local area but also the whole road network. This method was applied to variable channelization for merging sections of Tokyo Metropolitan Expressway (MEX) as a case study. Given OD volumes, the optimum variable channelization strategy was determined by using the method and was shown in this paper. In the study, performance measure was total queue length of the network, which is a sum of queue lengths of each link, and the result of the study shows that the optimum variable channelization strategy for the three study merging sections can reduce the total queue length. In the morning peak, the inbound direction of all the radial routes of MEX connected to Route C1 is extremely congested. Regarding this condition, the channelization scenario 2, which gives the radial routes two lanes and reduces one lane on Route C1 at the merging sections, is considered to be effective to reduce the congestion. However, the optimum strategy rarely adopted the scenario. The reason is that the scenario impedes the flow on Route C1, a circular route, and, consequently, increases the congestion on the radial routes. Therefore, this result proves that a channelization scenario which seems to be the best for the subject merging section does not always guarantee the best traffic performance for the whole network.

The case study is about a variable channelization, of which channelization scenario changes as scheduled. However, dynamic channelization which changes the scenario automatically must be better, because it is even capable for any traffic incident. Similarly as shown in the case study, dynamic channelization can be also evaluated by using the method, if an algorithm of automatic channelization-change is applied to the macroscopic or mesoscopic traffic simulator.

For better performance-evaluation method for variable/dynamic traffic operation, the followings are recommended for future works.

- Instead of one value of maximum discharge rate, a relationship between discharge rate and traffic condition on a merging section to a macroscopic/mesoscopic simulator will be better for evaluation of a variable or dynamic channelization strategy.
- Developing and using Hybrid traffic simulation model which performs partially microscopic simulation during macroscopic simulation simultaneously will be even better for the evaluation, because details of microscopic simulation results can be reflected to the macroscopic simulation directly.
- The frequency of the channelization-scenario change should be studied considering not only the traffic performance but also safety issue.

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