Standard Verification Process for Traffic Flow Simulation Model

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Contents

Released Papers

R. Horiguchi, M. Kuwahara and T. Yoshii: *A Manual of Verification Process for Road Network Simulation Models - an Examination in Japan*, Proceedings of 7th World Congress on Intelligent Transportation Systems, Turin, 2001.

R Horiguchi and M. Kuwahara: *The Art of Utilization of Traffic Simulation Models - How Do We Make Them Be Reliable Tools?*, Proceedings of the Internatinal Symposium on Transport Simulation, August 19-20, 2002, Yokohama, Japan.

Standard Verification Process for Traffic Flow Simulation Model

～Verification Manual (Draft)～

1. Introduction

This manual describes the standard verification process used to verify the model's reproducibility of traffic conditions in the development of a traffic flow simulation model. Many traffic flow simulation models have conventionally been developed. Due to independent verification of individual models or lack of wide recognition of the verification process, comparison of models in terms of performance was impossible and users other than a developer could not select the model appropriate for their purpose. If models can be compared on a common basis or if a standard verification process can be applies, users will have a tool for judgment. This in turn will promote utilization of simulation in practical transportation impact assessments.

The model verification process is roughly divided into two stages. In one stage, the reproducibility of assumed traffic phenomena is evaluated by comparing with theoretical values the result of model application to virtual data set for frequent appearance of phenomena. In the other stage, evaluation is made to see if the model can comprehensively reproduce actual traffic conditions, including various traffic phenomena. In this paper, the former is referred to as "verification" and the latter "validation." Validation requires data on traffic demand and operation, which are inputs to simulation, and highly reliable measurement data indicating traffic conditions to be compared with the simulation result. However, data gathering has imposed a substantial burden on model developers, hindering validation. Against this background, construction of benchmark data for reproduction verification is under way, so that model developers can share it during modeling. This manual specifically deals with the standard verification process while providing only an outline of how to proceed with validation. For specific details of validation, refer to the separate "Standard Benchmark Data Set Manual (Provisional Title)."

The main purports of verification in this manual are summarized as follows:

- This verification deals mainly with a so-called network simulation model. It generally consists of modeling by simplifying various phenomena to handle traffic conditions comprehensively. Contrary to this, local simulation models dealing with sag or weaving areas are generally developed on the basis of an approach that more precise logic is to be constructed through more detailed analysis of the traffic phenomena concerned.
- One problem here is that the simulation model logic has become a black box. Its characteristics are unknown to those other than the developer. It is difficult to understand everything only from the literatures.
- Before discussion of the adequacy of comprehensive reproducibility of a model while using actual data, it is necessary to clarify how phenomena critical in terms of traffic engineering are modeled and to check if specific phenomena are reproduced truly as modeled.
- Accordingly, it is not important here whether or not modeled phenomena agree correctly with actual

traffic phenomena. Similarly, verification is not to compare merits and demerits among models.

- We will discuss whether or not model behavior has sufficient (or practically applicable) reproducibility within the scope of application of the simulation model in the next validation stage.

Subsequently, the term, “simulation model,” unless otherwise indicated, refers to the network simulation model.

In this manual, we first describe how the verification process is positioned in the standard development process of a simulation model. After discussing critical traffic-engineering phenomena that the simulation model must take into account, the standard verification process is described with specific virtual data setting presented in each step. Finally, specific examples of applying the standard verification process to several existing simulation models are introduced in the Appendix.

2. Simulation Model Development Process

The simulation model development process generally follows the flow, including the processes shown in Fig. 1. Description below is concerned with how each process is positioned.

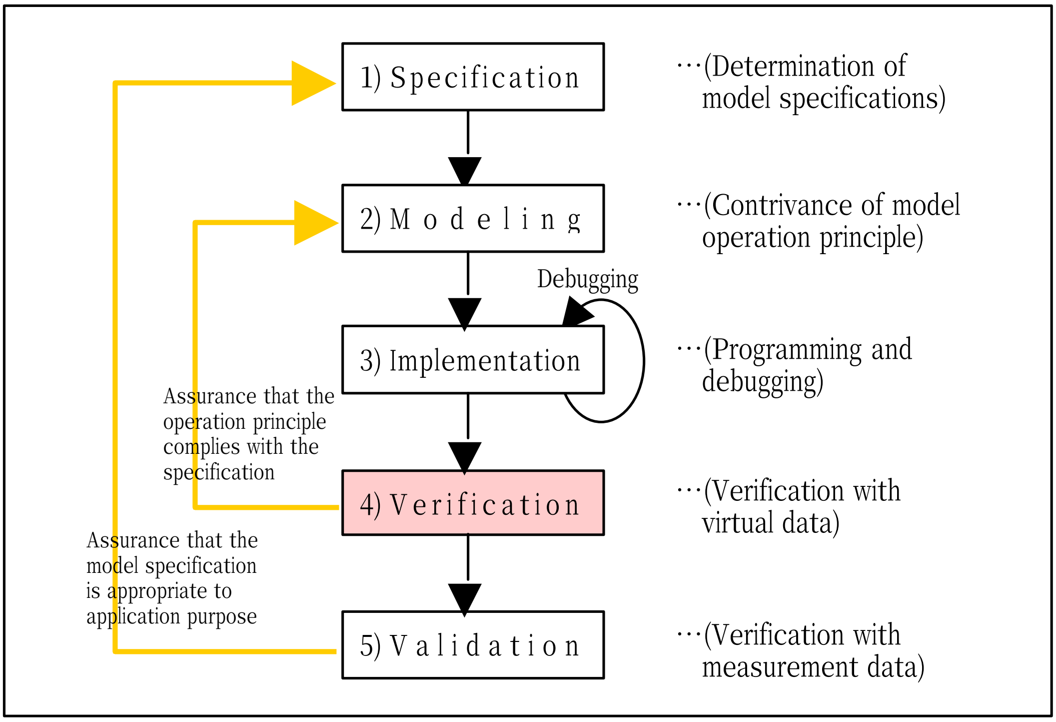


Fig.1 General simulation-model development process

1) **Specifications···(Determination of model specifications)**

From the users' point of view, the simulation model may be thought of as a black box defined by input and output. If this model is to be used widely, there must be a common recognition of its specifications or system input and output items, and its behavior must be guaranteed by the system. For this purpose, requirements must be organized on the basis of consideration of needs and application purposes when determining the model specifications. It is also necessary to determine what kind of traffic phenomena must be handled.

2) **Modeling···(Contrivance of the model operation principle)**

Contrivance of the model operation principle consists of the process of constructing an algorithm complying with the model specifications of 2.1 and of deciding how such an algorithm is to be incorporated into the model. Here the originality of the developer plays an important role, which may often result in operation according to a different algorithm depending on the model even when the same specifications are complied with.

3) **Implementation･･･(Programming and debugging)**

This process consists of programming to run the operation principle contrived in 2.2 on a computer and debugging to check if the computer operates according to the algorithm. Generally, debugging must be distinguished as an operation different in nature from verification.

4) **Verification･･･(Verification using virtual data)**

This process confirms that the program produced in 2.3 can reproduce the traffic phenomena considered in 2.1 (Model Specifications) thereby verifying that the operation principle of 2.2 is justified. In this case, an object of comparison with the simulation result is the traffic engineering theory already established, which often explains phenomena by means of macro indices. This process may be said to be an obligation of the developer in model development. Generally, verification involves extraction and verification of individual highlighted phenomena, one by one, while using virtual data with ideal conditions so that they can be free from various actual restraints, such as data accuracy, availability, etc.

5) **Validation･･･(Verification using actual data)**

This is a process used to evaluate the practical applicability of the model. Validation is carried out in terms of the adequacy of actual set model specifications or the accuracy of model output items using data available in the actual world. Assume that the adequacy of the model operation principle has been verified as described in 2.4 above. The model is not considered to be practically applicable, however, if the model specification itself is incomplete or if actual traffic conditions can not be fully reproduced due to problems, such as actual input data accuracy or accessibility. Furthermore, model performance as a system must also be confirmed. This includes determining whether or not the model can be implemented within a practically applicable time span or with hardware of an appropriate scale. Validation requires data on simulation inputs including traffic demand and operation as well as highly reliable data representing traffic conditions to be compared with the simulation result. Such data gathering has been a substantial burden for model developers, hindering validation. Against this background, construction of the benchmark data set to verify reproducibility is under way to make it available for common utilization of model developers. Because of the advantage that it allows models to be compared on a common basis, the Standard Benchmark Data Set, whose reliability as accurate measurement data is widely recognized, is expected to be used by developers for validation.

3. Traffic Phenomena to be Modeled through Simulation

This section discusses applications in which the modeling of basic traffic phenomena described below proves important. In addition, correspondence with the theory describing individual phenomena is cited and used as a key to establish the specific procedure for the standard verification process described in the next chapter.

1) Generation of vehicles

To implement simulation, it is necessary to generate the traffic at the entry end according to the arrival distribution of vehicles from outside the study area. The type of pattern to be assumed for arrival distribution when generating vehicles should be selected according to the type of road concerned and traffic volume. Generally, the following patterns may be considered:

a) Random arrival of vehicles···When the study area is an expressway, the arrival pattern of traffic not channeled outside the area may have spacing distributed randomly. In a situation with low traffic volume and vehicles running independently without affecting one another, the spacing of randomly arriving vehicles is distributed exponentially. As the traffic volume grows, approaching near-saturation, the prerequisite for independent spacing is lost. In this case, Erlang distribution is said to apply. Even for ordinary streets, many models employ this pattern because of differences in lag time that vehicles suffer at intersections adjacent to the entry end depending on whether or not random arrival is taken into account.

b) Arrival of vehicles at a given interval···When traffic is assumed to arrive after artificial channeling or due to bottlenecks outside the area, spacing is distributed uniformly. Certain models employ uniform arrival because there is no need to use the random number series and it is easy to implement.

c) Arrival of vehicle groups at a certain interval···When the vehicle group is assumed to arrive at a certain interval under influence of a signalized intersection in a vicinity outside the area, there is no such theory as random arrival. There are models that consider this kind of arrival pattern by using a unique mathematical model.

2) Bottleneck capacity／saturation flow rate at link's downstream end

Generally, a given flow rate or bottleneck capacity is steadily observed on the direct downstream side of the bottleneck section at the head of breakdown in the sag or lane blockage section, merge area. Substantial contribution of the reproducibility of bottleneck capacity to the reproduction accuracy of the lag time caused by breakdown can be explained by a simple model represented by the point-queue[1] of Fig. 2. Namely, when the demand with peak arrives at the bottleneck, the maximum slope of cumulative curve for the traffic volume outgoing from this bottleneck is restricted by the bottleneck capacity. Accordingly, this curve diverges from that of the arrival

[1] Model, in which a link is assumed to be a virtual point-queue without length, and the flow is controlled only with restrictions of the FIFO (first-in-first-out) principle and maximum flow rate. Since this model has no length concept, an infinitely large number of vehicles can exist in the link and drawing of breakdown is not considered.

traffic volume. The area of this diverging portion is the total lag time caused by the bottleneck, which is evidently substantially dependent on the bottleneck capacity. For the simulation model, it is essential that the bottleneck capacity is reproduced in a stable manner.

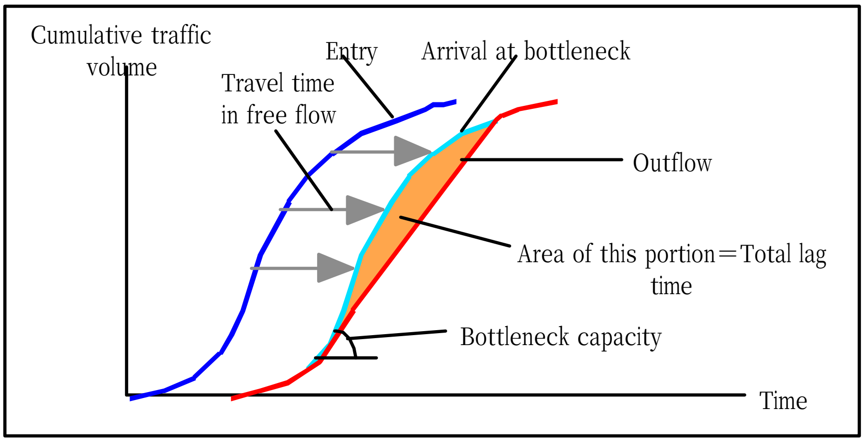


Fig.2 Conceptual view of lag time evaluation using Point-queue

For streets, on the other hand, signalized intersections become mostly bottlenecks. In these intersections, when vehicles retained during the red phase are about to outflow at the green phase, it is observed that they outflow at a certain rate, that is, the saturation flow rate after elapse of a few seconds. Fig. 3 shows the outflow pattern after the beginning of the green phase in an ordinary intersection. Outflow continues at the saturation flow rate till vehicles retained during the red phase are gotten rid of, and subsequently at the flow rate of arrival from the upstream side. The flow rate decreases gradually as the yellow phase begins, and becomes zero, that is, the traffic flow stops, at the red phase. Since the reproducibility of the saturation flow rate at the downstream end link contributes greatly to the reproduction accuracy of the lag time at a signalized intersection, it is important to clarify how these phenomena are modeled in the simulation model.

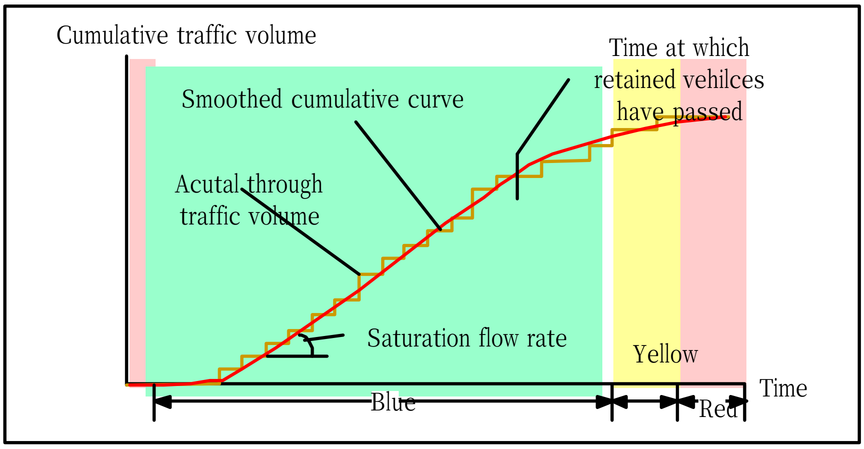


Fig.3　Conceptual view of one-cycle outflow pattern at a signalized intersection

3) **Drawing and elimination of breakdown and shock wave propagation speed**

When a breakdown beginning at a bottleneck is drawn to the upstream link, traffic that need not pass through this bottleneck is also affected (Fig. 4). Reproduction of this phenomenon requires handling of the physical-queue to control the density of breakdown flow according to the appropriate flow characteristic, that is, the traffic-density function, during simulation. In the case of physical-queue, the speed of drawing/eliminating breakdown can be expressed by the relationship between the demand arriving from the upstream side and the bottleneck capacity, as shown in Fig.5, while using the shock wave theory. As a difference in the breakdown drawing/elimination speed results in a difference in the degree of influence on the traffic that has nothing to do with the bottleneck, it is important that the simulation model can reproduce change in this breakdown correctly.

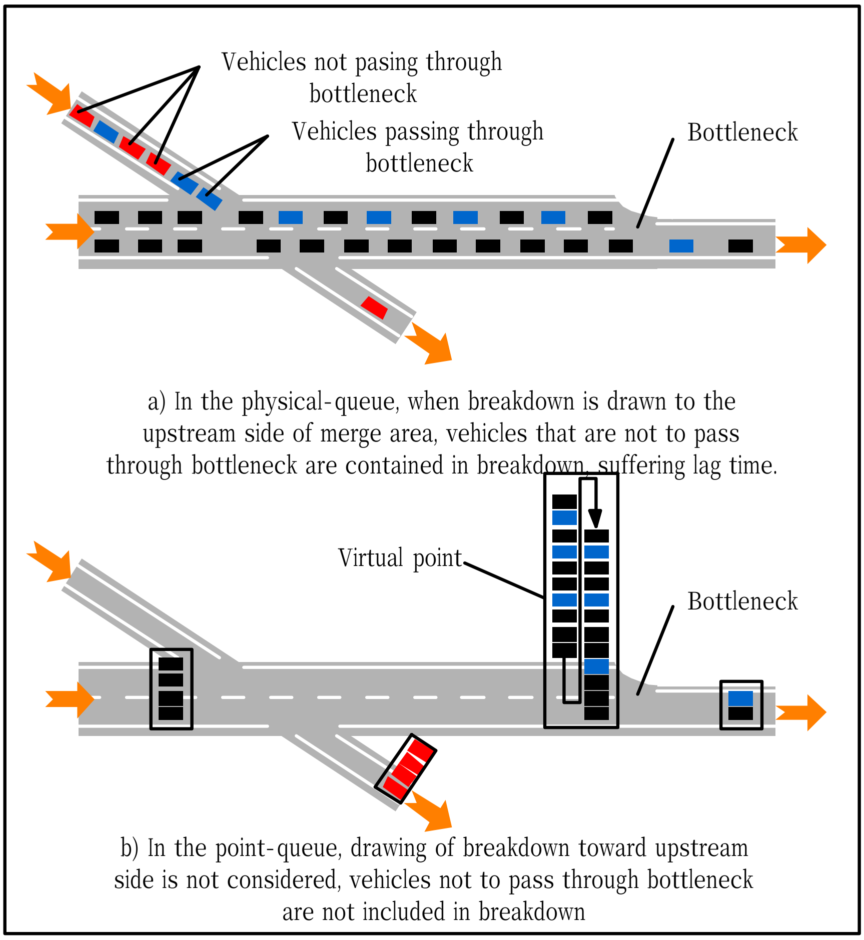


Fig.4 Difference between point-queue and physical-queue

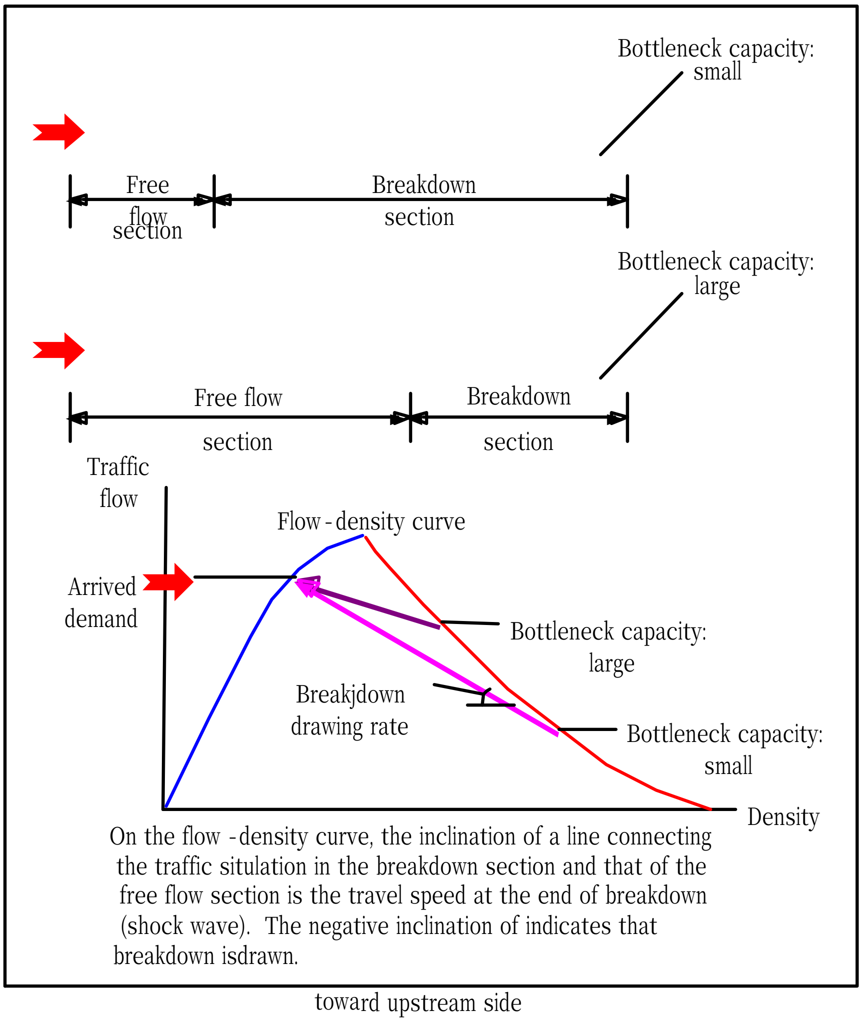


Fig.5 Calculation of breakdown drawing/elimination rate according to the shock wave theory

4) Capacity of merge/diverge area and merge/diverge ratio

The merge area is the most remarkable bottleneck of expressways. Bottleneck at the merge area causes either breakdown on both the main line and the merge branch or breakdown on either of them depending on the ratio of demand from the upstream side. Namely, assuming that the demand of main line a is Q_a, demand of a branch b is Q_b, the bottleneck capacity is C^*, and the merge ratios when breakdown occurs on both main line a and branch b are m_a, and m_b ($m_a+m_b=1$) respectively:

a) When $Q_a+Q_b>C^*$ and $Q_a/m_a>C^*$ and $Q_b/m_b>C^*$, breakdown occurs on both main line a and merge branch b.
b) When $Q_a+Q_b>C^*$ and $Q_a/m_a>C^*$ and $Q_b/m_b<C^*$, breakdown occurs only on the main line a.

With the simulation model, it is required to demonstrate the reproducibility of the bottleneck capacity and merge ratio at the merge area and the breakdown situation on both merging and merged sides while changing the distribution ratio of demand from the upstream side.

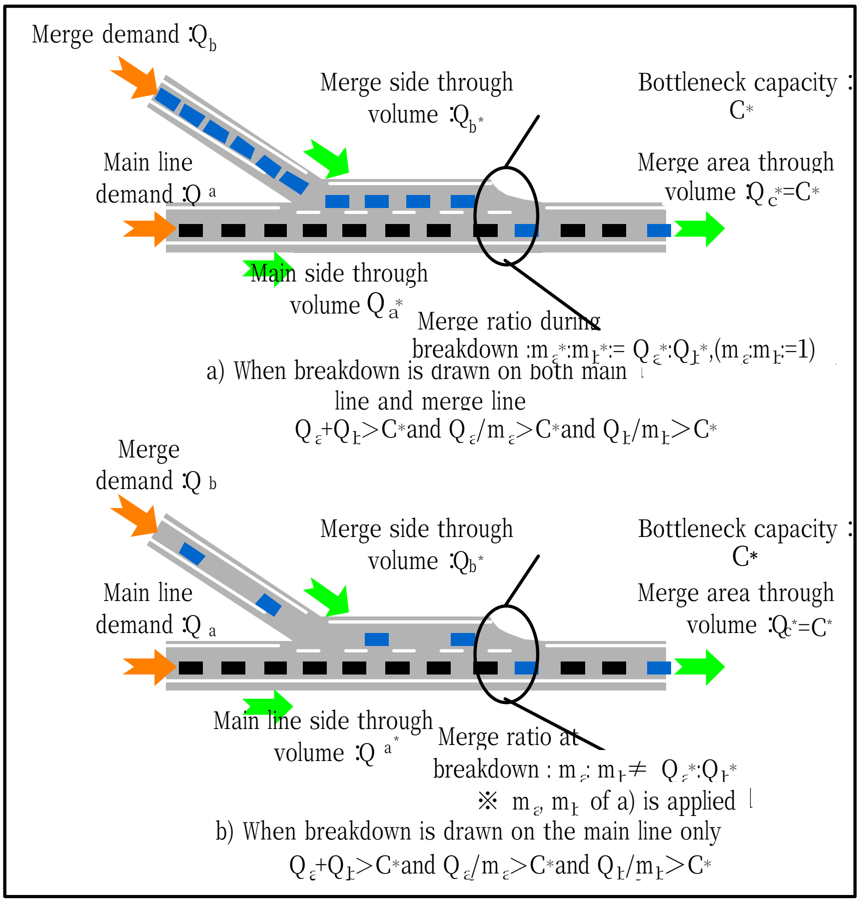


Fig.6 Difference of breakdown drawing at merge area depending on the capacity and merge/diverge ratio

On the other hand, in the diverge area, capacity varies according to the distribution ratio of demand from the upstream side to the main line and diverge branch, that is, the diverge ratio. Namely, assuming that the demand for main line a is Q_a, the demand for branch b is Q_b, the main line capacity downstream of the branch is C_a^* ; the diverge branch capacity is C_b^* ; and the distribution ratio of demand to main line a and diverge branch b is r_a and r_b (r_a+r_b=1), respectively. The capacity of the diverge branch C^* then becomes:

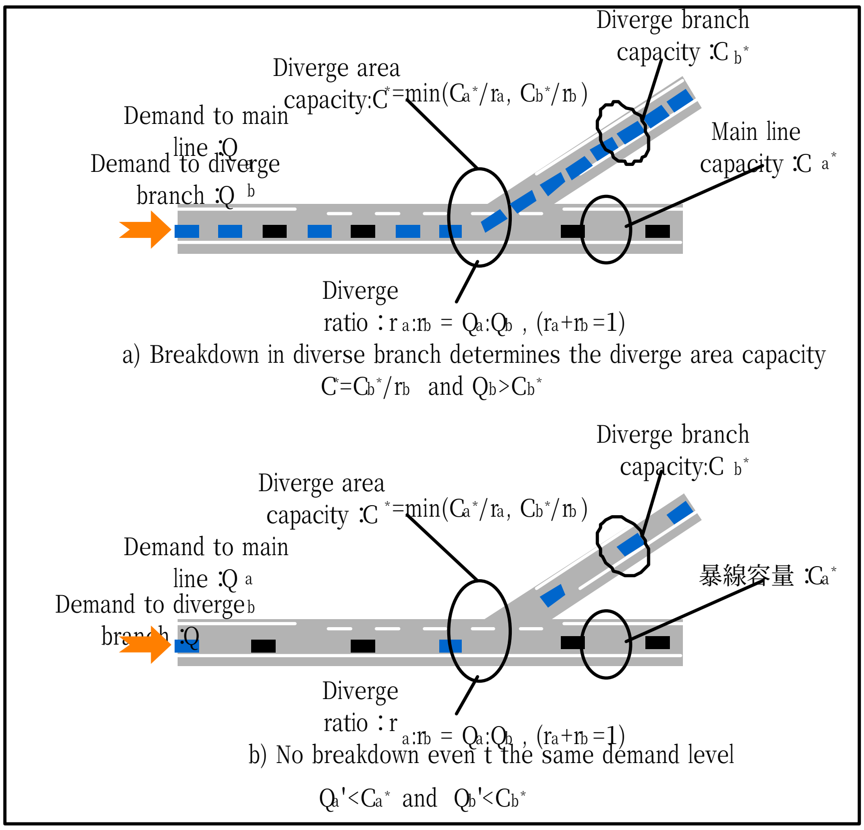
$$C^*=\min(C_a^*/ r_a, C_b^*/ r_b)$$

(Fig. 7). During simulation, it is necessary to check if the above relationship can be established.

In the case of a model handling the traffic flow discretely, it is necessary[2] to check if the intended diverge ratio can be achieved through elimination of error[3] due to discretion when there exists an extreme deviation in the diverge ratio and the demand from the upstream side is relatively small.

[2] In a model where the demand is provided for each 0D instead of setting the diverge ratio, a similar problem occurs when a substantial deviation exists in the route selection probability in a simple network with a 10D2 route.

[3] For example, assume here that there is the demand of 10 units per five minutes from the upstream side when the diverge ratio is 0.99:0.01. Since the discrete method can not divide the demand into 9.9 units and 0.1 unit, a certain contrivance is necessary.



a) Breakdown in diverse branch determines the diverge area capacity $C^*=C_b^*/r_b$ and $Q_b>C_b^*$

b) No breakdown even t the same demand level $Q_a'<C_a^*$ and $Q_b'<C_b^*$

Fig.7 Difference in breakdown depending on difference in capacity and diverge ratio in the diverge area

5) Decrease in the right-turn capacity due to opposing traffic in a signalized intersection

In ordinary streets, it is a daily observation that vehicles waiting for right-tun in a signalized intersection hinder travel of following vehicles, resulting in a breakdown. Such vehicles are waiting to find a gap in the opposing straight-through traffic in the green phase. As a result, the right-turn traffic capacity in this intersection is reduced by the opposing straight-through volume. Model verification is made by comparing the model describing this phenomenon macroscopically with the simulation result. As an example of macroscopic description, a calculation equation[4] for right-turn capacity by the Japan Society of Traffic Engineers is shown in Equation (1) below.

$$S_R=1800\, f\,(S\,G-q\,C)/(S-q)\,C+3600K/C \quad \cdots(1)$$

S_R···Capacity of exclusive right-turn lane [units/hour]

S···Saturation flow rate in the entry section of opposing straight-through traffic [units/effective green one-hour]

q···Volume in the entry section of opposing straight-through traffic [units/hour]

C···Cycle length [second]

G···Effective green time [second]

K···No. of units discharged at change of signal [units/cycle]

[4]"Plan and Design of Level Crossing – Fundamentals"; The Japan Society of Traffic Engineers, 1984

f···Gap acceptance probability determined from the following relationship:

f = 1.00 (q=0), 0.81 (q=200),
0.65 (q=400), 0.54 (q=600),
0.45 (q=800), 0.37 (q=1000),
0.0 (q>1000), Interpolation made for the median q value.

6) Route selection behavior

Modeling for users' route selection behavior considered in simulation is classified as follows:

a) Dynamic route selection model not incorporated···This is a type in which each vehicle, without any information on a destination, selects the next link according to the distribution ratio set for each diverse area. Since the OD volume need not be given as a demand, the input data is easy to obtain. When the network includes loop, however, the link volume is larger than the actual volume because there are vehicles that go around the loop.

b) Dynamic User Optimal (DUO) allocation incorporated···DUO is "to select the optimum route according to the route cost in the instant it is presented till the user reaches the destination." As the simulation itself represents the current situation through accumulation of situations at respective time points, modeling is relatively easy. This also represents the framework of travel information presentation in the actual world. Accordingly, many models incorporate a route selection model based on the DUO principle. Note however that the quality of the "route cost in the instant it is presented" is not defined in DUO. If the route cost is, for example, the "average required time up to the destination, which was observed five minutes ago," the selected route is not necessarily the optimum route to reach the destination. Namely, a so-called hunting phenomenon may occur.

c) Dynamic User Equilibrium (DUE) allocation incorporated···DUE is "to select the optimum route according to the route cost that a user actually experiences till he/she reaches the destination." Since the future traffic situation not known at time of selection must be projected, a complicated network may make theoretical solution difficult. Therefore, at present, there is no practically applicable simulation model that can achieve DUE in the strict sense of the word. Models approximating achievement of DUE are as follows: One is (c1) a model for selection through feedback of simulation result concurrently with advance projection of the traffic situation up to the near future by independent modules on the basis of the current traffic situation reproduced through simulation. The other is (c2) a model that repeats simulation to predict and converge the future route cost empirically from the previous simulation result.

d) Probabilistic route selection···In the case of b) and c) above, the minimum of presented route cost is always selected. Contrary to the above, this model assumes that human recognition error is distributed probabilistically, and the route with the minimum cost is not necessarily selected. Depending on the distribution pattern of recognition error, models are classified into a Logit model, a probit model, etc.

Of these models, the one using a) above is considered applicable for evaluation of short-term traffic operation policies that do not have to consider routes of road users. It can also be applied to networks without allowance for route selection. Verification of these models is not specifically necessary because it is equivalent to the previous verification of the merge/diverge ratio in that it involves verification of whether or not the set diverge ratio is actually achieved.

On the other hand, the simulation model using standards such as b) DUO or c) DUE adopts a framework in which users select routes on the basis of presented route cost. This type of model is mostly used to evaluate the dispersing of traffic spatially by means of information services and road construction. Generally, verification of these models is made using a simplified network with two routes because of the increased difficulty of determining flow patterns to achieve DUO and DUE as the network becomes complicated. Fig. 8 shows the flow pattern and route cost when DUE is to be achieved using the travel time as a cost for the two-route network. Namely, all vehicles select route 1 initially when the cost is small. As breakdown occurs at the bottleneck downstream of the merge area, and the cost of route 1 becomes equivalent to that of route 2, the traffic flows to both routes. The diverge ratio at this time point is equal to the capacity ratio in the merge area.

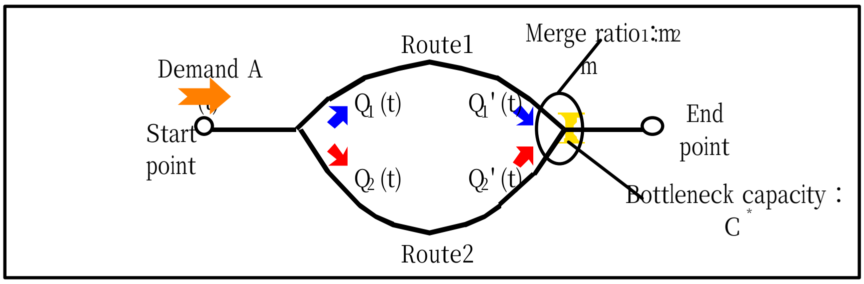


Fig.8 1OD2 route network

Figs. 9 and 10 show the flow pattern based on point-queue when the demand including peak *A(t)* exists in a simple 1OD2 route network and the merge area becomes a bottleneck. Specifically, they show the flow pattern for two cases: one with DUO allocation on the basis of the current route required time and the other where DUE is achieved. In the case of DUO based on the current route required time:

i) Initially, all vehicles select route 1 when the cost is small.
ii) At a time t_2, the cost or the travel time $t_2 - t_1$ of vehicles outgoing at this time point becomes equal to the initial cost p_2^0 of route 2.
iii) The cost of route 1 in the next instant is the travel time of vehicles that suffer larger delay than those outgoing immediately before this instant and thus becomes higher than that the cost of route 2. As a result, all vehicles select route 2 after t_2
iv) At a time t_3, part of the traffic volume outflows from route 2 to the merge area. At this time point, breakdown remains on the side of route 1, so that the run-off volume from both routes is equivalent to the bottleneck capacity allocated on the basis of the merge ratio.
v) Breakdown of route 1 is eliminated at a time t_4**.** Since no vehicles are left on route 1, the route cost decreases discontinuously to p_1^0. Therefore, after this time point, all vehicles select route 1 again.

In this case, the inflow volume for each route, $Q_1(t)$**,** $Q_2(t)$, increases in stages, step-by-step.

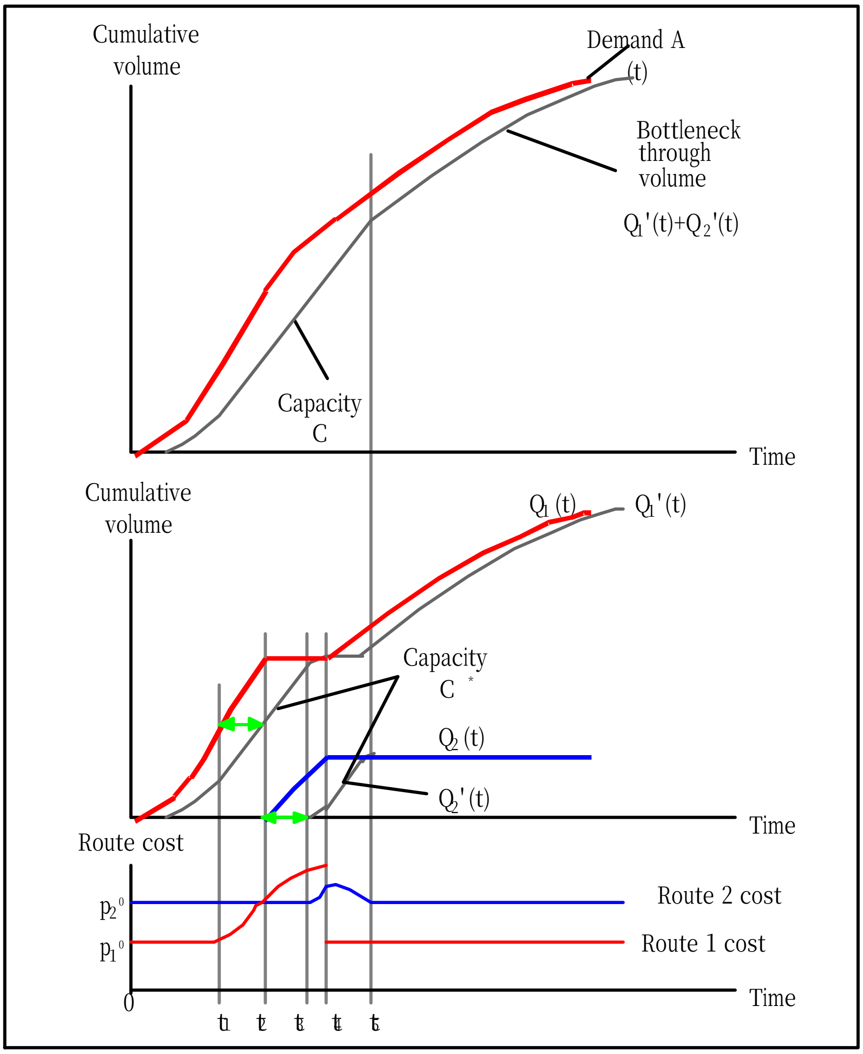


Fig.9 Flow pattern with DUO allocation based on current route required time

On the other hand, the flow pattern in which DUE is achieved for the same demand is substantially different from the case of DUO. Namely:

i) Initially, all vehicles select route 1 where the required time is short.
ii) At a time t_1, the cost becomes equal for routes 1 and 2, so that vehicles may select either route. The ratio of volumes for the respective routes becomes equal to the merge ratio during breakdown in the merge area, and the cost of each route changes equally.
iii) At a time t_3, vehicles moved into route 2 run off at a time t_4 when breakdown in the route 2 disappears. Therefore the cost becomes p_2^0. Since the cost of route 2 does not decrease further, all vehicles subsequently select route 1.

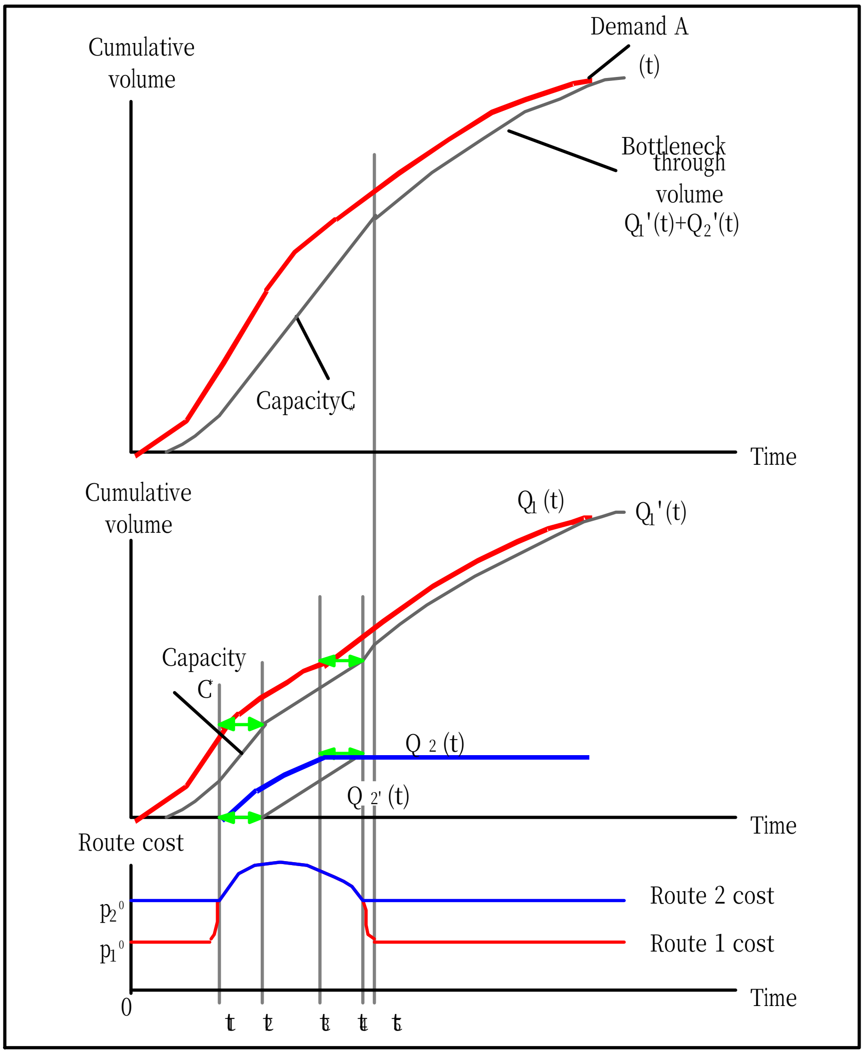


Fig.10 Flow pattern achieving DUE

In the case of DUE, the FIFO (first-in-first-out) principle is established in the bottleneck when both routes are selectable. This is because the required time is the same regardless of which route is taken. Therefore, it is known that the bottleneck through volume is quite similar to the breakdown phenomenon on a single route.

Figs. 9 and 10 show the theoretical value when point-queue is used without considering the effect (drawing) of a breakdown. In the simulation handling physical-queue, the figures may be different when a breakdown affects the diverge area. In any case, verification involves comparison with these theoretical values for evaluation.

4. Simulation Model Standard Verification Process - Verification

This chapter describes the verification process used while referring to the virtual data set. Here, the fundamental concept of verification is to compare “the established theory to described phenomena” and “the observed and accumulated results of dynamic traffic conditions represented by simulation.” Verification is not dependent on exact agreement of the simulation result with these theoretical values. The objective of verification is to define the model characteristics while confirming correlation with or difference from the theory. At the same time, it is considered important to define the relationship between certain model parameters and model behavior.

Verification steps are required to clarify conceptually how each model represents traffic phenomena concerned. In this case, the required verification procedure differs for the following two models because of substantial difference, in set parameters. They are a model which reproduces the flow by taking into account the follow-up behavior of individual vehicles (a car-following model) and a model to control the flow with the vehicle list by providing externally traffic flow characteristics such as the flow – density (Q-K) function. (a Q-K type model).

Verification steps corresponding to traffic phenomena described in the previous chapter are explained below step-by-step separately for Q-K and car-following models. As is said commonly for all items, it is necessary to describe in as much detail as possible how these phenomena are modeled. It is also necessary to describe clearly related parameters and settings. Unless otherwise described, the link is considered to be one lane. Namely, it is intended to perform verification while eliminating the effects of lane changes on capacity in a multi-lane situation.

(1) A. Q-K type model verification procedure

The Q-K model is a generic name for models that perform flow control with a list by providing macroscopic traffic flow characteristics. This type of model includes those establishing not only Q-K relationships, but also S-V (spacing – velocity) and Q – V (volume – velocity) relationships derived from them. These models are verified according to the procedures 1) through 6) described below. Note that certain models handle specific phenomena by partially providing microscopic characteristics (vehicle behavior, etc.). In this case, refer to the verification procedure for the car-following model that is described later.

1) Generation of vehicles

To verify the vehicle generation function of a simulation model the following points must be determined.

a) Whether the generation pattern assumed in the model is achieved.
b) Whether there exists substantial divergence from the assumed pattern due to a random number series.
c) Whether the quantity of vehicles is completely the same as the traffic demand set within a given

time period or within what range they increase/decrease.

d) Whether, in a situation with a breakdown within the study area being drawn outside the network, arriving vehicles are added to the end of breakdown outside the area, and finally, the entire set demand flows into the area.

Specific verification procedure examples are described below first for a) through c).

i) A network comprising the generation point shown in Fig. 11 and the link running off therefrom. The links are assumed to have a capacity of 2200 [units/hour].

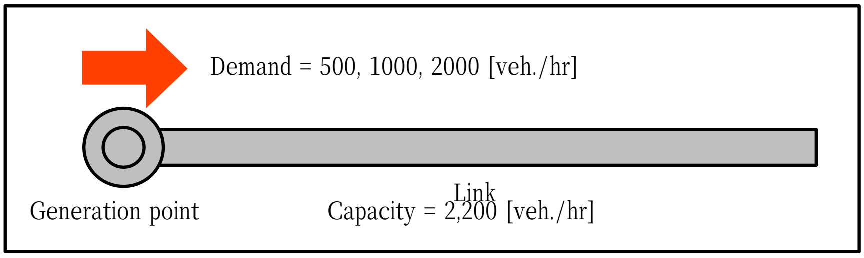


Fig.11 Example of verification data set for vehicle generation model

ii) Given three stages of traffic demand, 500, 1000, and 2000[units/hour], simulation is made for hour and the time interval headway from a preceding vehicle when vehicles are generated is recorded. For a model in which vehicle generation timing is difficult to record, observe the headway at the link upstream end. For a model approximating the fluid, the generated trips are recorded at a unit scan interval.

iii) As shown in Fig. 12, the appropriately discretized headway or the generated trips within a unit scan time is represented in the form of a histogram. For the purpose of comparison, the probability density distribution of a theoretical arrival pattern is also shown in this figure[5].

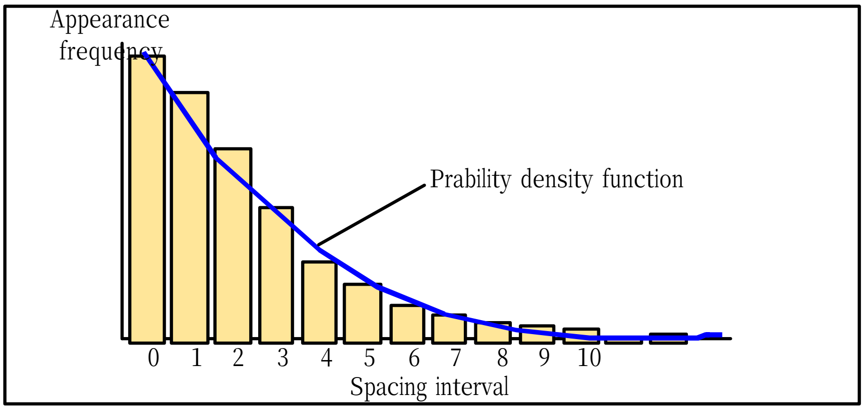


Fig.12 Histogram and theoretical value of headway

iv) Verification is made also on whether the total generated trips in one hour are larger or smaller than the set volume of 500, 1000, and 2000 units.

v) For a model in which random generation is made using random numbers, steps ii) to iv) are

[5]Verification focuses not on exact representation of theoretical values, but on definition of model behavior. It is therefore unnecessary to perform as much statistical calibration. It may be enough to check the graph visually.

repeated five times while changing the random series for each traffic demand.

Now verification of d) is described below.

i) Given the traffic demand in which the demand for the initial one hour is 4400 [units/hour] and no more, vehicles are generated after that, simulation is made till the volume at the link downstream end becomes zero as shown in Fig. 13.

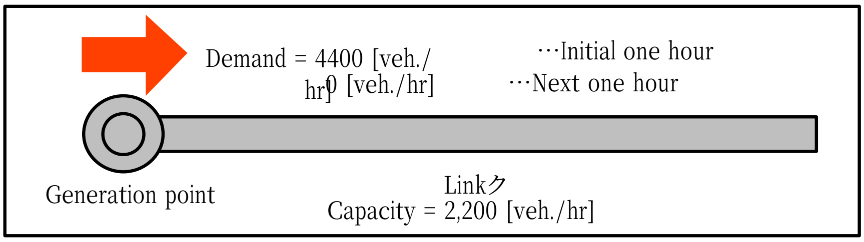


Fig.13 Volume conservation verification data set when cars in a jam are spread out outside the network

ii) The cumulative curve of through volume that is observed at the link upstream end is illustrated to see if 4,400 vehicles flow into the network finally. The curve expected here is as shown in Fig. 14.

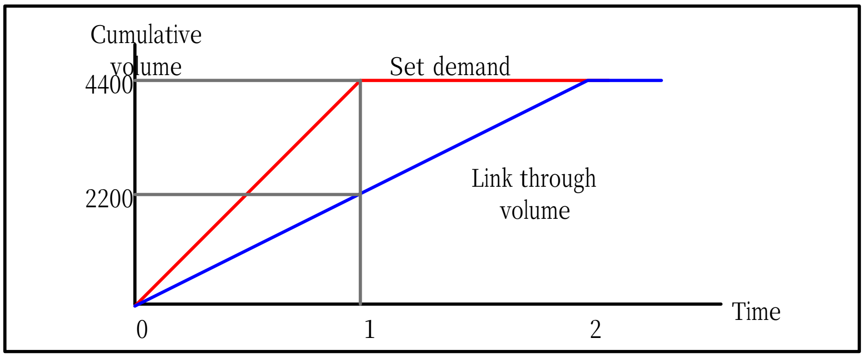


Fig.14 Volume cumulative curve expected when the demand of 4400[units/hour] is given

2) Bottleneck capacity／Saturation flow rate at link downstream end

First, reproducibility of the bottleneck capacity is verified. Given the sufficiently large demand to the bottleneck according to the procedure[6] described below, verification is made to determine whether the rate of flow on the downstream side is stable for the bottleneck capacity.

i) The network to be used consists of links whose downstream ends become bottlenecks as shown in Fig. 15. Set the model parameter so that the bottleneck capacity becomes 800, 1000, and 1200[units/hour]. The capacity is set to be around 2200 [units/hour] for other sections.

[6]For a model based on car-following travel, the procedure is approximately similar to the procedure to determine the Q-K curve on the breakdown flow side in the Appendix.

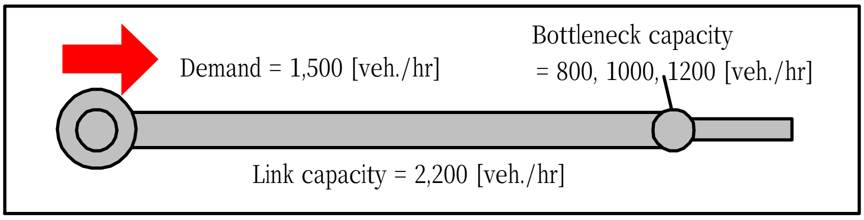


Fig.15 Bottleneck capacity reproducibility verification data set

ii) The traffic demand of 1500 [units/hour] is provided so that breakdown occurs always in the bottleneck.

iii) Simulation is made for one hour using respective model parameters and the through volume on the downstream side of the bottleneck is recorded.

iv) As shown in Fig. 16, the through volume cumulative curve is plotted[7], and verification is made to see if the bottleneck capacity is achieved.

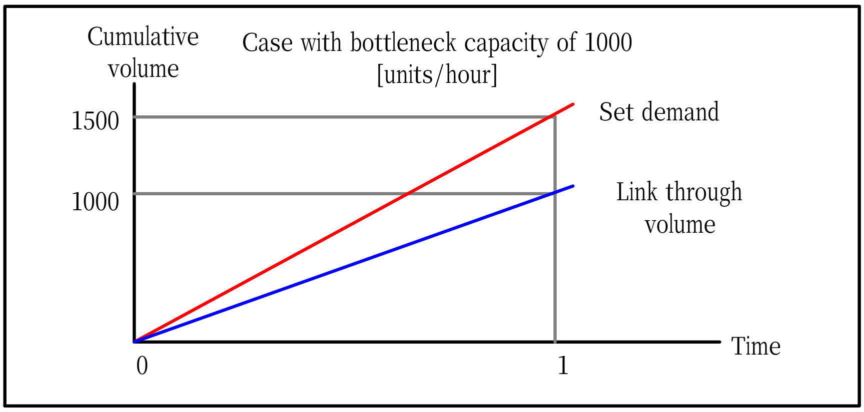


Fig.16 Verification on whether or not the bottleneck capacity is reproduced in a stable manner

Verification on the saturation flow rate at the link downstream end is made as follows. Namely, for a simulation model applied to ordinary streets including signalized intersections, verification is made to check the manner in which vehicles retained during the red phase run off during the green phase.

i) As shown in Fig. 17, a network is formed from one-lane links controlled by the signal at the downstream end. The signal is under the fixed-time control with a cycle length of 120 [seconds], a split of 50%, and a lost time of 10 [seconds/cycle].

[7] Be sure to enter the link through volume in one hour to the graph.

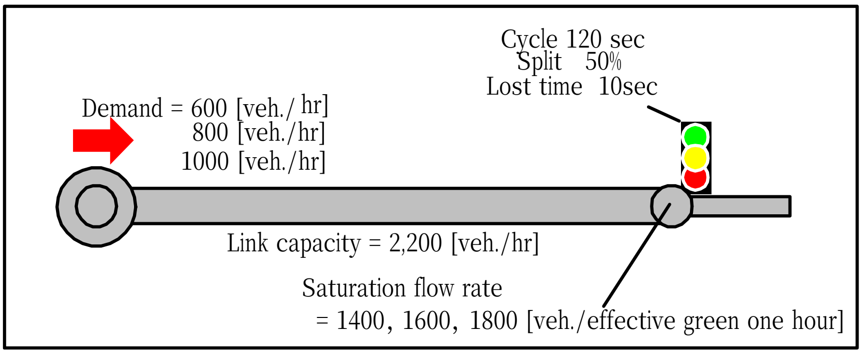


Fig.17 Verification data set on reproducibility of saturation flow rate at link downstream end

ii) Set the model parameter so that the saturation flow rate at the link downstream end becomes 1400, 1600, and 1800[units/effective for green phase in one hour]. Simulation is made for one hour on this case while changing the arrival demand from upstream to 600, 800, and 1000[units/hour].

iii) When ten cycles are completed after the start of simulation, observe run-off from the link for about ten cycles. The observation time interval is equal to the unit scan time of the model.

iv) The run-off volume per cycle after start of the green phase is plotted into the cumulative curve. As shown in Fig. 18, cumulative curves of ten cycles are overlapped and indicated.[8] Verification is made to confirm that the flow rate is reproduced in a stable manner in all cycles while the traffic flow is saturated.

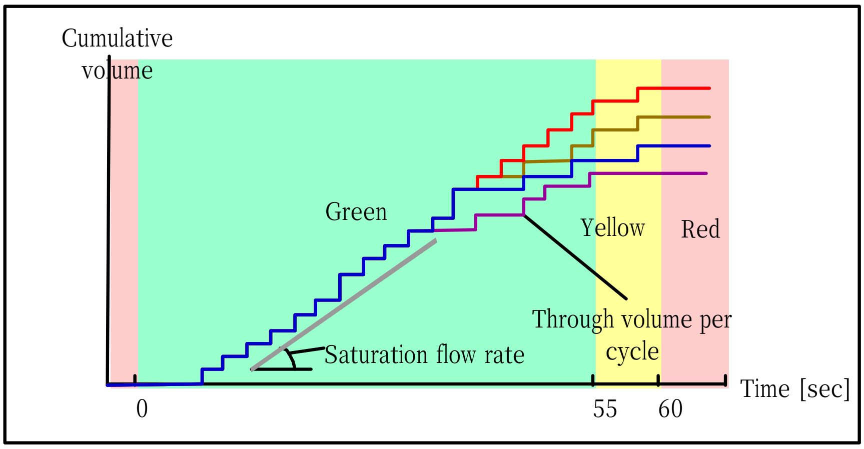


Fig.18 Saturation flow rate observed at link downstream end

3) Spreading out cars, eliminating jams and shock wave propagation rate

This verification is made on a basic segment including bottleneck in terms of followings:

e) Condition in which the demand exceeds the bottleneck capacity and breakdown is drawn to the upstream side

f) Condition in which the demand is smaller than the bottleneck capacity and breakdown is

[8]For the sake of reference, a straight line with a gradient of saturation flow rate is entered in the graph.

dissipated downward from the upstream side.

This is done to verify that drawing and dissipation of breakdown are reproduced according to the theory. For a model that handles traffic flow controlled by signals, further verification is made on the following points:

g) Condition in which breakdown is eliminated upward from the downstream side when the signal phase changes from red to green.

Specific procedure is described first for a) and b).

i) A basic-segment network is formed from multiple links with bottleneck section on the downstream side, as shown in Fig. 19.

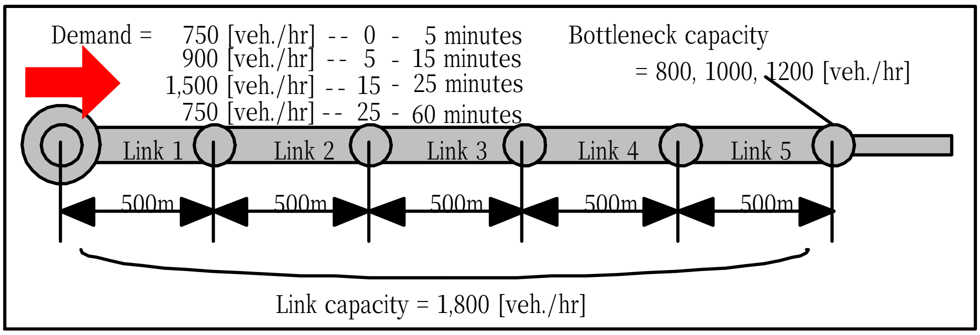


Fig.19 Verification data set for spreading cars out and eliminating traffic jams

ii) Three cases are set up, each with the bottleneck capacity of 800, 1000, and 1200[unit/hour]. The capacity for other sections is set to 1800[unit/hour].

iii) Provide the demand that has a peak in such a manner that breakdown occurs at bottleneck and is dissipated subsequently. Provide the demand as follows after simulation start:

- ·0〜5 minutes···750[units/hour]
- ·5〜15 minutes···900[units/hour]
- ·15〜25 minutes···1500[units/hour]
- ·25〜60 minutes···750[units/hour]

iv) As shown in Fig. 20[9], the shock wave propagation rate is determined[10] from the Q-K curve provided to the model. Then, the traffic condition transition diagram on the downstream side of the bottleneck is prepared as shown in Fig. 21.

v) Simulation is made for each bottleneck capacity to handle the traffic jam by observing the run-off volume from each link.

vi) As shown in Fig. 21, the traffic condition transition diagram is overlapped on the run-off

[9] For the sake of simplification, this figure shows an example approximating the Q-K curve as a triangle. This does not necessarily pertain to certain models. In this case, five forward waves (FW1 through 5) and one backward wave BW1 occur.

[10] In a model which defines the relationship of not Q-K, but S-V, the shock wave propagation rate is determined by converting this relationship into the Q-K relationship.

volume cumulative curve of each link, and verifying is made[11] on whether the jam is spread out or eliminated at this rate.

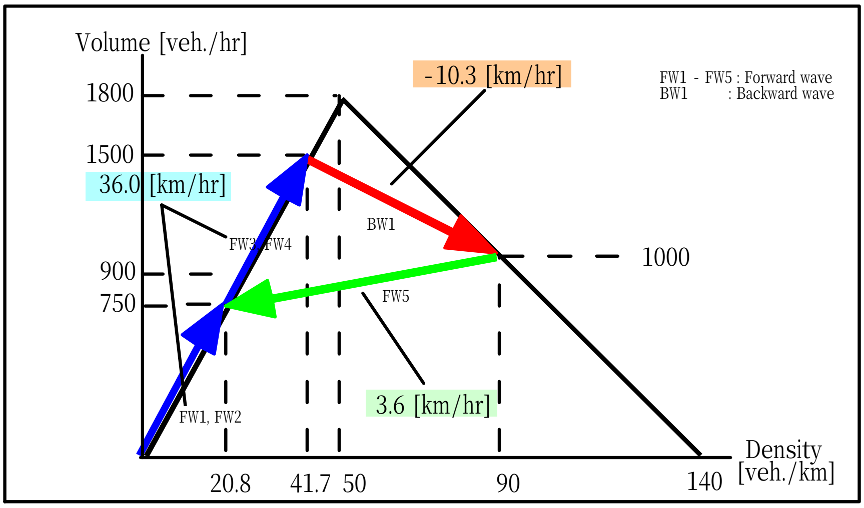


Fig.20 Shock wave propagation rate when the bottleneck capacity is 2000[units/hour]

[11] Considering the purport of verification, it is enough here to see visually on the graph if the time point at which the link run-off rate changes on the cumulative curve agree with that at which the shock wave is propagated theoretically. As the run-off rate is not stable during simulation, it is difficult to indicate, exactly by using numerals, the time point at which the shock wave is propagated

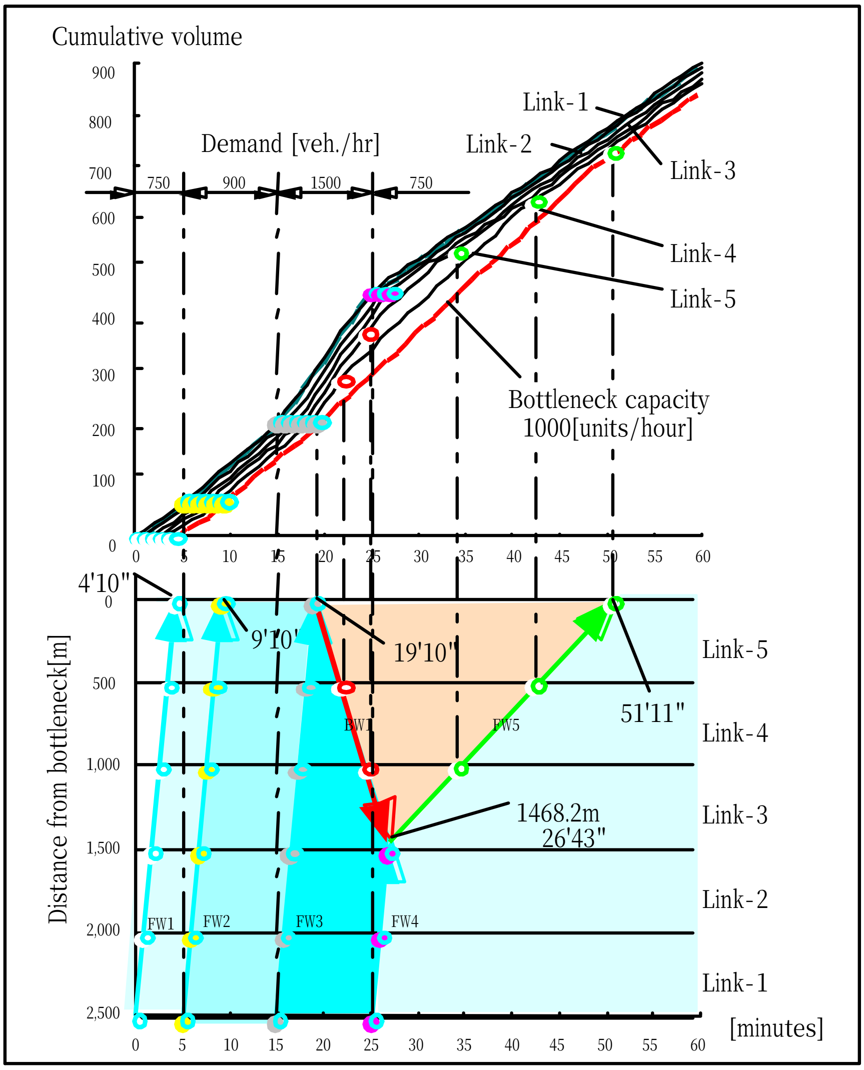


Fig.21 Traffic condition transition diagram on the bottleneck downstream (lower) and observed volume cumulative curve (upper)

The procedure concerning c) is described below. Verification is made here for the simulation model for ordinary streets including signalized intersections — specifically, on the manner in which vehicles retained during the red phase run off in the green phase. Verification is made on whether or not start and stop wave propagation rates according to the signal agree with theoretical values determined from the shock wave theory.

i) A network is formed from one-lane links with signal control on the downstream end, as shown in Fig. 22. The signal is under the fixed-time control with a cycle length of 120 [seconds], split of 50%, and lost time of 10 [seconds/cycle].

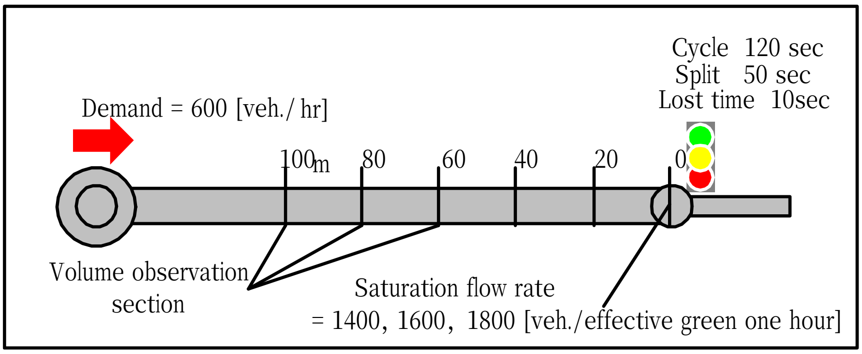


Fig.22 Verification data set for reproducibility of start/stop wave according to signal

ii) Set the model parameter so that the saturation flow rate is 1400, 1600, and 1800[units/effective, green one hour] and carry out simulation of these three cases.

iii) Provide the demand of 600 [units/hour] so that it is not saturated for a signalized intersection. In this case, it is desirable that vehicle generation is assumed to be for uniform arrival because excessive random arrival causes hindrance to verification of whether or not the stop wave is propagated according to the theory[12].

iv) Simulation is made on each parameter set to observe the through volume at points of 0, 20, 40, 60, 80, 100 m …. from the signalized intersection. The observation time interval is the unit scan time of model.

v) For a one-cycle time span beginning with a red phase, the cumulative curves of through volumes at each point are overlapped mutually in the graph. In the case of a model providing the link capacity externally, verification is made of whether start and stop waves are propagated at the shock wave propagation rate determined from the Q-K curve assumed by the model as shown in Fig.23[13]. Namely, this curve is overlapped to the cumulative curve as shown in Fig. 24 to verify whether the inclination change time points agree[14].

[12] In a model not assuming uniform arrival, it is essential to take such a measure as provision of a given demand within the shortest possible interval. For example, vehicles may be generated at a rate of 10 units every minute.

[13] For the sake of simplification, similar to the previous phrase, the example of approximating the Q-K curve in a triangle is shown here.

[14] Considering the purport of verification, it is enough to visually check the graph to determine whether the time point at which the link run-off rate on the cumulative curve agrees with that at which the shock wave is propagated theoretically. As the run-off rate is not stable during simulation, it is difficult to precisely and numerically indicate the time point at which the shock wave is propagated

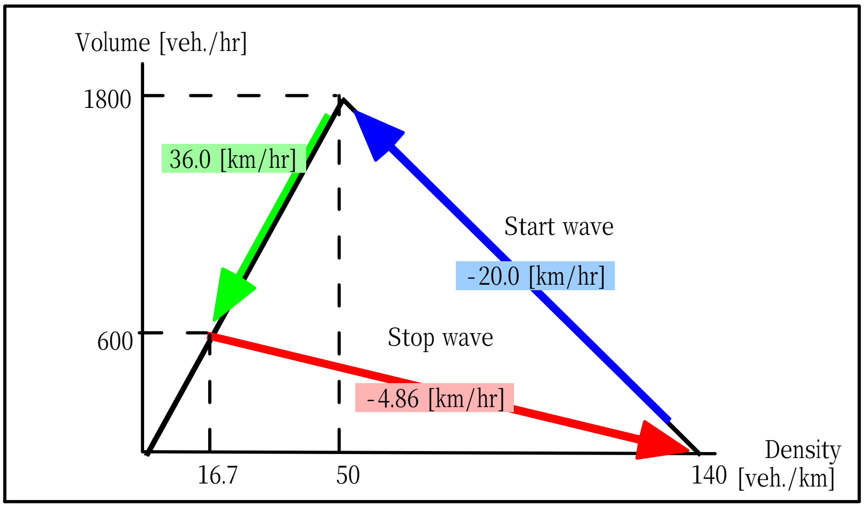


Fig.23 Start and stop wave rate determined from the Q-K curve

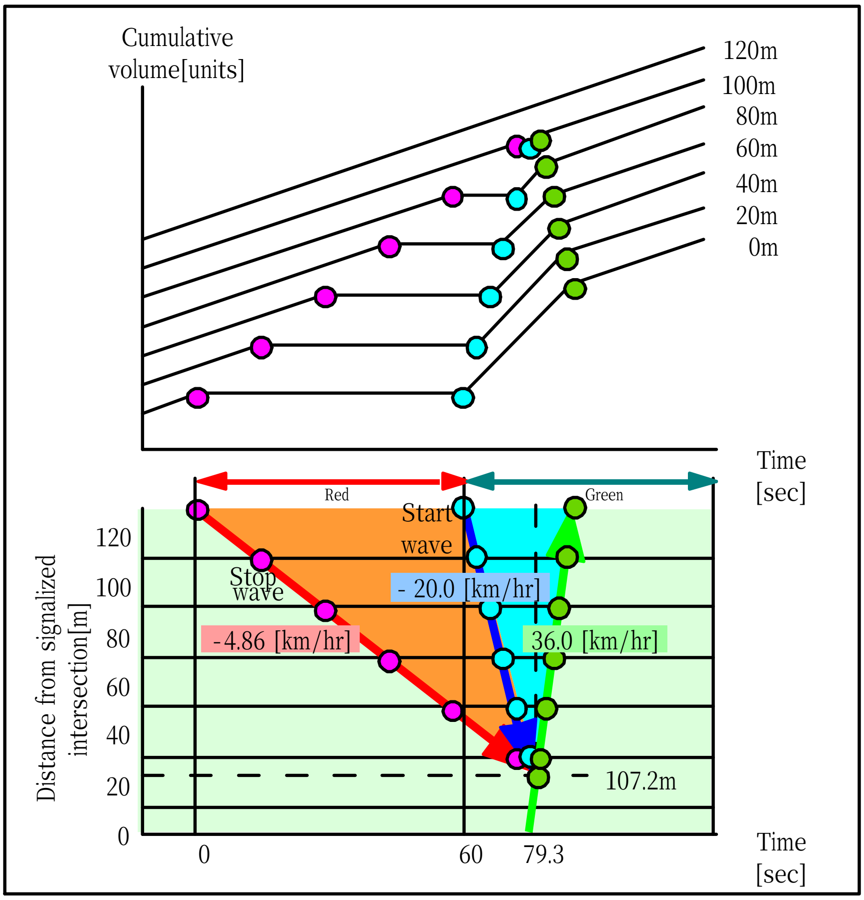


Fig.24 Start and stop wave propagation manner and cumulative volume at each point

4) Capacity and merge ratios in the merge section

For the merge area, verification is made to see if the achieved capacity and merge ratio are as set by changing the demand ratio between the main line and merge sides. The behavior verification procedure for the merge area is described below.

i) A network is formed from two (a and b) merge branches with a capacity of 1800 [veh/hr] as shown in Fig. 25. The capacity of the section directly downstream of the merge area is assumed to be 2200 [veh/hr], which is smaller than the sum of the merge branch capacities.

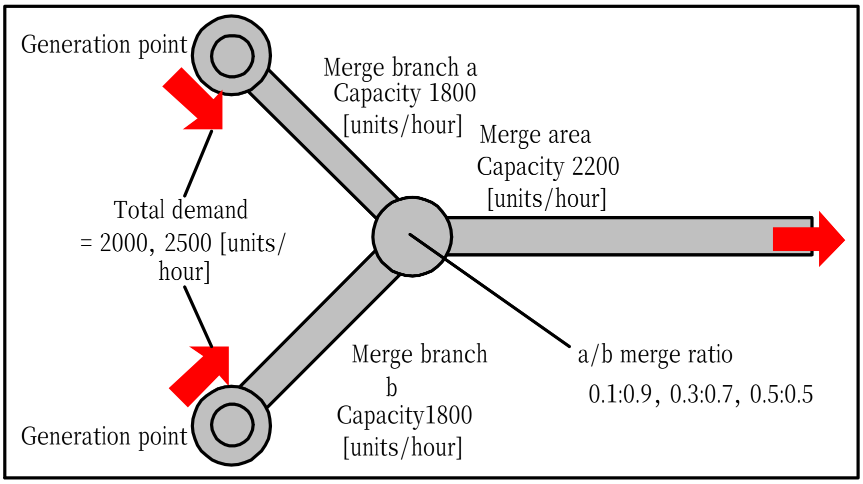


Fig.25 Verification data set for reproducibility of merge capacity

ii) In the model giving externally the merge ratio during a traffic jam, the a/b merge ratio is set in two ways at 0.3:0.7 and at 0.5:0.5. Simulation is made for each of them.

iii) For each parameter set, the total demand to the merge area is assumed to be 2000 and 2500[veh/hr] and the demand distribution ratio from branches a and b is set to three stages: 0.1:0.9, 0.3:0.7, and 0.5:0.5. With a total of six patterns, 12 simulation times are derived. Each simulation may take about one hour.

iv) The demand for each merge branch and the cumulative through volume at the downstream end are graphed for each case to determine whether a jam has occurred. The jam situation is expected to result as shown in Tables 1 and 2. Concurrently, the cumulative through volume on the downstream side of merge area is also entered in the graph to determine whether the set capacity is achieved.

Table1 Traffic jams in each merge branch when the merge ratio is 0.3:0.7

Total demand │ a/b distribution ratio	0.1:0.9	0.3:0.7	0.5:0.5
2000[veh/hr]	No jam	No jam	No jam
2500[veh/hr]	Jam in b	Jam in both	Jam in a

Table2 Traffic jams in each merge branch when the merge ratio is 0.5:0.5

Total demand │ a/b distribution ratio	0.1:0.9	0.3:0.7	0.5:0.5
2000[veh/hr]	No jam	No jam	No jam
2500[veh/hr]	Jam in b	Jam in b	Jam in both

For the diverge area, verification is conducted as follows to confirm that the diverge ratio changes according to the capacity.

i) A network is formed from two (a and b) branches with a capacity of 900 [veh/hr]. The capacity before the diversion area is assumed to be 2200 [veh/hr].

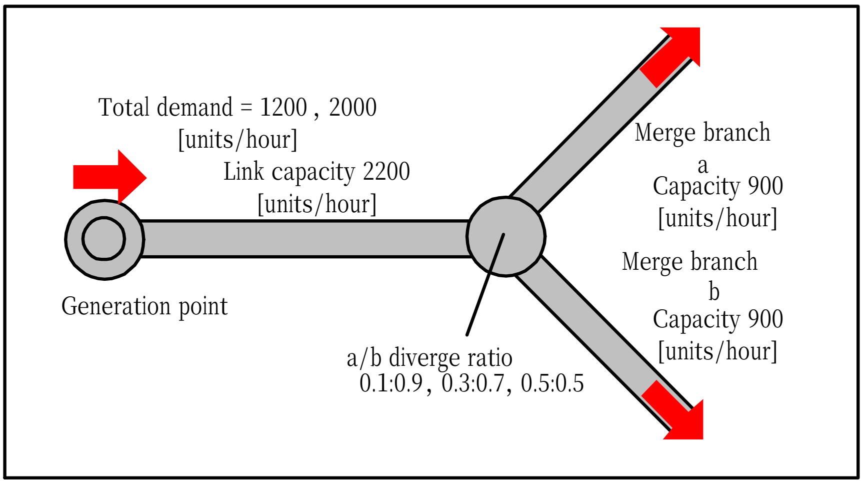


Fig.26 Verification data set for reproducibility of diverge area capacity

ii) Total demand at the diverge area is assumed to be 1200 and 2000[veh/hr]. Then, simulation is carried out six times for each demand level while changing the distribution ratio or diverge ratio of demand to each of the a and b branches in three patterns of 0.1:0.9**,** 0.3:0.7**,** and 0.5:0.5.

iii) For each case, judgment is made from the through volume of diverge area on whether or not a jam has occurred and the capacity is observed. The result shown in Table 3 is expected.

Table3 Traffic situation in the diverge area

Total demand ｜ a/b distribution ratio	0.1:0.9	0.3:0.7	0.5:0.5
1200[veh/hr]	Jam (Capacity1000[veh/hr])	No jam	No jam
2000[veh/hr]	Jam (Capacity 1000[veh/hr])	Jam (Capacity 1286[veh/hr])	Jam (Capacity 1800[veh/hr])

5) Decrease in right-turn capacity due to straight through traffic in the signalized intersection

To verify the right-turn capacity, the result is compared with the right-turn capacity calculation equation[15] of the Japan Society of Traffic Engineers. The verification procedure is described below:

i) As shown in Fig. 27, a network, including one signalized intersection is formed. The saturation flow rate of opposing straight through traffic is set to 2000 [units/effective green one hour] or to an equivalent level. The basic right-turn capacity is set to 1800 [veh/hr]. The number of vehicles that can stay in the intersection waiting for a right-turn is assumed to be two units.

[15] This equation is used not to present theoretical values, but only for reference.

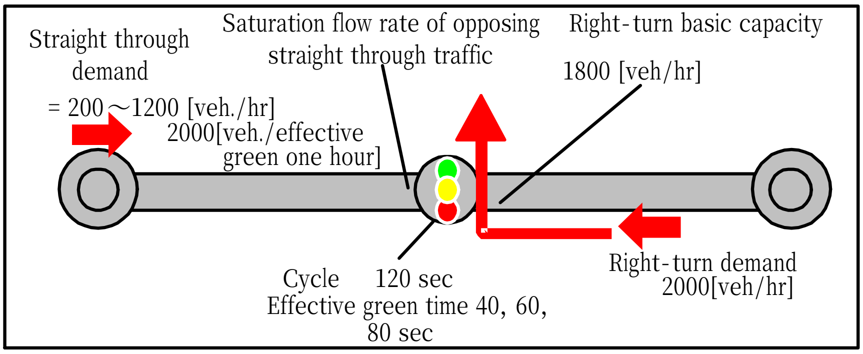


Fig.27 Verification data set for decrease in right-turn capacity

ii) For the signal parameter, the cycle is set to 120 seconds and the effective green time is changed in three stages to 40, 60, and 80.

iii) With each signal parameter set, the right-turn volume is observed while changing the demand of opposing straight through traffic in six stages to 200, 400, 600, 800, 1000, and 1200. In order to ensure supply of vehicles at all times, the traffic demand for right turns in the intersection is set at approximately 2000 [veh/hr].

iv) The simulation observation result is compared with equation (1) of Section 5, Chapter 3. Namely,

$$S_R = 1800\, f\,(S\,G - q\,C)/(S - q)\,C + 3600K/C \quad \cdots(1)$$

S_R···Capacity of an exclusive right-turn lane [veh/hr]

S ··· Saturation flow rate at approach of opposing straight through traffic [veh/effective green one hour]

q···Volume at the approach of opposing straight through traffic [veh/hr]

C···Cycle length [sec]

G···Effective green time [sec]

K···No. of vehicles that can be discharged at change of signal [veh/cycle]

f···Gap acceptance probability determined from the following relationship

f = 1.00 (q=0), 0.81 (q=200),
0.65 (q=400), 0.54 (q=600),
0.45 (q=800), 0.37 (q=1000),
0.0 (q>1000), Interpolation for median q value

When comparing simulation results, plot the opposing straight through volume on an abscissa and the right-turn capacity (= through traffic volume) on an ordinate for each signal parameter set, as shown in Fig. 28.

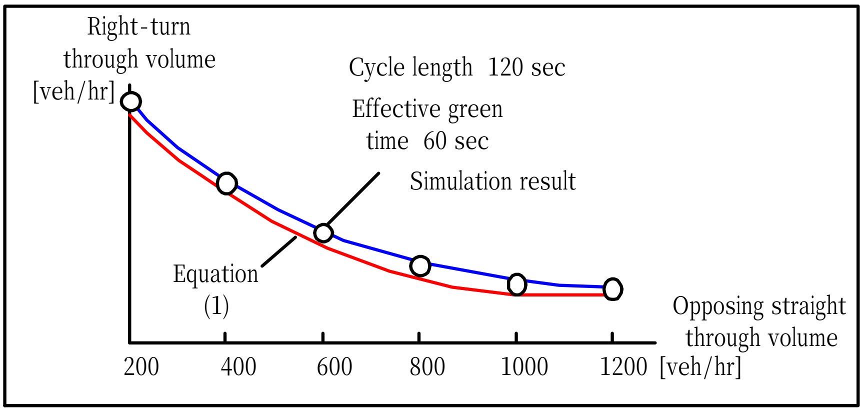


Fig.28 Comparison of right-turn capacity simulation results and theoretical values

6) Route selection behavior

This verification is used to confirm the route selection model the simulation model assumes and how truly the theoretical value is reproduced. The theory in this case is either DUO or DUE. Since an excessively complicated network makes calculation of the theoretical value itself impossible, a simple network comprising a 10D2 route is used for verification. Verification is carried out as follows:

i) The 10D2 route network shown in Fig. 29 is used. The capacity is set to 900 veh/hr or an equivalent so that the merge area becomes a bottleneck and to 1800 veh/hr for other sections. The merge ratio during a jam is assumed to be 0.5:0.5.

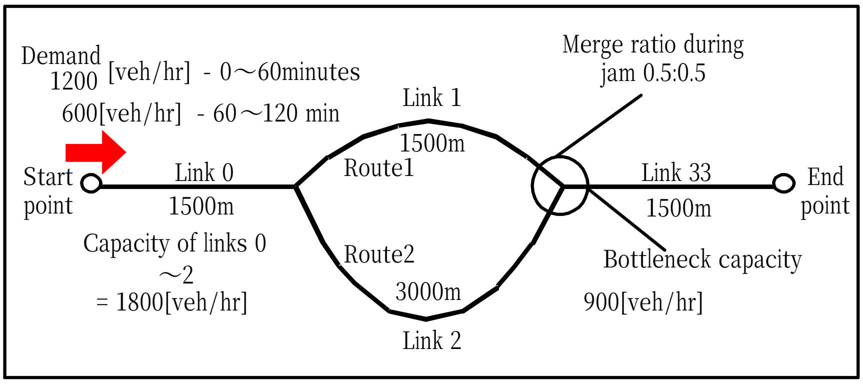


Fig.29 Verification data set for reproducibility of route selection behavior

ii) Prepare three model setting patterns[16] for each of the model selection standards (DUO/DUE, shortest cost selection/probability selection, etc.) and route cost renewal time interval, and route selection timing.

iii) For each setting pattern, simulation is for two hours. Set the demand to 1200 veh/hr for the initial one hour and 600 veh/hr for subsequent one hour.

[16] Parameters and set items vary greatly depending on the model and are thus not specifically given here. Each model user must define pertinent parameters and set appropriate values

iv) Observe the cumulative volume of incoming and run-off for links 1 and 2 in each case and compare the observed results with the theoretical flow pattern. For reference, the flow pattern when DUE is achieved with a free flow rate of 36 km/h (= 10 m/sec)[17] is shown in Fig. 30. It should be noted that, to avoid complication, the link volume is handled with point-queue and spreading out cars from the traffic jam to the diverge area is not considered.

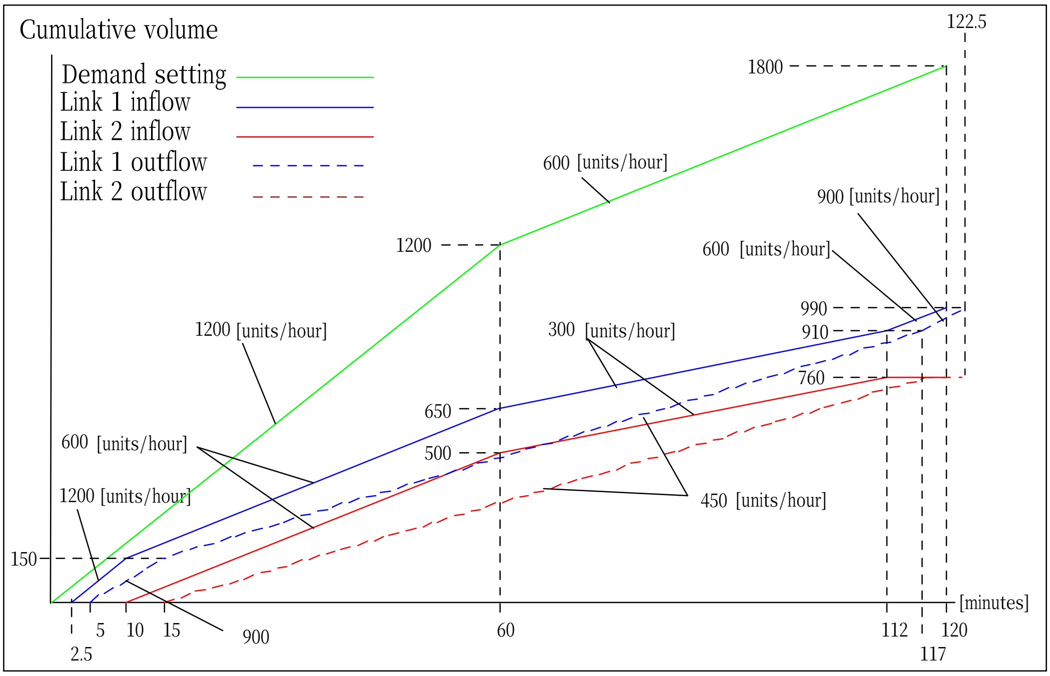


Fig.30 Flow pattern of a case in which DUE is achieved

[17] The difference in free travel time between both routes is 2.5 minutes.

(2) B. Car-following Type Model Verification Procedure

The car-following type model is a model that simulates travel in the lane according to set parameters concerning driving behaviors such as reaction delay, maximum acceleration, and target headway, etc. Verification of these models proceeds according to steps 1) through 7) below.

1) Generation of vehicles

In this step, the function of a simulation model to generate vehicles is verified. The following points are checked:

h) Whether the generation pattern assumed for the model is achieved.
i) Whether or not substantial deviation has occurred from the assumed pattern due to a random number series.
j) Whether vehicles of exactly the same quantity as the demand set for a given time span have been generated or to what degree the quantity increases/decreases.
k) Whether, with breakdown drawn from the inside of the study area to the outside of network, arrived vehicles are added to the end of the jam outside the area and the finalized demand flows into the area without elimination.

Examples of specific verification procedures are shown below, first for a) to c):

i) A network is formed from a generation point and a link running off from this point, as shown in Fig. 31. The link is assumed to have an effective width of 3.5 m and gradient of 0% so that it can have sufficient capacity.

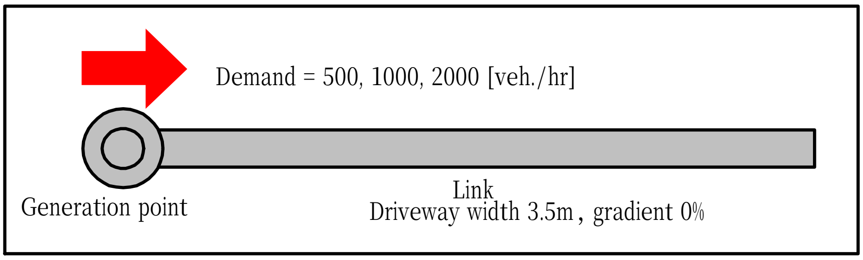


Fig.31 Example of data set for verification of the vehicle generation model

ii) One-hour simulation is made for a case with three stages, each 500, 1000, and 2000veh/hr, of demand. In this simulation, recording is made for the time interval headway from a previous vehicle when vehicles are generated. For a model for which the vehicle generation timing is difficult to record, headway is observed at the link upstream end. For a model approximating fluid (?), the generated trips are recorded at the unit scan interval.
iii) As shown in Fig. 32, the generated trips at an appropriately discretized headway or within the unit scan time are represented in a histogram for respective results. For the sake of comparison, the probability density distribution of the theoretical arrival pattern is also shown

in the figure[18] below.

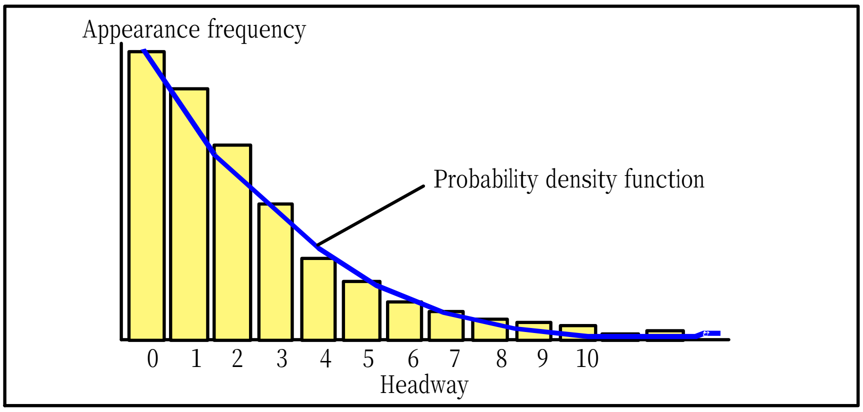


Fig.32 Histogram and theoretical values for headway

iv) Verification is also carried out to determine whether the total generated trips per hour have increased or decreased from the set trips of 500, 1000, and 2000 units.

v) For a model achieving random vehicle generation using random numbers, steps ii) through iv) are repeated five times while changing the random number series for respective demands.

Verification of d) is described below.

i) Given demand of 4400 veh/hr for the initial one hour and totally zero after that, as shown in Fig. 33, simulation continues until the volume at the link downstream end becomes zero.

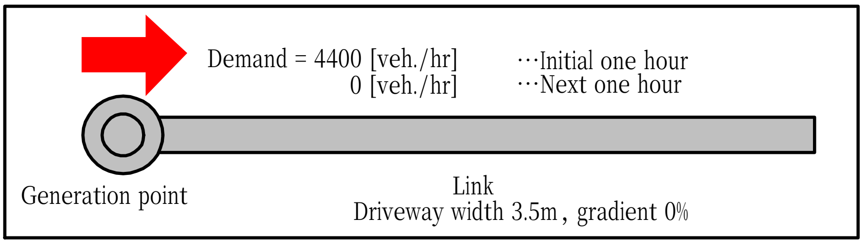


Fig.33 Verification data set for volume conservation when cars in traffic jam are drawn outside the network

ii) The cumulative curve of through volume observed at the line upstream end is illustrated to verify that 4400 vehicles have finally flowed into the network. The curve shown in Fig. 34 is projected.

[18] Verification focuses not on exact representation of theoretical values, but on definition of model behavior. It is therefore unnecessary to perform statistical calibration. Checking the graph visually is sufficient.

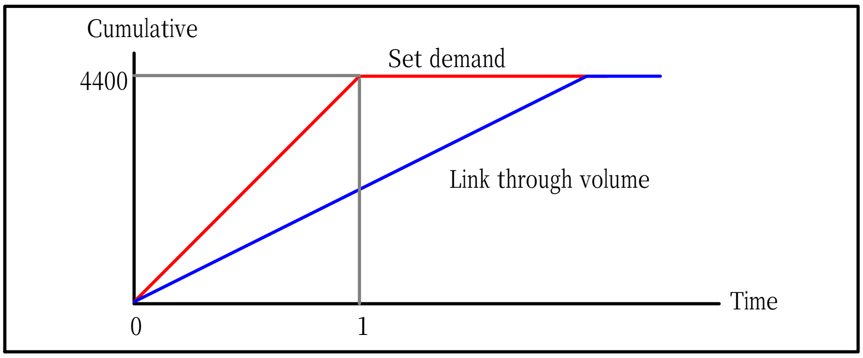


Fig.34 Volume cumulative curve projected when the 4400veh/hr demand is given

2) Relationship between model parameters, flow characteristics and bottleneck capacity

In a car-following type model, the principal parameters are roughly classified into those related to driving behavior and those related to location and road section. The former includes reaction delay, desired speed, intensity of acceleration/deceleration, etc. while the latter includes the speed limit, lane width, gradient, etc. Namely, the link capacity and Q-K curve necessary for verification are not given externally, but reproduced as a result of synthesis of individual vehicle behaviors. Therefore, the objective of this verification step is to elucidate the relationship between input data and model parameters with flow characteristics. In other words, the link capacity reproducible within the scope of actual input items and recommended parameters[19] by the model, or range of saturation flow rate must be clarified.

In this section, a car-following type model is assumed, with input items and model parameters as shown in Table 4, and with standard values and setting range, determining the Q-K curve reproducible through simulation. Model users must first list principal input items and parameters that similarly affect reproducibility of capacity. Standard values and the setting range[20] must be specified.

[19] This section does not deal with whether or not the recommended range of the model parameter is adequate in terms of traffic engineering because determination of exact values is meaningless. For example, a model parameter called "reaction delay time" in a simulation appears to be similar to the reaction delay time of actual driving behavior, but it is practically totally different from that.

[20] When the adequate parameter setting range is not described in the manual, the value range that is considered generally applicable from past experience of operation of the model must be specified.

Table4 Principal input items and parameters of an assumed model

Name		Standard	Minimum	Maximum
a) For driving behavior of vehicles				
a-1)	Reaction delay time	1.0 sec	0.7 sec	1.5 sec
a-2)	Desired headway	2.0 sec	1.7 sec	3.0 sec
a-3)	Max. acceleration (light) (Heavy)	2.5 m/sec^2 1.4 m/sec^2	1.8 m/sec^2 0.8 m/sec^2	2.5 m/sec^2 2.0 m/sec^2
a-4)	Desired speed	60 km/sec	40 km/sec	100 km/sec
b) For demand				
b-1)	Traffic demand	Set freely as required		
b-2)	Heavy vehicle ratio	15 %	0 %	30 %
c) For link performance				
c-1)	Speed limit	60 km/sec	40 km/sec	100 km/sec
c-2)	Gradient	0 %	-6 %	6 %
c-3)	Driveway width	3.5 m	2.75 m	3.5 m
c-4)	Min. headway	2.0 sec	1.7 sec	3.0 sec

To determine what kind of traffic characteristics a model demonstrates when certain input data and parameter settings (hereinafter called simply "parameter set") are used, the cumulative volume is recorded at link upstream and downstream ends in a "steady state[21]" of free and breakdown flows. Then, the volume and density within a certain time span are sampled and plotted on a Q-K plane. In this case, the average Q-K curve must also be determined from the plot for use in subsequent verification steps.

Simulation is made for a one-link network according to the procedure described below, and the Q-K curve is determined.

i) Prepare 11 types of parameter set as shown in Table 5. In the case of free flow, parameters related to c) link performance are not changed to prevent bottlenecks.

Table5 Parameter set to verify traffic characteristics in free flow

Free-1	All standard values
Free-2	a-1) minimum, the rest are all standard values
Free-3	a-1) maximum, 〃
Free-4	a-2) minimum, 〃
Free-5	a-2) maximum, 〃
Free-6	a-3) minimum, 〃
Free-7	a-3) maximum, 〃
Free-8	a-4) minimum, 〃
Free-9	a-4) maximum, 〃
Free-10	b-2) minimum, 〃
Free-11	b-2) maximum, 〃

ii) Set a sufficiently low traffic demand level for a certain parameter set to prevent breakdown, and start simulation.

iii) Wait till the link becomes a "steady state" in free flow. Observe the cumulative volumes at upstream and downstream ends of the link that has reached the "steady state." For heavy

[21] For the concept of "steady state," refer to Appendix A.

vehicles, carry out counting while assuming the personal vehicle conversion factor as 1.7.

iv) For certain ten minute periods, determine the number of vehicles within a section from the difference of cumulative volume between link upstream and downstream ends. Take the average and assume the average value as a vehicle density in ten minutes.

v) Assume that the number of vehicles passing through the downstream end within the same ten minutes is the traffic volume.

vi) Plot the result on the Q-K plane.

vii) Repeat steps v) through vii) for the next ten minutes and carry out plotting similarly.

viii) Repeat the same operation ten times, that is, perform simulation for 100 minutes, and carry out plotting on the Q-K plane.

ix) End the simulation once. Then, increase the demand in steps and repeat steps i) through viii). When the demand exceeds a certain level, the link through volume is saturated. This volume is considered to be the link capacity value in this parameter set. After observation of the link capacity, proceed to x), the next step.

x) Draw a straight line or curve to interpolate the average value plot in each parameter set. This is the Q-K curve on the free flow side in a certain parameter set.

xi) Return to i), change the parameter set, and repeat the procedure.

The procedure described above is shown in Fig. 35.

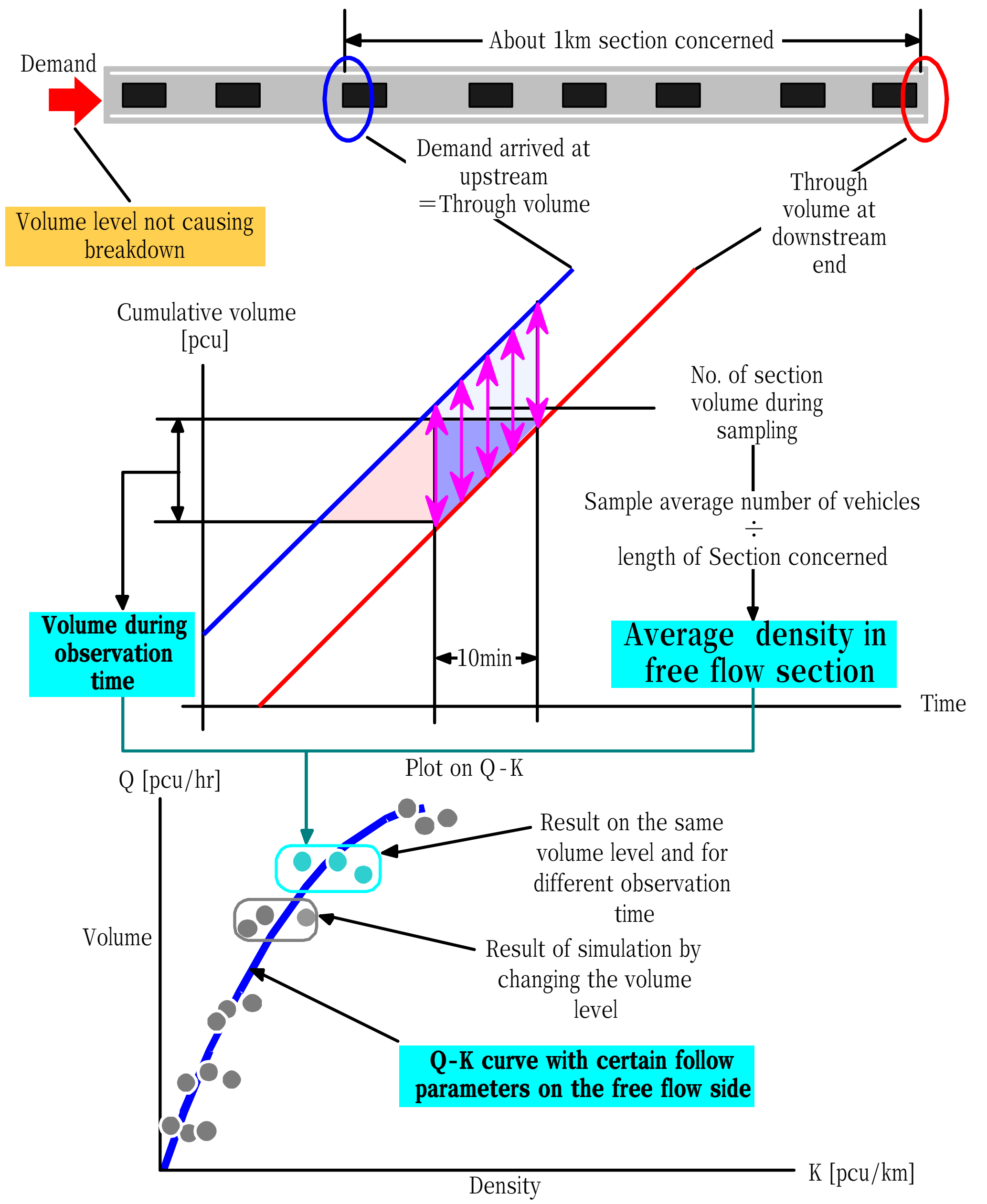


Fig.35 How to determine Q-K characteristics of free flow

To determine the Q-K curve on the breakdown side, a link or bottleneck is provided on the downstream side for the above Free-1～Free-11 parameter sets and simulation is made as follows while changing parameters related to link performance.

i) Prepare forty-four parameter sets as shown in Table 6.

Table6 Parameter set to determine traffic characteristics in the breakdown flow

Jam-1	Change Free-1 + c-1) of downstream link from standard to lower limit
Jam-2	Change Free-1 + c-2) of downstream link from standard to upper limit
Jam-3	Change Free-1 + c-3) of downstream link from standard to lower limit
Jam-4	Change Free-1 + c-4) of downstream link from standard to upper limit
Jam-5	Change Free-2 + c-1) of downstream link from standard to lower limit
Jam-6	Change Free-2 + c-2) of downstream link from standard to upper limit
Jam-7	Change Free-2 + c-3) of downstream link from standard to lower limit
Jam-8	Change Free-2 + c-4) of downstream link from standard to upper limit
Jam-9	Change Free-3 + c-1) of downstream link from standard to lower limit
Jam-10	Change Free-3 + c-2) of downstream link from standard to upper limit
Jam-11	Change Free-3 + c-3) of downstream link from standard to lower limit
Jam-12	Change Free-3 + c-4) of downstream link from standard to upper limit
Jam-13	Change Free-4 + c-1) of downstream link from standard to lower limit
Jam-14	Change Free-4 + c-2) of downstream link from standard to upper limit
Jam-15	Change Free-4 + c-3) of downstream link from standard to lower limit
Jam-16	Change Free-4 + c-4) of downstream link from standard to upper limit
Jam-17	Change Free-5 + c-1) of downstream link from standard to lower limit
Jam-18	Change Free-5 + c-2) of downstream link from standard to upper limit
Jam-19	Change Free-5 + c-3) of downstream link from standard to lower limit
Jam-20	Change Free-5 + c-4) of downstream link from standard to upper limit
Jam-21	Change Free-6 + c-1) of downstream link from standard to lower limit
Jam-22	Change Free-6 + c-2) of downstream link from standard to upper limit
Jam-23	Change Free-6 + c-3) of downstream link from standard to lower limit
Jam-24	Change Free-6 + c-4) of downstream link from standard to upper limit
Jam-25	Change Free-7 + c-1) of downstream link from standard to lower limit
Jam-26	Change Free-7 + c-2) of downstream link from standard to upper limit
Jam-27	Change Free-7 + c-3) of downstream link from standard to lower limit
Jam-28	Change Free-7 + c-4) of downstream link from standard to upper limit
Jam-29	Change Free-8 + c-1) of downstream link from standard to lower limit
Jam-30	Change Free-8 + c-2) of downstream link from standard to upper limit
Jam-31	Change Free-8 + c-3) of downstream link from standard to lower limit
Jam-32	Change Free-8 + c-4) of downstream link from standard to upper limit
Jam-33	Change Free-9 + c-1) of downstream link from standard to lower limit
Jam-34	Change Free-9 + c-2) of downstream link from standard to upper limit
Jam-35	Change Free-9 + c-3) of downstream link from standard to lower limit
Jam-36	Change Free-9 + c-4) of downstream link from standard to upper limit
Jam-37	Change Free-10 + c-1) of downstream link from standard to lower limit
Jam-38	Change Free-10 + c-2) of downstream link from standard to upper limit
Jam-39	Change Free-10 + c-3) of downstream link from standard to lower limit
Jam-40	Change Free-10 + c-4) of downstream link from standard to upper limit
Jam-41	Change Free-11 + c-1) of downstream link from standard to lower limit
Jam-42	Change Free-11 + c-2) of downstream link from standard to upper limit
Jam-43	Change Free-11 + c-3) of downstream link from standard to lower limit
Jam-44	Change Free-11 + c-4) of downstream link from standard to upper limit

ii) Simulation is made with demand equivalent to link capacity that can cause jams at bottleneck.

iii) Wait till the upstream link becomes a “steady state” with breakdown flow. In this “steady state”, observe the cumulative volume at the upstream and downstream ends of the upstream link.

iv) For a certain ten minutes, determine for every minute the number of vehicles in a section from the difference in cumulative volume between upstream and downstream ends of the link. Take the average and use it as the vehicle density for the ten minutes.

v) Assume also that the number of vehicles passing through the downstream end within the same ten minutes is the traffic volume.

vi) Plot the result on the Q-K plane.

vii) Repeat steps iv) through vi) in the next ten minutes and carry out plotting similarly.

viii) Repeat this operation ten times, that is, for simulation for 100 minutes, and carry out plotting on the Q-K plane. Variance of plotting serves as a guideline to see if the bottleneck capacity is reproduced in a stable manner.

ix) End simulation once. Then, repeat steps ii) through viii) while changing the parameter c) concerning the performance of the downstream link. It is recommended to change the c) value in about five steps.

x) Draw a curve to interpolate these results. This is the Q-K curve of a certain parameter set for the jam side. Specify the lower limit value to define the range of bottleneck capacity reproducible only with model parameters.

xi) Close the road at the link downstream end to determine the jam density. Count the number of vehicles that are stopped in a traffic jam.

xii) Return to step i) and repeat the same procedure while changing the parameter set.

The above procedure is shown in Fig. 36.

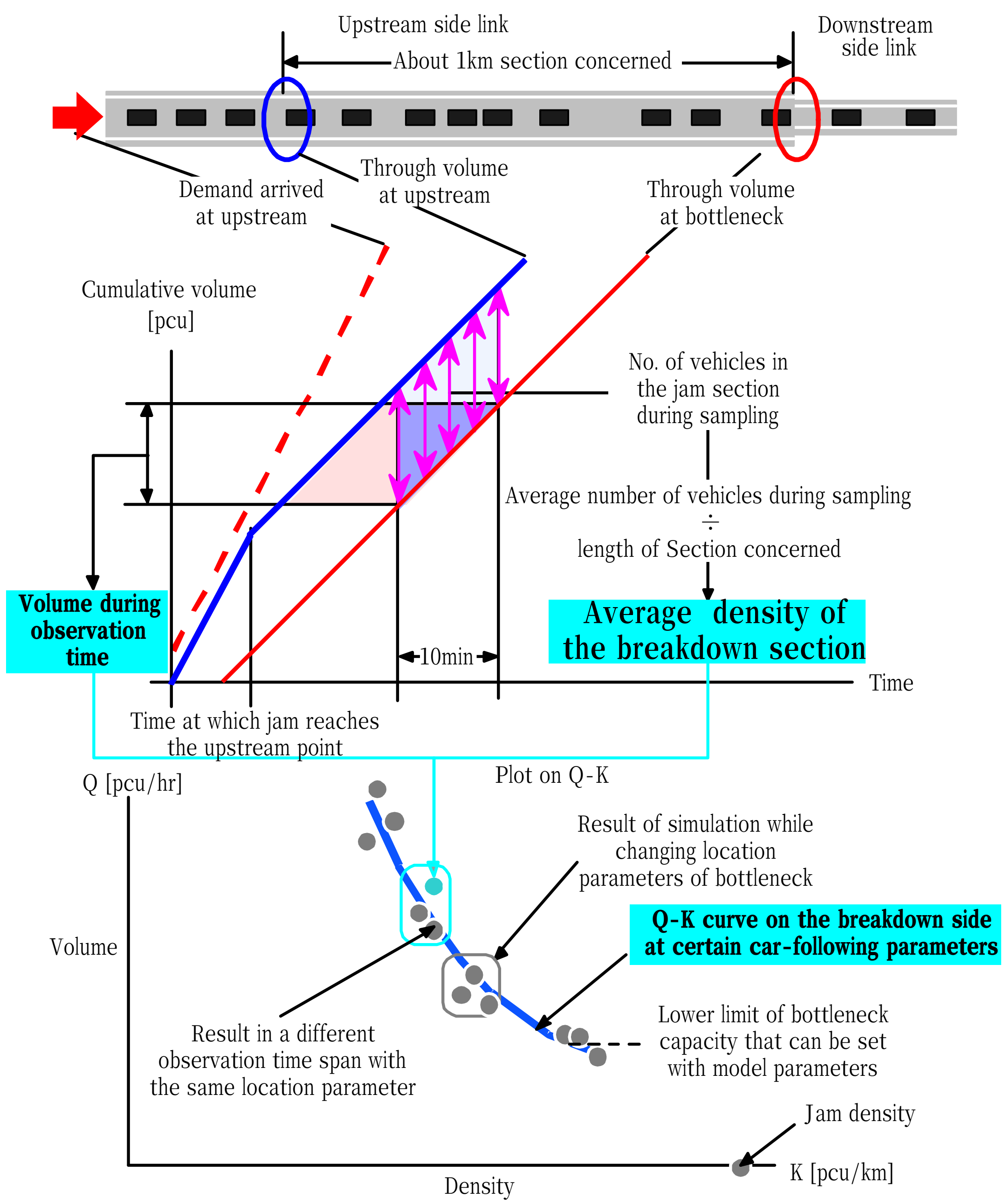


Fig.36 How to determine the Q-K characteristics in the breakdown flow

Q-K curves determined in this way for free flow and breakdown sides are overlapped to be used as traffic characteristics[22] of a certain parameter set.

3) Relationship between model parameter and saturation flow rate

Verification of reproducibility of the saturation flow rate at the link downstream end is as follows. Namely, verification is conducted for the simulation model for ordinary streets, including signalized intersections, by checking the manner in which vehicles retained during red phases run off during green phases.

[22] In this case, a total of 11 types of Q-K characteristics are obtained. They are “Free-1 + Jam-1, Jam-2, Jam-3, Jam-4” to “Free-11 + Jam-40, Jam-41, Jam-42, Jam-43.”

i) A network is made from a one-lane link controlled by a signal at the downstream end, as shown in Fig. 37. The signal is under a fixed-time control with a cycle length of 120 [seconds], a split of 50%, and a lost time of 10 [seconds/cycle]

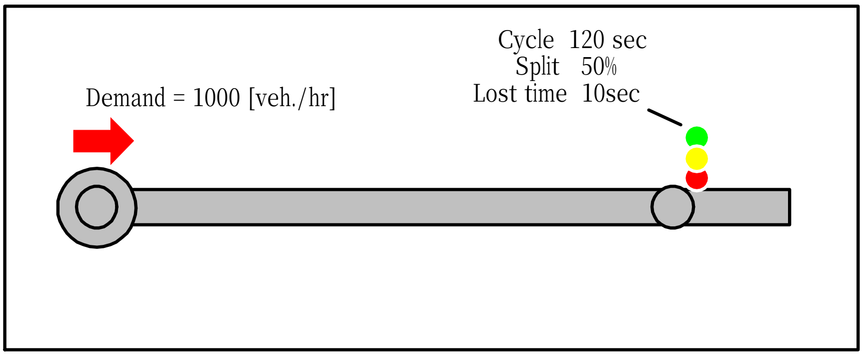


Fig.37 Verification data set for saturation flow rate at the link downstream end

ii) Assume that the demand arrived from the upstream is 1000veh/hr, and carry out simulation for one hour for each of 19 parameter sets shown in Table 7.

Table7 Parameter sets used for verification of saturation flow rate

SFR-1	All standard values
SFR-2	a-1) minimum, the rest are all standard values
SFR-3	a-1) maximum, 〃
SFR-4	a-2) minimum, 〃
SFR-5	a-2) maximum, 〃
SFR-6	a-3) minimum, 〃
SFR-7	a-3) maximum, 〃
SFR-8	a-4) minimum, 〃
SFR-9	a-4) maximum, 〃
SFR-10	b-2) minimum, 〃
SFR-11	b-2) maximum, 〃
SFR-12	c-1) minimum, 〃
SFR-13	c-1) maximum, 〃
SFR-14	c-2) minimum, 〃
SFR-15	c-2) maximum, 〃
SFR-16	c-3) minimum, 〃
SFR-17	c-3) maximum, 〃
SFR-18	c-4) minimum, 〃
SFR-19	c-4) maximum, 〃

iii) In ten cycles after simulation start, observe run-off from the link for about ten cycles. The observation time interval is the model unit scan time[23].

iv) With each parameter set, the run-off volume per cycle after start of green phase is represented by the cumulative curve. Cumulative curves for ten cycles are overlapped as shown in Fig. 38[24]. Verification is carried out to confirm that the flow rate is reproduced in a stable manner in any cycle while the flow is saturated.

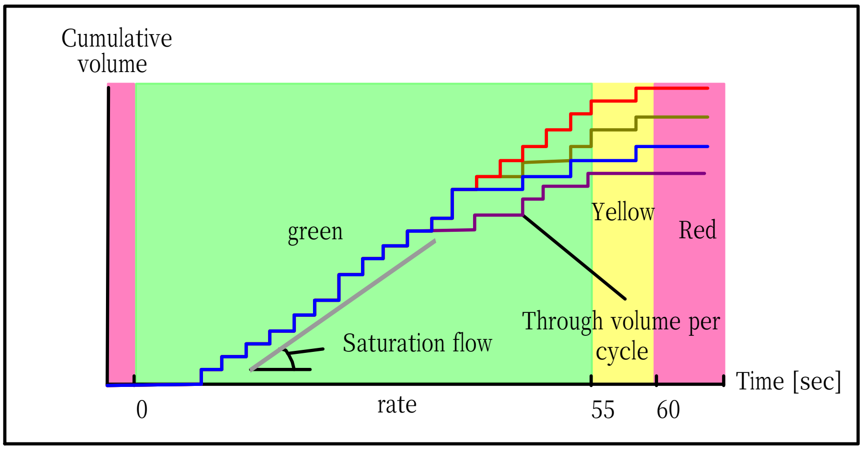


Fig.38 Saturation flow rate observed at the link downstream end

[23] For an event scan type simulation model, observation must be made at least every second.

[24] Draw a straight line with a slope equivalent to that of the cumulative curve while the flow is saturated in the graph. The inclination or the saturation flow rate must be entered in the graph. Note that this is only a guideline and the exact value of inclination is not necessarily significant.

4) Spreading out vehicles, and eliminating traffic jams, and shock wave propagation rates

This verification is carried out for the basic segment, including bottlenecks, under the following conditions:

l) Demand exceeding the bottleneck capacity, with jammed traffic is drawn to the upstream
m) Demand below the bottleneck capacity, with jams disappearing downward from the upstream side

Verification consists of confirming how spreading vehicles out and eliminating jams are reproduced as compared with the shock wave theory. For the model controlled with signals, further verification is done for the following condition:

n) Condition in which jams are eliminated upward from the downstream as the signal phase changes from red to green

The specific procedure is described first for a) and b).

i) For verification, a basic segment network with a bottleneck section on the downstream side is formed. About three to five sections are set to observe the through traffic. To verify the traffic flow characteristics, three types of parameters set with typical Q-K characteristics are provided from the sets used in step 2). In these parameter sets concerning road conditions, standard values are used for the entire basic segment on the bottleneck upstream side. The bottleneck section reproduced with the smallest capacity is used. The section length for which the cumulative number of through vehicles is observed should be determined appropriately according to the flow characteristics, so that the shock wave propagation can be grasped[25]. In this model, observation sections are arranged every 500 m.

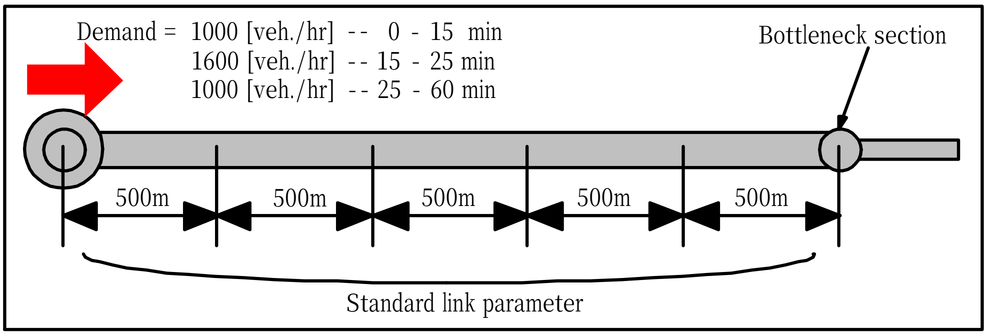


Fig.39 Verification data set for spreading vehicles and eliminating jams

ii) The demand[26] is given, in which there are peaks of jams at bottleneck and elimination of jams. In this verification, the following levels of demand are given for the bottleneck capacity after

[25] Namely, the traffic condition transition diagram on the bottleneck upstream side is first prepared from the shock wave propagation rate determined in Fig. 40. And the section length is set so that the shock wave surface is grasped at as many sections as possible.
[26] The demand to be provided must generate jams relative to the bottleneck capacity shown in Fig. 40.

start of simulation:

- 0〜15 min･･1000veh/hr
- 15〜25 min･･1600veh/hr
- 25〜60 min･･1000veh/hr

iii) As shown in Fig. 40[27], the shock wave propagation rate is determined from the Q-K curve that the parameter set of the model represents. And the traffic condition transition diagram on the bottleneck upstream side, shown in Fig. 41, is prepared beforehand.

iv) Simulation is made for each of three types of parameter sets. The condition of spreading out vehicles is grasped by recording the cumulative through volume at each observation section.

v) As shown in Fig. 41, the traffic transition diagram is overlapped to the through volume cumulative curve at each section, and verification[28] is made for how spreading vehicles and eliminating jams are reproduced with reference to the theory.

[27] In this case, four forward waves of FW1 through FW4 and one backward wave BW1 are generated.

[28] Considering the purport of verification, it is enough here to see visually on the graph if the time point at which the flow rate changes on the cumulative curve agrees with that at which the shock wave is theoretically propagated. As the flow rate is not stable during simulation, it is difficult to precisely and numerically indicate the time point at which shock waves are propagated. In addition, the Q-K curve to determine the theoretical value shows only the average and has originally been prepared as a guideline.

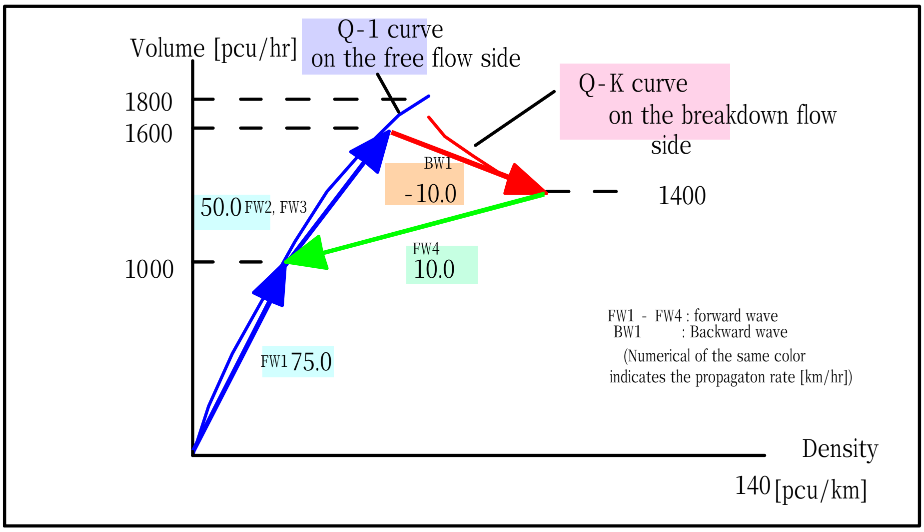


Fig.40 Shock wave propagation rate determined from Q-K curve

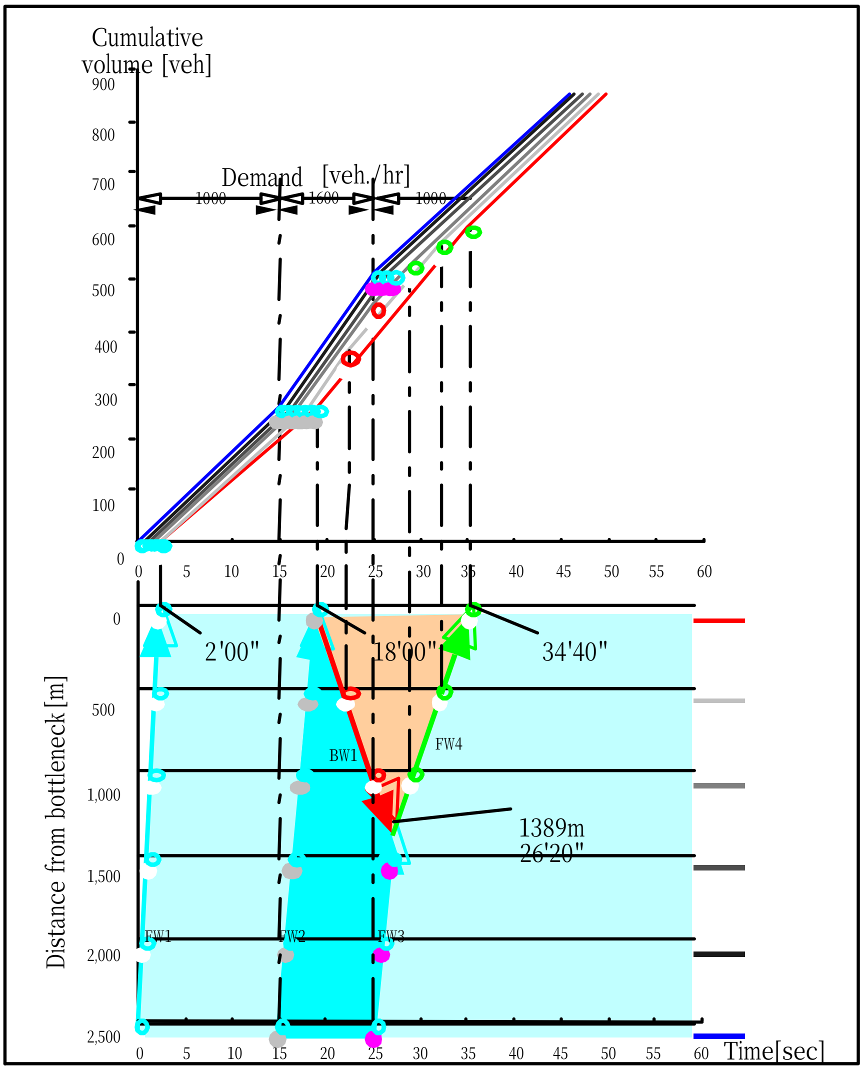


Fig. 41 Traffic condition transition diagram upstream of bottleneck (below) and through volume cumulative curve at each observation section (above)

Now the procedure for c) is described below. Verification is carried out here of a simulation model of ordinary streets including signalized intersections by checking the manner in which vehicles held up during red phase run off at green phase. In this verification, the propagation rate of forward and backward waves under control of signals is compared with the theoretical values obtained from the shock wave theory.

v) A network is made from a basic-segment network, including signalized intersections, as shown in Fig. 42. The signal is under a fixed-time control with a cycle length of 120 [seconds], a split of 50%, and a lost time of 10 [seconds/cycle]. Sections to observe the through volume are arranged every 20 m on the upstream side of the signalized intersection. The observation time interval is the model unit scan time[29].

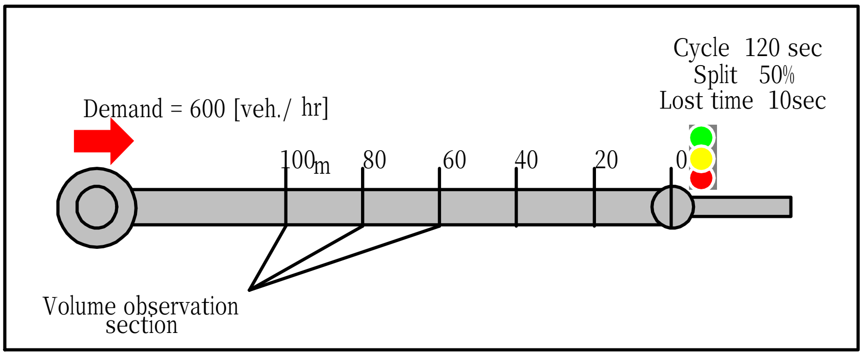


Fig.42 Verification data set for start/stop wave under control of signal

vi) Three typical parameter sets to give the typical saturation flow rate are prepared to verify the saturation flow rate. Given a demand of 600 [veh/hr], simulation is made for each set. Since highly random arrival causes difficulty in comparison because the stop wave is not propagated uniformly, it is desirable that uniform arrival is assumed for vehicle generation[30].

vii) From the Q-K curve and saturation flow rate corresponding to the given parameter set, the start/stop wave propagation rate is determined from Fig. 43. Then, the traffic condition transition diagram upstream of the signalized intersection is prepared as shown in Fig.44 (below).

viii) For an appropriate one-cycle time span beginning with a red phase, the cumulative curve of through volume at each point is overlapped as shown in Fig. 44 (above). This is then overlapped with the traffic condition transition diagram to check if the time points at which the inclination changes agree[31].

[29] For an event scan type simulation, observe the volume at intervals of about 1 second.

[30] For a model for which uniform arrival is not assumed, a contrivance must be used, such that a given demand is provided within the shortest possible interval. For example, 10 vehicles are generated every minute.

[31] Considering the purport of verification, it is enough here to see visually on the graph if the time point at which the link run-off rate changes on the cumulative curve agrees with that at which the start/stop wave is propagated theoretically. As the run-off rate is not stable during simulation, it is difficult to indicate precisely and numerically the time point at which the start/stop wave is propagated.

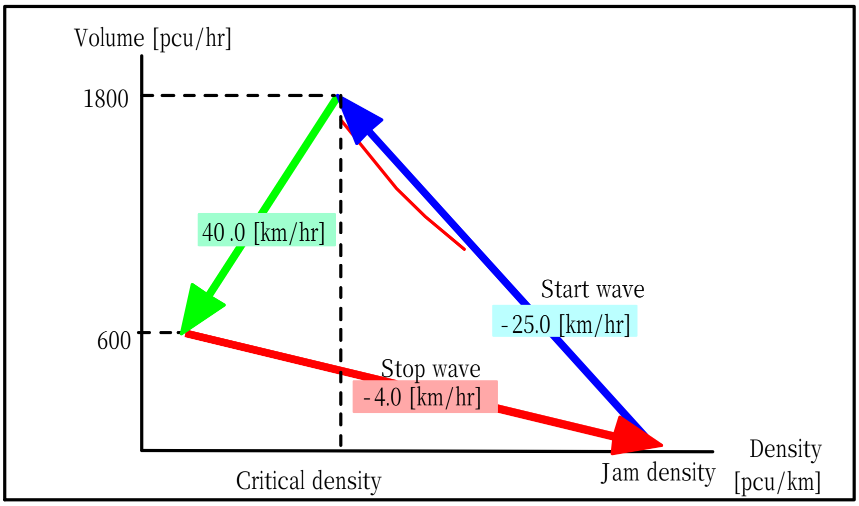


Fig.43 Start/stop wave velocity determined from the Q-K curve

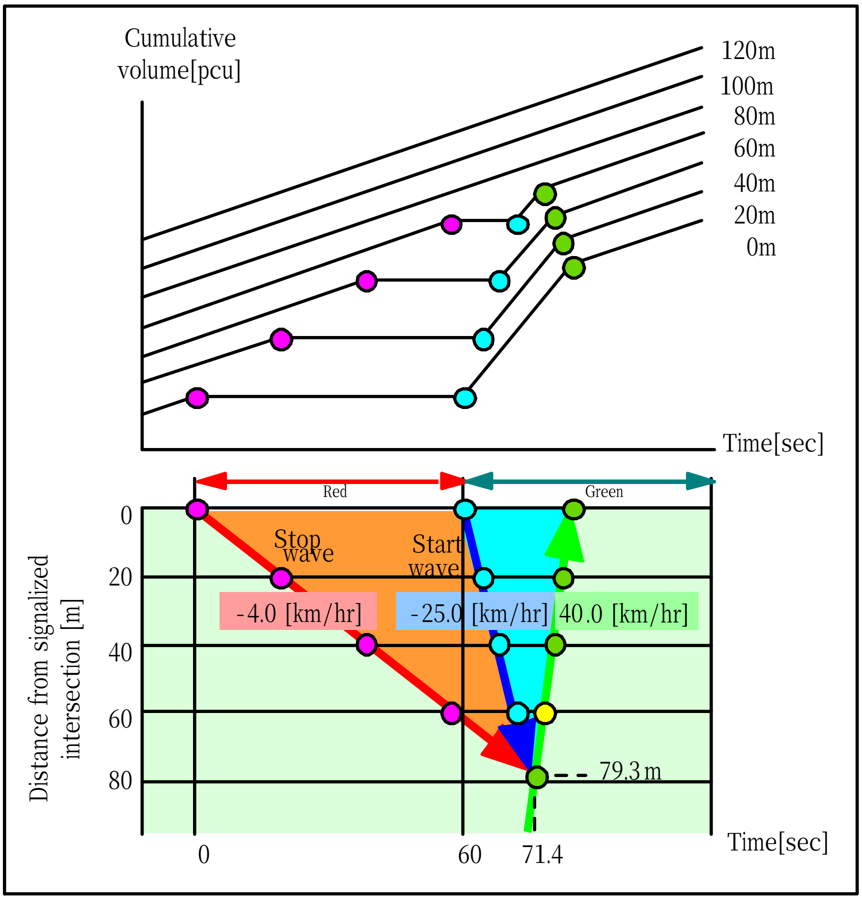


Fig.44 Start/stop wave propagation condition and cumulative volume at each point

5) Capacity and merge ratio of the merge area[32]

For verification of the merge area, the standard values and setting ranges must be clarified not only for the input data and parameters used to define the characteristics of car-following travel of Table 4, but also for others that may affect merge behavior. Table 8 provides examples of principal input items and parameters for an assumed model.

Table8 Principal input items and parameters affecting merge behavior of an assumed model

Name		A	B	C
d) For driving behavior of vehicles				
d-1)	Gap acceptance threshold[33]	1.0 sec	0.7 sec	1.5 sec
e) For the merge section				
e-1)	Merge section length	100m	0m	200m
e-2)	Max. entry speed from a merge branch	50km/h	30km/h	80km/h
f) Merge branch and main lane demand ratio				
f-1)	Total 2000[veh/hr]	3:7	1:9	5:5
f-2)	Total 2500[veh/hr]	3:7	1:9	5:5

In this case, Standard values of Table 4 (i.e., Free-1 of Table 5) is used as parameters related to car-following travel. Furthermore, input items and parameters of Table 8 are changed as shown in Table 9. The capacity and merge ratio in the merge area are verified each case.

Table9 Parameter sets used for verification of merge area

Merge-1	"Free-1" + "d-1-A" + "e-1-A" + "e-2-A" + "f-1-A"
Merge-2	"Free-1" + "d-1-B" + "e-1-A" + "e-2-A" + "f-1-A"
Merge-3	"Free-1" + "d-1-C" + "e-1-A" + "e-2-A" + "f-1-A"
Merge-4	"Free-1" + "d-1-A" + "e-1-B" + "e-2-A" + "f-1-A"
Merge-5	"Free-1" + "d-1-A" + "e-1-C" + "e-2-A" + "f-1-A"
Merge-6	"Free-1" + "d-1-A" + "e-1-A" + "e-2-B" + "f-1-A"
Merge-7	"Free-1" + "d-1-A" + "e-1-A" + "e-2-C" + "f-1-A"
Merge-8	"Free-1" + "d-1-A" + "e-1-A" + "e-2-A" + "f-1-B"
Merge-9	"Free-1" + "d-1-A" + "e-1-A" + "e-2-A" + "f-1-C"
Merge-10	"Free-1" + "d-1-A" + "e-1-A" + "e-2-A" + "f-2-A"
Merge-11	"Free-1" + "d-1-A" + "e-1-A" + "e-2-A" + "f-2-B"
Merge-12	"Free-1" + "d-1-A" + "e-1-A" + "e-2-A" + "f-2-C"

The verification procedure for the merge area is described below.

i) With a network made up from merge branches and the main lane as shown in Fig. 45, simulation is made for each parameter set for about one hour.

[32] In the case of car-following type model, verification of the merge area is omitted because the FIFO rule is evidently observed, and the capacity of the downstream link is synthesized according to parameter setting. Verification of this capacity is the same as for verification of the bottleneck in the basic element. Contrary to this, the Q-K type model requires verification of whether or not the FIFO rule is observed in the link upstream of the diverge area and the volume is shifted so that it is subject to restrictions of the downstream link capacity.

[33] In this table, a model is assumed, which judges merging by means of 0/1 while using the gap acceptance threshold as a border. For a model based on probability determination, three types of probability distributions must be provided.

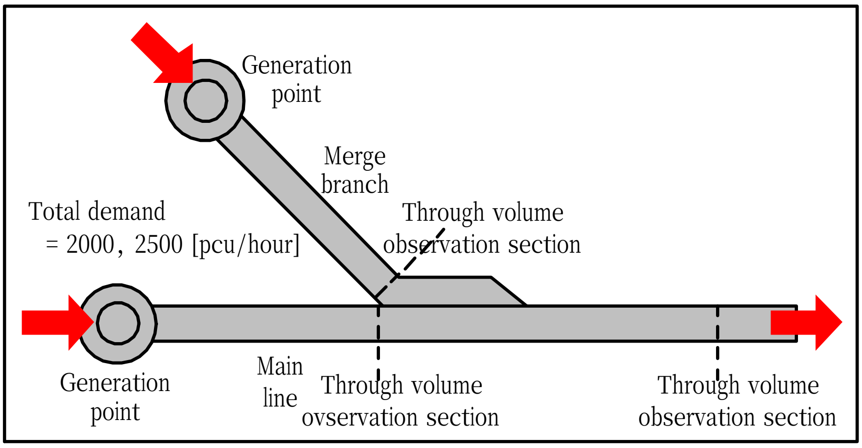


Fig.45 Verification data set for reproducibility of the merge area capacity

ii) The volume is observed at the downstream end of the diverge branch and main line for each case. The cumulative volume of each case and the total cumulative volume (= cumulative volume of the merge area) are plotted into a graph. The cumulative demand curve is also entered in this graph to determine if breakdown has occurred in the merge branch and main line. The merge ratio determined from the through volume of the merge branch and main line is also entered in the graph.

6) Decrease in the right-turn capacity due to opposing traffic in signalized intersection

To verify the right-turn capacity, the result is compared with the right-turn capacity calculation equation[34] of the Japan Society of Traffic Engineers, which is widely employed in Japan. Standard values and setting ranges must be clarified not only for the input data and parameters used to define the characteristics of car-following travel of Table 4, but also for others that may affect merge behavior. Table 10 provides examples of principal input items and parameters for an assumed model.

[34] This equation is not used to produce the theoretical value. It is used only for reference during comparison.

Table10 Principal input items and parameters affecting right-turn capacity of an assumed model

Name		A	B	C
g) For driving behavior of vehicles				
g-1)	Opposing straight through gap acceptance threshold[35]	3.0 sec	5.0 sec	8.0 sec
h) For intersection structure				
h-1)	No. of vehicles retained in the intersection	1 veh	2 veh	4 veh
h-2)	Min. right-turn headway	1.7sec	2sec	3sec
i) Signal parameters				
i-1)	Cycle	120sec (common to all cases)		
i-2)	Effective green time	Three type of 40, 60, and 80sec		
j) For demand				
j-1)	Opposing through demand	Variable in 200 steps from 200〜1200[veh/hr]		
j-2)	Right-turn demand	2000[veh/hr] (common to all cases)		

In this case, the Standard values of Table 4 (i.e., SFR-1 of Table 7) are used as parameters related to car-following travel. Furthermore, input items and parameters of Table 10 are changed as shown in Table 11. The achieved right-turn capacity is verified for each case.

Table11 Parameter sets used to verify the right-turn capacity

Rturn-1	"SFR-1" + "g-1-A" + "h-1-A" + "h-2-A"
Rturn-2	"SFR-1" + "g-1-B" + "h-1-A" + "h-2-A"
Rturn-3	"SFR-1" + "g-1-C" + "h-1-A" + "h-2-A"
Rturn-4	"SFR-1" + "g-1-A" + "h-1-B" + "h-2-A"
Rturn-5	"SFR-1" + "g-1-A" + "h-1-C" + "h-2-A"
Rturn-6	"SFR-1" + "g-1-A" + "h-1-A" + "h-2-B"
Rturn-7	"SFR-1" + "g-1-A" + "h-1-A" + "h-2-C"

The verification procedure is described below as an example.

i) A network including one signalized intersection is formed as shown in Fig. 46.

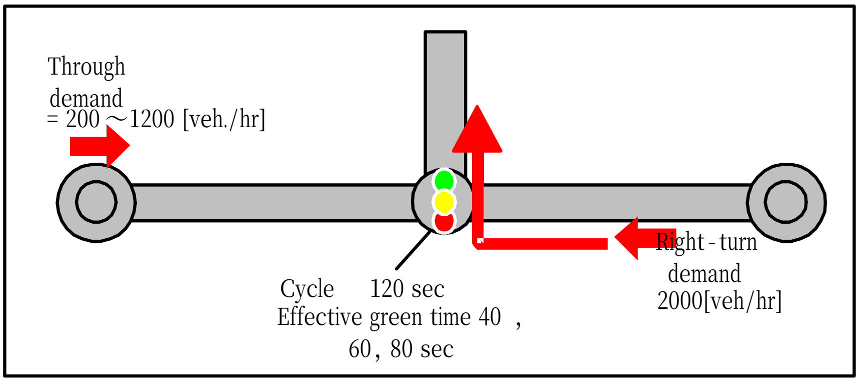


Fig.46 Verification data set for right-turn capacity

35 In this table, a model is assumed, which judges merging by means of 0/1 while using the gap acceptance threshold as a border. For a model based on probability determination, three types of probability distributions must be provided.

ii) Set the cycle to 120 sec for the signal parameter and change the effective green time in three stages of 40, 60, and 80 sec. While changing the opposing through demand in six stages of 200, 400, 600, 800, 1000, and 1200 for each signal parameter, carry out simulation for about one hour, observing the right-turn capacity.

iii) Compare the simulation observation result with the equation below:

$$S_R=1800\, f\,(S\,G - q\,C)/(S - q)\,C + 3600K/C \quad \cdots(1)$$

$S_R\cdots$Inverse number of min. headway of right-turn(=right-turn capacity) [veh/hr]

$S\cdots$Value reproduced with SFR-1 during verification of saturation flow rate [veh/effective green one hour]

$q\cdots$Volume at approach of opposing through traffic [veh/hr]

$C\cdots$Cycle length [sec]

$G\cdots$Effective green time [sec]

$K\cdots$No. of vehicles discharge at change of signal [veh/cycle]

$f\cdots$Gap acceptance probability determined as follows:

f =	1.00 (q=0),	0.81 (q=200),
	0.65 (q=400),	0.54 (q=600),
	0.45 (q=800),	0.37 (q=1000),
	0.0 (q>1000),	Interpolation made for median q value

When comparing simulation results, plot the opposing straight through volume on an abscissa and the right-turn capacity (=through volume) on a coordinate for each signal parameter setting, as shown in Fig. 47.

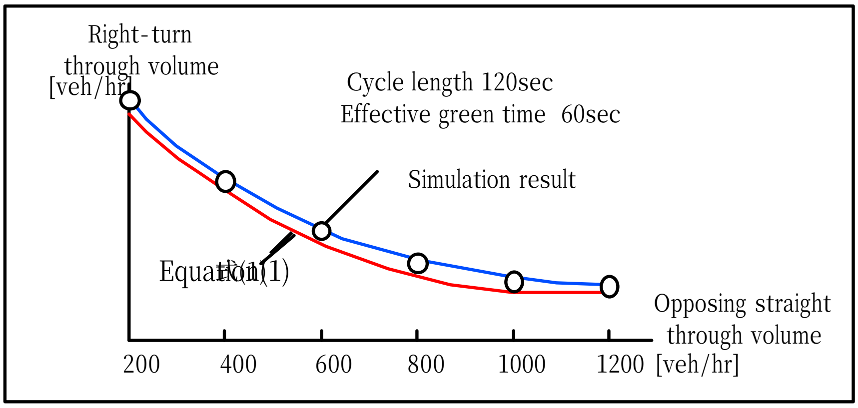


Fig.47 Comparison of simulation result and theoretical values for right-turn capacity

7) **Route selection behavior**

This verification is carried out to confirm the route selection model the simulation model assumes and how truly the theoretical value is reproduced. The theory in this case is based on a dynamic allocation principle — either DUO or DUE. Since an excessively complicated network makes calculation of the theoretical value itself impossible, a simple network comprising a 1OD2 route is used for verification. Verification is carried out here as follows:

i) The 1OD2 route network shown in Fig. 48 is used. The parameter on the link performance of Table 4, c) is set so that the merge area becomes a bottleneck. Namely, use values with which the capacity of link 3 is smaller than links 0 to 2. For the merge area, set the parameter concerning merge behavior of Table 8 so that the merge ratio during a jam becomes 1:1.

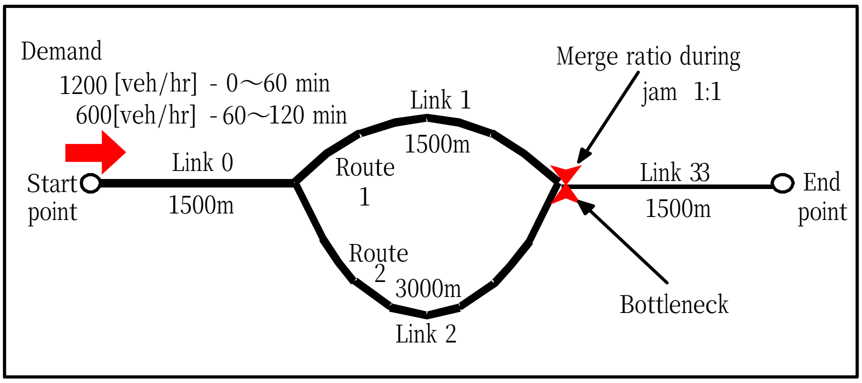


Fig.48 Example of verification data set for reproducibility of route selection behavior

ii) Prepare three model setting patterns[36] for each of the model selection standards (DUO/DUE, shortest cost selection/probability selection, etc.) and route cost renewal time interval, and route selection timing.

iii) For each setting pattern, simulation is made while providing peak demands that cause jams. Observe the cumulative volume of incoming and run-off for links 1 and 2 in each case, and compare the observed result with the theoretical flow pattern. For reference, set the demand to 1200 [veh/hr] for the initial one hour and 600 [veh/hr] for subsequent one hour. The flow pattern when DUE is achieved with the free flow rate being 36 km/h (= 10 m/sec)[37] is shown in Fig. 49. It is also assumed that the link capacity achieved with the set model parameters is 1800 [veh/hr] for links 0 to 2 and 900 [veh/hr] for link 3. It should be noted that, to avoid complication, the link volume is handled with point-queue, and that drawing of jammed vehicles to the diverge area is not considered.

[36] No specific parameters and set items are specified here because they differ substantially from one model to another. Model users must specify pertinent parameters and set up appropriate values.
[37] The difference of free travel time between both routes is 2.5 minutes.

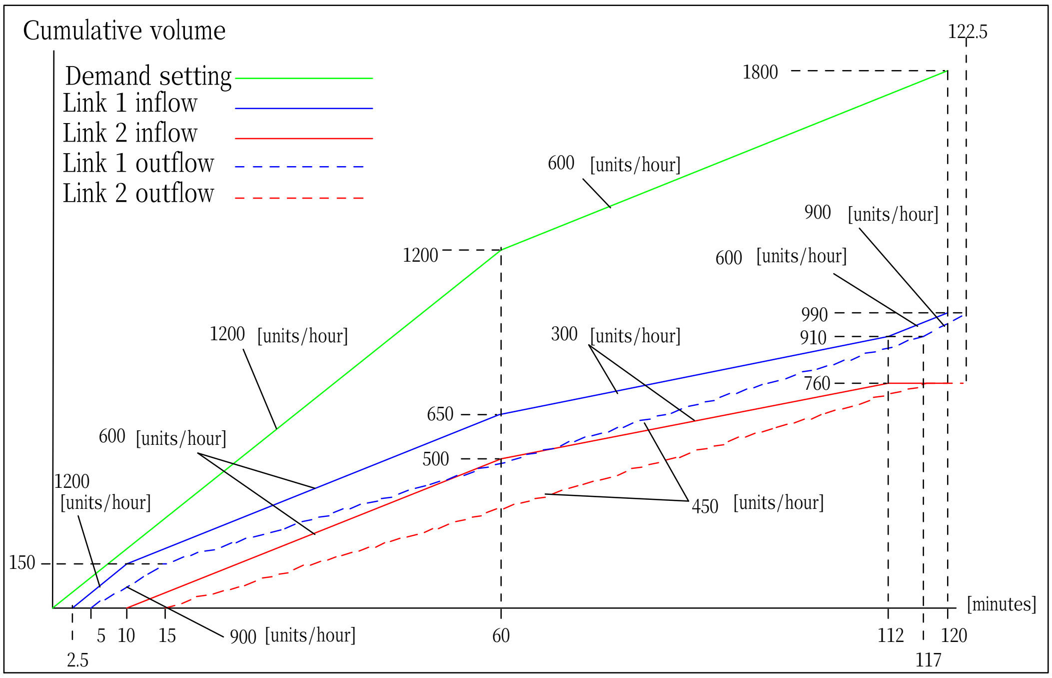


Fig.49 Flow pattern when DUE is achieved

Appendix A
Concept of Steady State

Verification of flow characteristics represented by the car-following type model is made separately for the free flow condition and traffic jam flows. Here, simulation with a simple one-lane basic segment is made for a combination of a certain model parameter. When traffic conditions in a certain section becomes "steady," the traffic density and volume of this section are plotted to determine the Q-K curve. In this case, the "steady" traffic condition can be defined as a condition in which "the volume observed at any point in the section concerned shows an equivalent flow rate within a given tolerance range regardless of the time span." Needless to say, the size of the tolerance varies[38] depending on the time span length to be determined, making determination of specific standard values difficult. Therefore, more simplified criteria are described below:

i) To determine whether or not the free flow is in a steady state, simulation is made with a given demand[39] every hour. After elapse of sufficient time[40], the cumulative volume is determined every ten minutes at the volume generation point and at the link upstream and downstream ends. In this case, the condition is judged to be steady when the difference in cumulative volume between upstream and downstream ends does not increase as time passes and no vehicles are retained at the generation point.

ii) To determine whether or not a jam flow is in a steady state, simulation is made by applying a given demand exceeding the bottleneck capacity to a basic segment network made up from a link with the bottleneck at the downstream end. After elapse of sufficient time, the cumulative volume is determined every ten minutes at the volume generation point and at the link upstream and downstream ends. Concurrently, the average travel speed in the link concerned and that in the section further downstream of the link downstream end are measured every ten minutes. The condition is judged to be steady when the difference in cumulative volume between the upstream and downstream ends does not increase as time passes, and when an increasing number of vehicles are retained and can not enter the link at the generation point, and the average travel speed of the link concerned is below that on the further downstream side.

[38] The traffic condition which may be judged "steady" for the time span of 30 minutes is no longer "steady" when the time span is changed to 5 seconds because the volume measured during the time span varies depending on the location and time.
[39] This means that the same volume is given for each time span.
[40] This time is the time period till the volume arrives at the link downstream end.

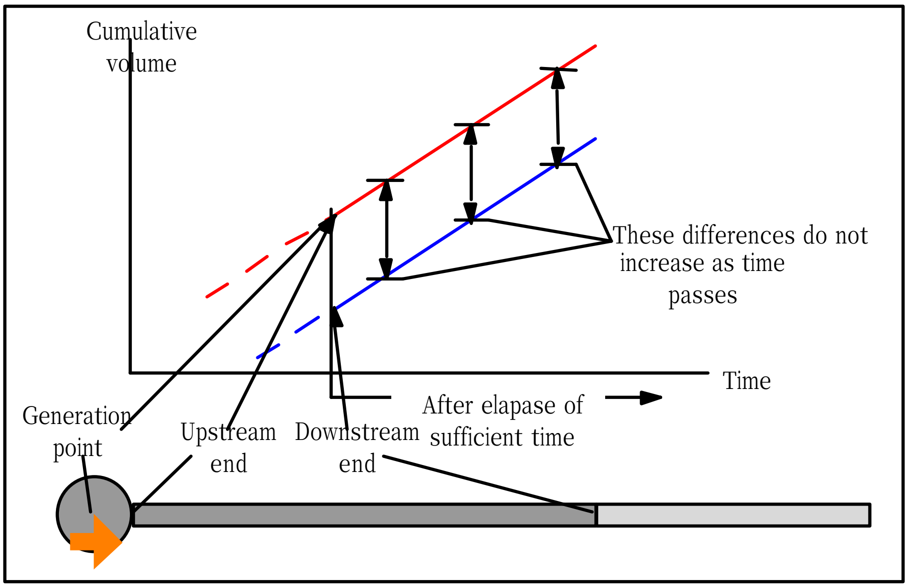


Fig.A1-1 Conceptual view when the free flow is in a steady state

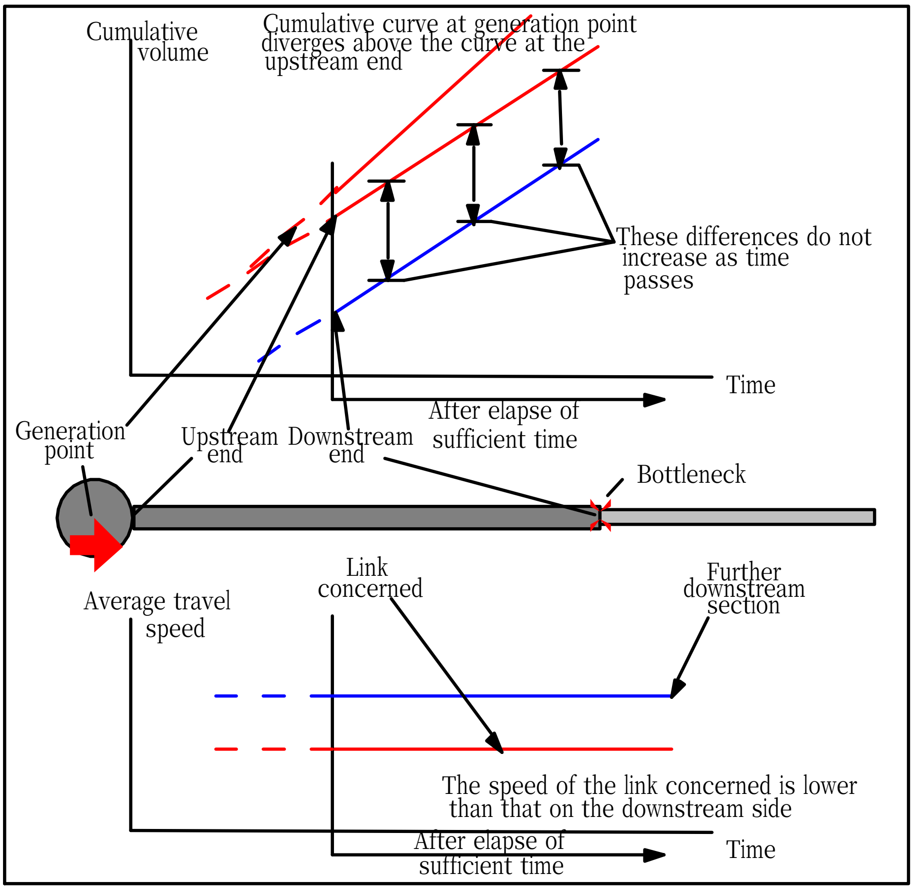


Fig.A1-2 Conceptual view when the flow in a traffic jam is in a steady state