Development of a Network Traffic Simulator for the Entire Inter-urban Expressway Network in Japan

Shoichi Hirai [a][*], Jian Xing[a], Ryota Horiguchi[b],
Tomoyoshi Shiraishi[b], Masato Kobayashi[b]

[a]Nippon Expressway Research Institute Co., Ltd.,1-4-1 Tadao Machida-shi Tokyo, Japan
[b]i-Transport Lab. Co., Ltd., 3-10 Kanda-Ogawamachi, Chiyoda-ku, Tokyo, Japan

Abstract

This paper describes the development of a network traffic simulator for the entire inter-urban expressway network in Japan. With recent developments, the network topology is getting more complex, and traffic prediction based on statistical analysis is becoming harder since it does not take into account the drivers' behavioural changes on the network. Looking at the issue from the seeds and needs perspective, there would be needs to develop a network traffic simulator dealing with traffic flow dynamics and driver behaviors. From the seeds side, road operators are now motivated to utilize the electronic toll collection (ETC) trip data collected every time a vehicle passes an ETC tollgate located at interchanges. Fully using ETC data is expected to improve the accuracy of time-dependent O-D matrix and route choice behavior model which is important in simulation studies. In this paper, the concept of traffic modeling and route choice behavior modeling in the expressway network simulation will be described, followed by calibration of time-dependent O-D matrix.

Keywords: traffic simulation, expressway network, O-D matrix calibration, route choice behavior

[*] Corresponding author. Tel.: +81-42-7911679.
E-mail address: s.hirai.aa@ri-nexco.co.jp (S. Hirai)

1. Introduction

This paper describes the development of a network traffic simulator for the entire inter-urban expressway network in Japan (Fig. 1). Inter-urban expressways stretch for more than 8,000 km over Japan and serve approximately 5 million trips per day. There are more than 20,000 detectors installed on the expressways, collecting vehicle counts and speeds every 5 minutes.

Fig. 1: Inter-urban expressway network in Japan

The road-operator companies use this traffic sensor data to predict traffic congestion caused by weekend leisure traffic, road works, incidents, etc. So far, they simply apply statistical analysis of the travel purposes and their expertized heuristic knowledge to make the prediction. With recent developments, however, the network topology is getting more complex, and traffic prediction is becoming harder since statistical analysis does not take into account the drivers' behavioral changes on the network. Therefore, there is a need to develop a network traffic simulator based on traffic flow dynamics to deal with traffic congestion, considering driver behaviors.

Looking at the issue from the seeds side, road operators are now motivated to utilize the electronic toll collection (ETC) trip data, collected every time a vehicle passes an ETC toll gate located at interchanges. Nowadays, ETC is used in close to 90% of the total number of trips on expressways. Fully using ETC data, therefore, is expected to improve the accuracy of time-dependent O-D matrix and route choice behavior model which is important in simulation studies.

In the following chapters, the concept of traffic modeling and route choice behavior modeling in the expressway network simulator (ENS) will be described, followed by calibration of time-dependent O-D matrix.

2. Modeling concept of the Expressway Network Simulator

The ENS is developed based on a mesoscopic traffic simulation model, SOUND [SOUND, 2014], which was developed at the University of Tokyo [Yoshii and Kuwahara, 1995] and has been revised through its use in many practical studies. This chapter outlines major modeling components in SOUND and their modifications for the ENS.

2.1. Discrete vehicle trip generation with time-dependent O-D matrix

SOUND deals with the discretized trip of each vehicle attributing its origin, destination, departure time, vehicle type, etc. The trip generation number of each vehicle type is aggregated to time-dependent O-D matrix with designated time interval. At the beginning of each interval, all generated vehicles are accumulated into the departure queue of their origins. The accumulated vehicles are randomly shuffled and provided their departure times in the interval according to the Poisson arrival model.

In the case of the ENS, the time interval is set to 15 minutes. As a ramp link at an interchange is connected to an origin and destination point (centroid), as shown in Fig. 2, there are more than 1300 interchanges in the entire network of the ENS, resulting in approximately 1.7M O-D pairs for each time interval and vehicle type.
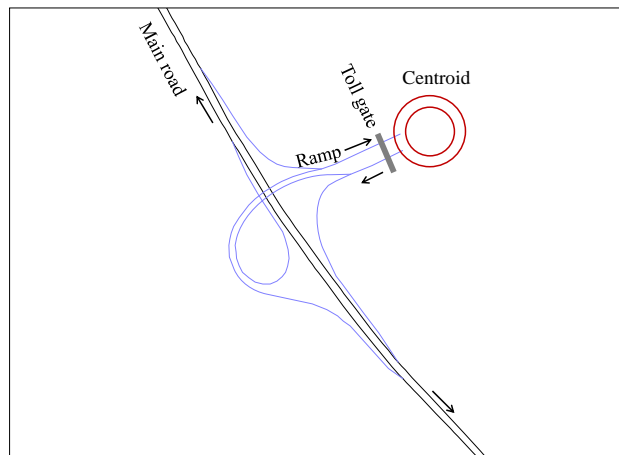

Fig. 2: A centroid connecting to interchange ramp links

2.2. Modelling of traffic flow dynamics

2.2.1. Flow-density evolution with the kinematic wave theory

Fig. 3 shows the inner-link structure adopted by SOUND, i.e. a link length L consists of a vehicle queue for the thru-lanes and queues for the auxiliary lanes, if they exist, at both left and right sides of the road. A vehicle arriving at the link is pushed at the end of the thru lane queue, and will be ready to discharge after the lapse time L/v_f. The vehicle ready to discharge will be removed from the thru queue keeping the first-in-first-out law, unless the discharging flow rate per unit time exceeds q_d. A vehicle changing the lane is exceptionally extracted from the middle of the thru lane queue when the vehicle reaches the upstream end of the auxiliary lane, and is added to the end of the auxiliary lane queue.
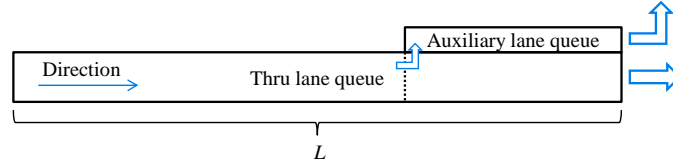
Fig. 3: Inner-link spatial components of SOUND

Similar to other mesoscopic traffic simulation models (e.g. [Dynasmart, 2011], [INTEGRATION, 2014], etc.), SOUND maintains traffic density and vehicle positions on a link, second by second, according to the fundamental diagram of traffic flow. As shown in Fig. 4, SOUND uses the triangular approximation of flow-density relationship which is parameterized with v_f – free flow speed, k_j – jam density, q_c – link capacity. Another parameter, q_d, is given to regulate the discharging flow rate from the thru lane queue.
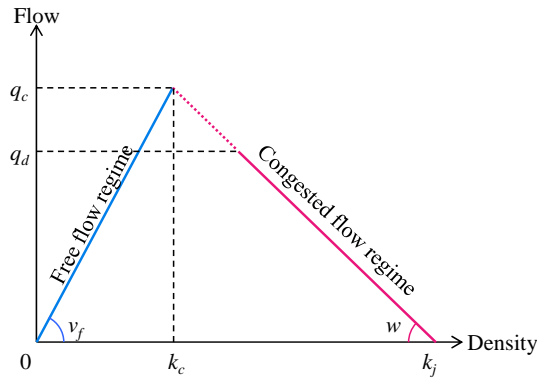

Fig. 4: Triangular approximation of the flow-density relationship of fundamental diagram

As for the queue length and the vehicle position update, SOUND features the simplified kinematic wave theory (K-wave) [Newell, 1993]. Fig. 5 illustrates the update procedure. The upper graph is the cumulative flow diagram of a link where A^* denotes the cumulative demand curve to the link (i.e. ready-to-discharging flow from the upstream link) and D denotes the cumulative discharging flow curve the slope of which is regulated by q_d. The backward wave occurring at the downstream end reaches to the upstream end and forms the cumulative curve D' which is given by shifting D to the right with $w^{-1}L$ and to the top with k_jL. As D' means the acceptable cumulative flow to this link, the cumulative arrival flow curve A can be drawn by taking the lower curves either A^* or D'.

The cumulative flow curve $Q^{(x)}$ at a certain middle section x distance from the upstream end of the link can be drawn with the same procedure, namely by taking the lower curves of either the forward wave or the backward wave. The forward wave from the upstream end will reach x to form the cumulative curve $A^{(x)}$ which is given by shifting A to the right with $v_f^{-1}x$. The backward wave forms $D^{(x)}$ at the section x the curve of which is given by shifting D to the right with $w^{-1}(L-x)$ and to the top with $k_j(L-x)$.

SOUND calculates the cumulative flows for every inner-link sections discretized with Δx interval iteratively applying the procedure above. The location of the i-th vehicle the cumulative volume of which is Q at the upstream end can be found between the section where $Q^{(x)} \leq Q$ and $Q < Q^{(x+\Delta x)}$.
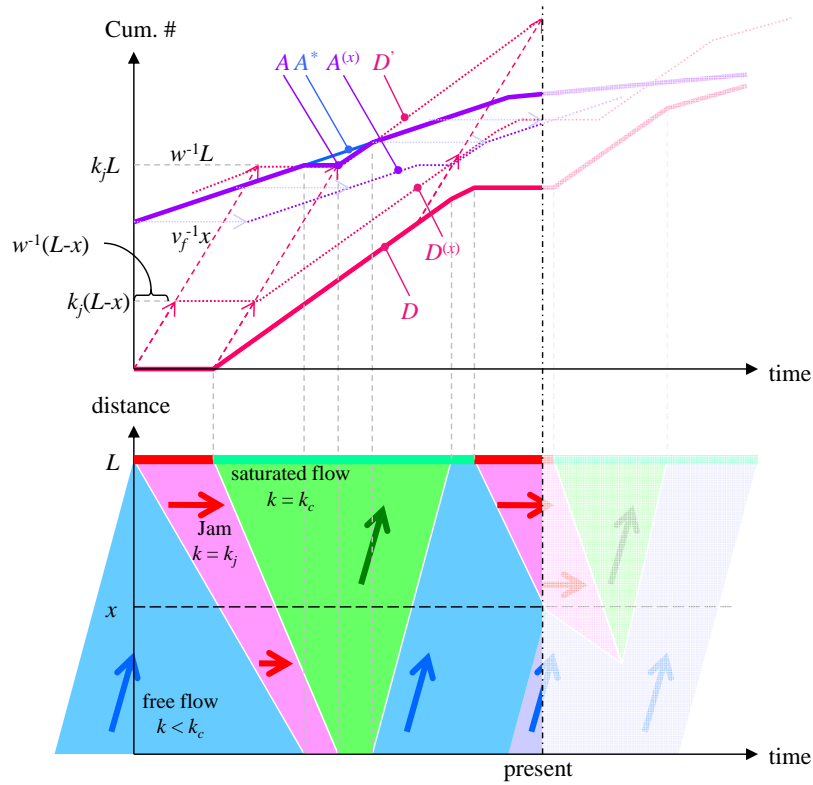
Fig. 5: Shockwave propagation and inner-link traffic status updated by the K-wave theory

2.2.2. Consideration of bottleneck capacity change for a stationary bottleneck

It is known that the capacity of an expressway bottleneck changes depending on various factors, e.g. day of week, lighting conditions, weather conditions, etc. [Ishida and Xing, 2000], as shown in Fig. 6. Also known is that the flow rate peaks just before congestion starts, and gradually drops as the queue grows.

The ENS emulates those phenomena by adjusting the discharging capacity of SOUND link depending on time of day and the lapse duration from the start of congestion. Fig. 7 is an example of the capacity and the flow rate changes at a bottleneck section. In this case, the discharging capacity q_d is initially set to the level of BDF (break-down flow rate). Once the demand rate exceeds q_d and a queue forms, the ENS watches the average travel speed of the bottleneck section. When the travel speed becomes lower than the threshold speed, (a) the ENS gradually reduces q_d to the level of QDF (queue discharging flow rate). The level of QDF varies during twilight (b) and nighttime (c).

For the practical use of the ENS, the parameters BDF and QDF for 465 known bottleneck sections on the expressways were calibrated through analysis of detector data collected over 5 years, if incidence of congestion is enough. Otherwise, let us follow the capacity model proposed by [Ishida and Xing, 2000] as shown in Table 1.
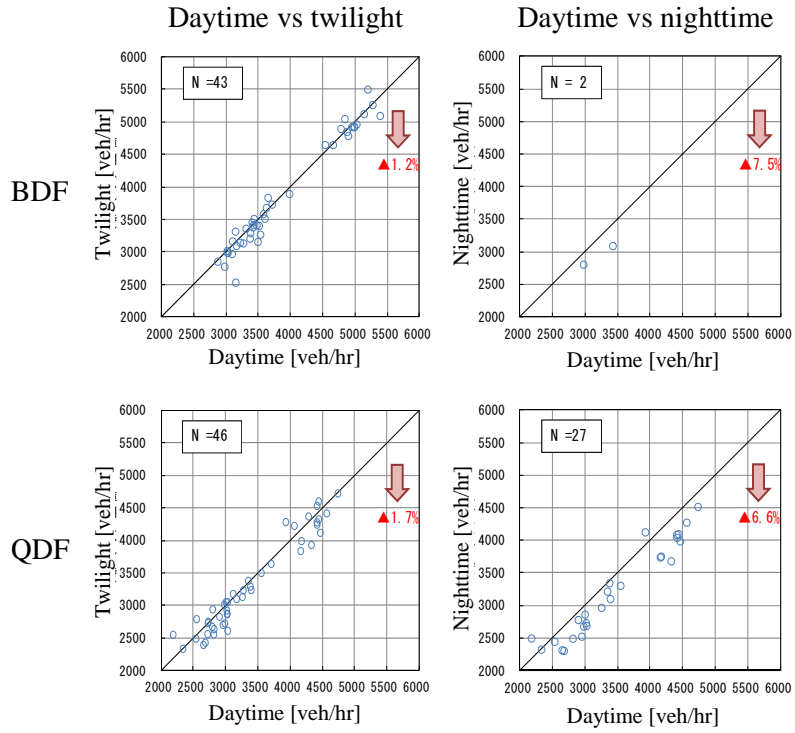
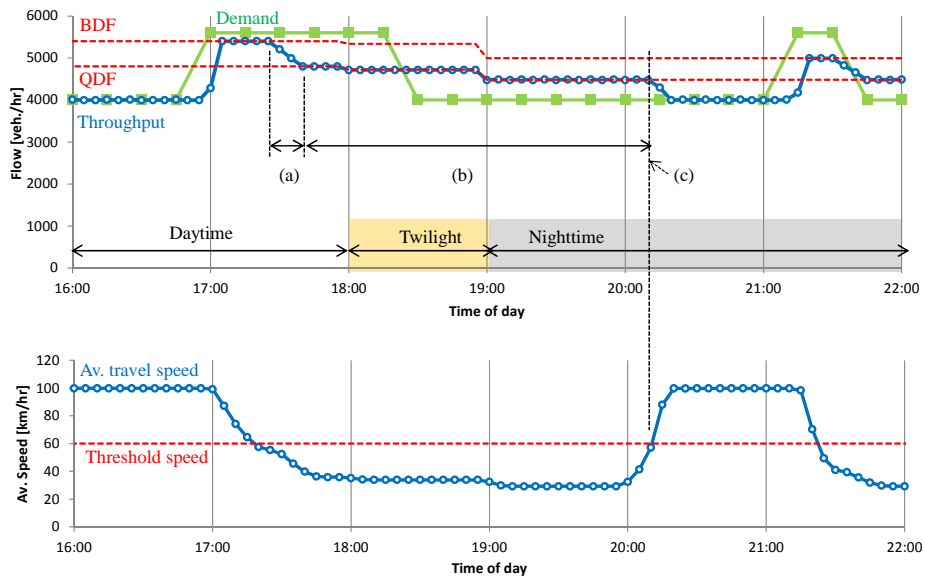Fig. 6: The capacity drop rate for twilight and night to daytime [Ishida and Xing, 2000]

Fig. 7: The capacity and flow rate changes at a bottleneck section on the ENS

Table 1: Bottleneck capacity estimation model for the sag sections [Ishida and Xing, 2000]

	2 lanes				3 lanes			
	BDF	t	QDF	t	BDF	t	QDF	t
Horizontal curvature [1/km]	-106.65	1.23	-145.98	1.58	-	-	-	-
Gradient of upstream section [%]	-34.90	0.64	-62.84	1.08	-	-	-	-
Length of upstream section [m]	-	-	-	-	-87.49	2.54	-83.84	1.69
Gradient of downstream section [%]	-128.32	2.86	-185.98	3.87	-9.88	0.19	-153.03	1.97
Length of downstream section [m]	-158.88	2.63	-129.04	1.95	-167.89	3.59	-190.22	2.50
Difference of gradient [%]	90.27	1.98	130.33	2.65	20.16	0.68	140.06	2.68
Vertical curve radius [km]	0.24	1.22	0.38	0.69	5.06	2.72	3.03	1.25
Dummy for holidays	-22.43	0.37	-42.12	0.65	-79.83	1.34	-86.48	0.98
Intercept	3548.97	29.64	3238.35	25.49	5171.23	28.77	4628.42	15.70
R	0.64		0.70		0.82		0.80	
R^2	0.41		0.49		0.67		0.64	

2.3. Modeling of drivers' route choice behavior

SOUND incorporates drivers' route choice model with dynamic stochastic user optimal (DSUO) principle, namely the logit choice model according to the generic cost function weighting the distance, the expected travel time under the present traffic condition, the toll fare, and the total queue length along each route from the present position to the destination. Table 2 shows the coefficients used in the generic cost function of the route choice model derived from the analysis on the observable route choice data [Ishida, 2013].

Table 2: Parameters for the route choice model in the ENS [Ishida, 2013]

	Small cars		Large vehicles	
	Value	t-value	Value	t-value
Toll fare [yen]	-0.011	-57.290	-0.005	-58.871
Estimated travel time [min]	-0.038	-40.276	-0.079	-57.809
Queue length [km]	-0.015	-6.717	-0.040	-9.827
Dummy for incident occurrence	-0.137	-1.462	-0.564	-6.556
Likelihood ratio	0.448		0.550	
Hitting ratio	0.835		0894	
Num. of samples	20000		20000	

The original route choice model of SOUND assumes the perfect rationality of driver. However, the available traffic information on the real expressway is limited. For instance, drivers at an expressway junction are informed of traffic conditions through the variable message signboard (VMS) installed at roadside, but the content of the information is different with the type of VMS, as shown in Fig. 8.

The most informative VMS is installed at type A junctions that can display pictures of queue length

and travel time for both alternative routes. The type B simply provides travel times. No available dynamic information at type C junctions. The ENS takes into consideration these differences of the information available to the driver at each junction.
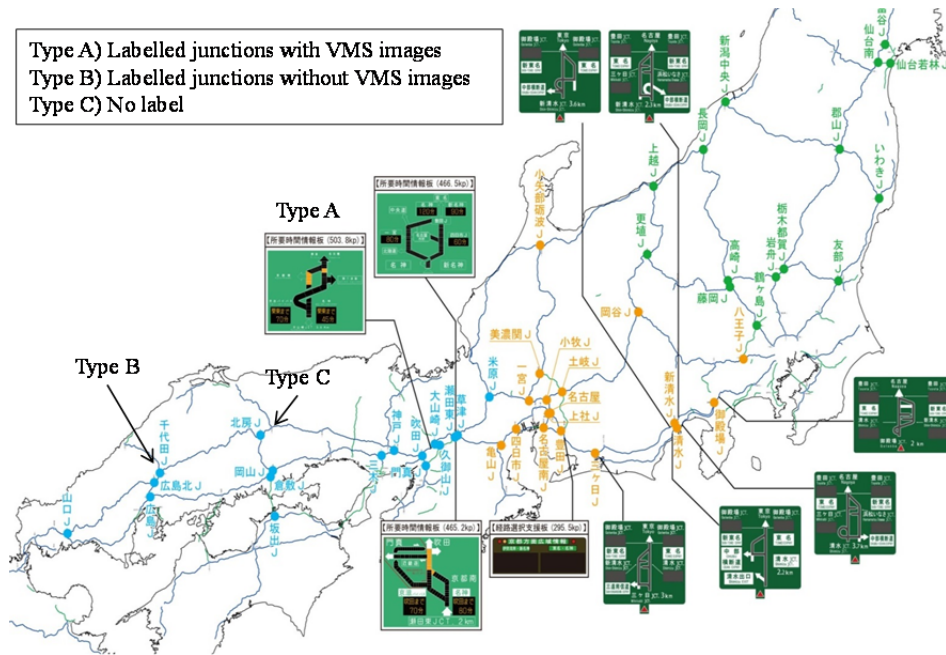

Fig. 8: Various VMSs installed on the expressways

3. Calibration of time-dependent O-D matrix using ETC data

Providing accurate O-D matrix is one of the most important issues to ensure reliability of the simulation results, but, on the other hand, is one of the most difficult tasks in the data acquisition phase. Many researchers have worked on this topic, and most of them take the numerical searching approach to minimize errors in link flows evaluated through the iterative framework with simulation which establishes the relation between link flows and O-D path flows. Oneyama [1996] developed the estimation methodology of time-dependent O-D matrix by enhancing the road network to 3-D (X-Y and time axis) and by applying the entropy maximization method to minimize error in vehicle counts. Kitaoka [2002] applied the genetic algorithm to search the optimal O-D matrix to minimize the errors in vehicle counts. Balakrishna [2007] applied the simultaneous perturbation with stochastic approach (SPSA) [Spall, 1998] to reduce the computational cost for the numerical search.

Those iterative approaches, however, repeat simulations many times, and will consequently be less practical when the simulation run time is costly. As the ENS takes couple of hours for one run, it is expected to calibrate the O-D matrix within a few runs, hopefully 3 to 5 runs.

3.1. Calibration framework combining traffic simulation and mathematical model

To reduce the number of simulation runs, we have proposed the combined framework with simulation and mathematical model [Kobayashi, 2012]. Fig. 9 illustrates the procedure for the O-D matrix estimation

in which the framework consists of two iteration loops. The outer loop (1) runs the ENS to evaluate the link flows and their O-D compositions, and the inner loop (2) iteratively applies the numerical search algorithm which is less costly than the ENS to the mathematical model derived from the simulation results.
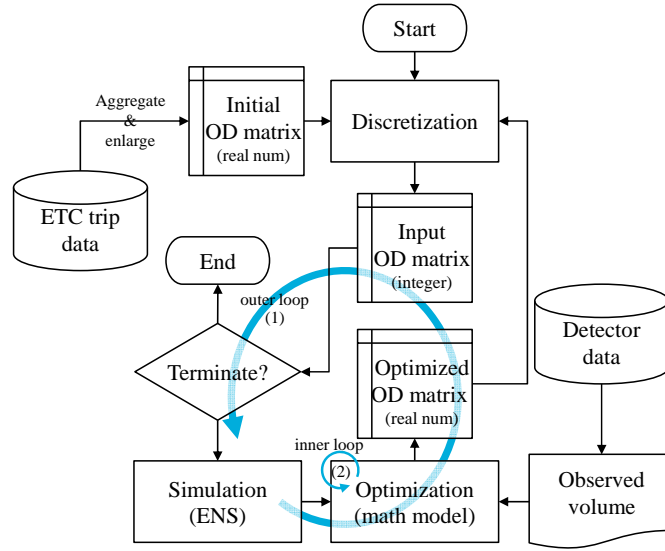

Fig. 9: Estimation process for O-D matrix

The mathematical model which establishes the relation between link flows and O-D path flows can be derived from the simulation result as follows:

$$q_{k\tau u} = \sum_{wh} p_{k\tau}^{whu} Q^{whu}$$

(eq. 1)

$$p_{k\tau}^{whu} = \frac{q_{k\tau}^{whu}}{Q^{whu}}$$

(eq. 2)

where k suffix of a link,
   w suffix of an O-D pair,
   u suffix of a vehicle type,
   τ suffix of a time slot for link throughput volume,
   h suffix of a time slot for departure (demand),
   $q_{k\tau u}$ link throughput volume of the vehicle type u for the link k at τ,
   $p_{k\tau}^{whu}$ choice probability for the O-D flow w for type u departing at h to the link k at τ,
   Q^{whu} O-D flow w for type u departing at h,
   $q_{k\tau}^{whu}$ link throughput volume of the O-D flow w for type u at h for the link k at τ.

As the choice probability can be also calculated from the cost difference of two alternatives by assuming the logit choice model as follows:

$$p_{k\tau}^{whu} = \frac{1}{1\_exp(-\theta_u \Delta c_{k\tau}^{whu})}$$

(eq. 3)

where θ_u logit sensitivity parameter for cost difference,
$\Delta c_{k\tau}^{whu}$ cost difference for the O-D flow w for type u departing at h to the link k at τ.

From (eq. 2) and (eq. 3), the cost difference can be estimated from the simulation result as follows:

$$\Delta c_{k\tau}^{whu} = -\frac{1}{\theta_u} ln\left(\frac{Q_{k\tau}^{whu}}{q_{k\tau}^{whu}} - 1\right)$$

(eq. 4)

The evaluation function to minimize the errors in link volumes now can be determined as follows:

$$E = \sum_{k\tau u} (q_{k\tau u} - \hat{q}_{k\tau u})^2$$

(eq. 5)

where $\hat{q}_{k\tau u}$ observed link throughput volume.

As the optimization formula with (eq. 1) ~ (eq. 5) is differentiable with the O-D flow Q^{whu} and the route choice sensitivity parameter θ_u, we may now apply any numerical search algorithm using differential coefficient, the calculation costs of which are much less than traffic simulation, and find the optimal O-D matrix and the logit sensitivity parameter. In this paper, we use simple steepest descent method, which it is not essential.

3.2. Accumulation of ETC trip data for initial O-D matrix

In Japan, the electronic toll collection (ETC) system started operations in 1996 and its rate of use, nowadays, is close to 90% of the entire number of trips on expressways. As the ETC system collects the on-board unit ID when a vehicle passes a toll gate, it is easy to accumulate the IDs into the O-D matrix (ETC-OD) at any desired time interval. If the vehicle count data at each entrance toll gate is available, the ETC-ID will be expanded in proportion to the ETC trip number to the vehicle count at the entrance. The (expanded) ETC-OD can be used as the initial O-D matrix for the calibration.

3.3. Calibration results

For validation, the O-D matrix on a specific day, Sunday, 12 October 2012, has been calibrated following the procedure above. Fig. 10 compares the link traffic volumes reproduced by the ENS with the vehicle counts from detector data. The coefficient of determination (R^2) in the simulation result with the initial O-D matrix was 0.809 and, after 2 simulation runs in the outer loop, was improved to 0.963, which is fairly accepted. The RMS error was also reduced to almost half of the initial value.

Fig. 11 shows the speed contour maps of major expressways (Kan'etsu, Joban and Tohoku Expressways) bound for Tokyo. On this day, many leisure travelers returning to Tokyo in the afternoon peak hours caused considerable traffic jam. Although the speed changes in the simulation results seem to be drastic as they follow the triangular approximated fundamental diagrams, we may see a similarity in the queue growth and shrink in the evening peak.

Initial   Optimized (2 times)

RMSE	R^2
5658.23 [veh/day]	0.809

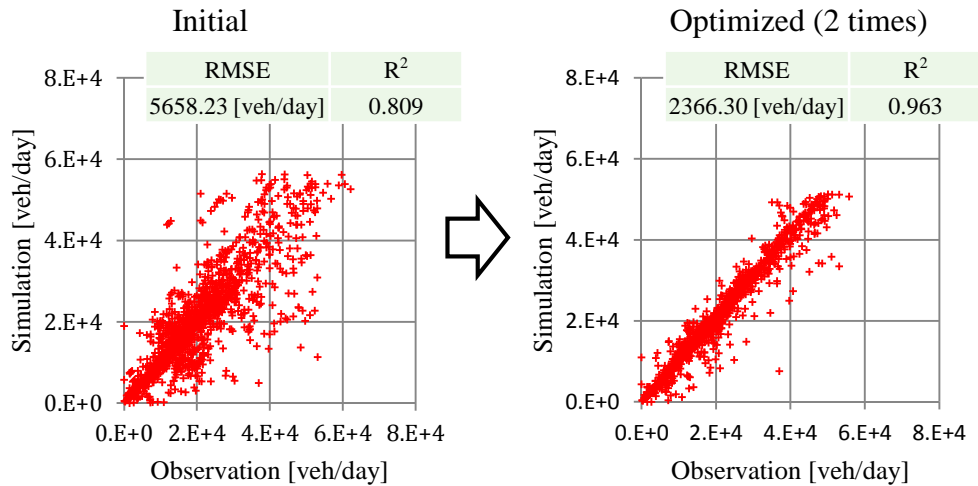| RMSE	R^2
2366.30 [veh/day]	0.963

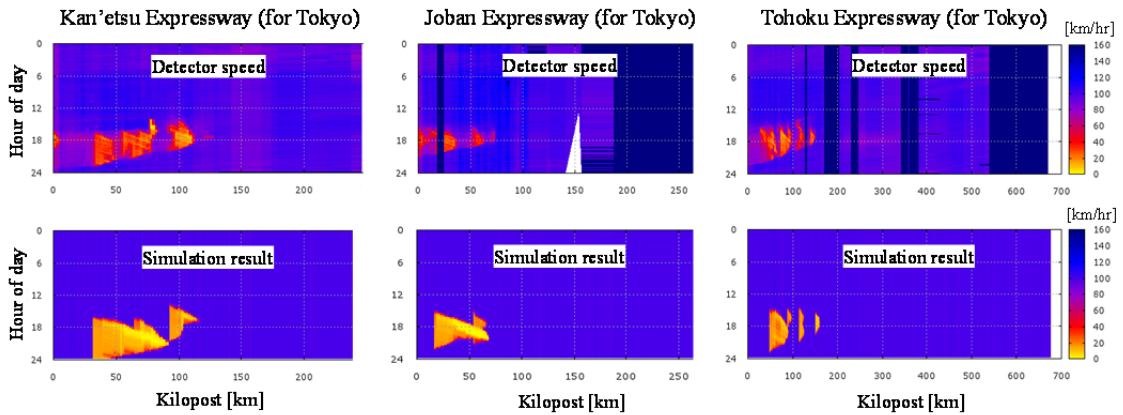Fig. 10: Comparison with the link traffic volumes before and after the O-D matrix calibration

Fig. 11: Speed contour map reproduced by the ENS with the calibrated O-D matrix

4. Conclusions and future directions

In this paper, the concept of the expressway network simulator (ENS) was described followed by the calibration of time-dependent O-D matrix using ETC trip data. By using well calibrated O-D matrix, we may conclude that the ENS can reproduce traffic volumes and queues on expressways with acceptable accuracy. Following items are our future scope:

- Efficient calibration of the fundamental diagram for evident and hidden bottlenecks
- Improving the triangular shaped fundamental diagram in SOUND so that it is more realistic such as λ-shaped

- Improving drivers' route choice modeling
- Incorporating the urban expressway network in metropolitan areas
- Incorporating arterial road network, and departure time choice relating to time-varying toll fare
- Incorporating the resting behaviors of long trip drivers at service areas

Acknowledgements

References

Balakrishna, Antoniou, Ben-Akiva, Koutsopoulos and Wen (2007), *Calibration of microscopic traffic simulation models: methods and application*, Transportation Research Record 1999, pp. 198-207.

Dynasmart (2014), description available at http://www.its.uci.edu/ctss/sim_models/dynasmart.html (website visited on May 8, 2014)

INTEGRATION (2014), description available at http://filebox.vt.edu/users/hrakha/Software.htm (website visited on May 8, 2014)

Ishida, Fukase, Ishibashi, and Kiyomiya (2013), *Analysis of route choice behavior on intercity expressways*, Proceedings of 33rd Conference of Japan Society of Traffic Engineers (in Japanese).

Kitaoka, Teramoto, Oneyama and Kuwahara (2002), *Reproduction of traffic condition based on estimation of origin-destination flow*, Proceedings of Infrastructure Planning (in Japanese).

Kobayashi, Horiguchi, Hanabusa and Koide (2012), *Estimation of time-dependent O-D matrix and route choice model parameter for a large scale network simulation*, Proceedings of 32nd Conference of Japan Society of Traffic Engineers (in Japanese).

Newell (1993), *A simplified theory of kinematic waves in highway traffic, part I: General theory*, Transportation Research B, Vol. 27B No. 4, pp. 281-287.

Oneyama, Kuwahara and Yoshii (1996), *Estimation of time dependent OD matrices from traffic counts*, Proceedings of the 3rd World Congress on Intelligent Transport Systems, Orlando.

SOUND (2014), description available at http://www.i-transportlab.jp/products/sound/index.html (website visited on May 8, 2014, in Japanese)

Spall (1998), *An overview of the simultaneous perturbation method for efficient optimization*, Johns Hopkins APL Technical Digest, 19(4), pp. 482-492.

Ishida and Xing (2000), *Status and subjects on capacity of intercity expressways*, Proceedings of Infrastructure Planning, 660, pp. 79-87 (in Japanese).

Yoshii and Kuwahara (1995), *SOUND: A traffic simulation model for oversaturated traffic flow on urban expressways*, Preprint at 7th World Conference on Transportation Research, Sydney.