Estimating Traffic Conditions of the Radial-ring Expressway Network by Assimilating Probe and Detector Data into Traffic Simulation

Azusa Goto1*, Kazunori Ooshima1, Kosuke Yamada2, Ryota Horiguchi3, Shin Sakaki1, Hidenori Yoshida1

1. ITS Division, National Institute for Land and Infrastructure Management (NILIM), Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan
   E-mail: goto-a92uj@mlit.go.jp
2. Pacific Consultants Co, Ltd. Japan
3. i-Transport Lab. Co., Ltd. Japan

Abstract
This paper introduces a framework to estimate road network traffic conditions by assimilating probe and detector data into traffic simulations. In this traffic simulation, the trajectories of some vehicles are controlled by the observed probe vehicles, then the speed reductions of these vehicles propagate according to the kinematic wave theory. In addition, the origin-destination matrix is optimized using a mathematical model so that the errors in the estimated link traffic volumes from the detector data can be minimized. By applying this framework, the traffic conditions on the Tokyo Metropolitan Expressway Network were estimated. By comparing the estimation results with the detector data, it was confirmed that the estimation showed a good accuracy in terms of link traffic volumes, and traffic congestion at the typical bottlenecks could be reasonably represented to some extent.

Keywords:
Traffic simulation, probe data, detector data

1. Introduction
The Tokyo Metropolitan Expressway Network in Japan has developed for a long time since the 1960s. First, radial roads were constructed to make the surrounding areas accessible to the metropolitan centres, currently the ring roads that connect these radial roads have been mostly completed [1]. Since various routes will become available for road users after the completion of this radial-ring expressway network, it will be more important to utilize ITS technologies, such as dynamic route guidance or congestion charges, to realize a more efficient road network operation.

In order to implement such operational measures, it is essential to understand traffic conditions in a network, which means not only traffic flows and speeds of individual sections but also traffic flow...
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distributions from each origin to destination. This information allows road network operators to recognize where congestion happens, where vehicles within the congestion come and go, and where and how they can alleviate congestion by encouraging vehicles to detour. However, existing detectors (or sensors) give us limited information about traffic flows and speeds at specific sites. Since these detectors are not so densely located, this information is not enough to understand traffic flow distribution conditions over a whole network.

On the other hand, we were recently able to obtain some probe data by vehicle-infrastructure cooperative system so-called “ETC 2.0 system” in Japan. Although the number of probe vehicles is still limited, this data contains a series of time and position (longitude and latitude) information of probe vehicles, which tells us where and when they reduced their speeds. It is expected that we will able to estimate traffic conditions in more detail by fully utilizing these different kinds of data.

Therefore, the objective of this research is to develop a framework to estimate road network traffic conditions by assimilating probe and detector data into traffic simulations. In the simulation, vehicles are generated and attracted according to the origin and destination matrix (hereafter referred to as “OD matrix”), which is optimized using detector data, and their positions are estimated based on the kinematic wave theory with the boundaries by probe vehicle trajectories. This can give us information about traffic conditions where detectors are not installed, as well as traffic flow distributions, which are not limited for probe vehicles.

So far, the framework has been developed for performing post evaluations of an operational measure by comparing estimated traffic conditions before and after implementation, thus all data was collected and inputted offline. However, it is also applicable to real-time traffic monitoring if all the data is connected online in the future. This will contribute to realizing effective road network management by implementing some operational measures based on dynamic traffic conditions.

2. Literature Review

Previous studies (for example, [2] ~ [4]) have already developed the frameworks for estimating and/or monitoring road network traffic conditions by inputting observed data into traffic simulations. In most of these frameworks, the OD matrix is estimated or calibrated according to the observed traffic volumes by some detectors and/or sensors based on typical traffic conditions in the past, and which are input into the traffic simulator. For example, Dynasmart-X [2], DynaMIT [3], and Aimsun Live [4] select the OD matrix based on the database that contains the relationship between OD matrices and observed traffic volumes by detectors and/or sensors in the past, and use that relationship to estimate traffic on the highway and motorway network.

Focusing on the expressway network in Japan, which has limited access points of onramps and off-ramps, since some of the expressway companies put detectors at onramps and directly measure the onramp traffic volumes, the existing frameworks of HEROINE [5] and RISE [6] have been developed for utilizing them. In these frameworks, the OD matrix was calibrated based on the temporary changes of onramp traffic volumes, as well as the historical pattern, considering the day of the week and so on.

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For another example, since road administrators have recently been able to obtain the OD matrix of vehicles that use the electric toll collection (ETC) system, this data was also utilized for the traffic estimation in the previous study [7]. This OD matrix of ETC users was called “ETC-OD matrix”. Since users of the ETC system accounted for about 90% of all expressway users, the ETC-OD matrix could provide good information for estimating the OD matrix of all users.

On the other hand, utilization of probe data for traffic estimation is now regarded as one of the most substantial challenges. Several attempts can be found in the previous studies, for example, Work et al. [8], Herring et al. [9], and Fabritiis et al. [10].

As a previous study for utilizing both probe and detector (fixed traffic volume and speed measurement) data, Mehran et al. [11] estimated vehicle trajectories by fusing probe and fixed sensor data based on Daganzo’s variational theory [12]. However, the application of this study was limited to the arterial corridor. Hanabusa et al. [13] assimilated probe data into network traffic simulations; specifically, they obtained probe vehicle macroscopic fundamental diagrams of each 1-km² mesh and used them for optimizing the OD matrix and other parameters in order to estimate urban road network.

The feature of our research is to utilize both probe and detector data in traffic simulations, which is expected to improve estimation accuracy. In detail, because the amount of probe data from the ETC 2.0 system is increasing recently, we developed the assimilation framework that fully utilizes the trajectories of individual probe vehicles for estimating those of other vehicles, which had already been done at the corridor level in the previous study [11], but not done yet at the network level.

3. Methodology

3.1. Subject network

The subject road network was a whole expressway network in the Tokyo metropolitan area as illustrated in Fig. 1. It has 1599.7 km for both directions, covering the area of about 11,000 km², consisting of 2214 links in Digital Road Map (DRM). As shown in the figure, the network is outlined by three ring roads (C2, C3, and C4) and several radial roads with 29 junctions. This allows road users to choose several routes, especially when passing through the metropolitan area from and to outside the outer ring road (C4).

The three different colours in Fig. 1 stand for the companies that are in charge of construction, operation, and management for these expressway sections: Metropolitan Expressway Co., Ltd., (MEX) for the central part, Central Nippon Expressway Co. Ltd., (NEXCO Central) for the west part, and East Nippon Expressway Co., Ltd., (NEXCO East) for east and north part.

3.2. Overview of traffic estimation process

In this research, traffic conditions were estimated using a traffic simulator with different kinds of observed data. Fig. 2 shows the flowchart of the whole estimation process.

The estimation process consisted of the two steps. At the first step, we optimized the OD matrix, which was one of the most important inputs for traffic simulations. The OD matrix in this study must
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specify the traffic demands between the onramps and off-ramps on the subject expressway network during each time interval. In order to obtain the OD matrix, we prepared the initial OD matrix based on the ETC-OD matrix, and calibrated it through the iterative process of traffic simulation and minimization of the errors in link traffic volumes from the detector data. By inputting the optimized OD matrix at the first step, we carried out the traffic simulation with ETC 2.0 probe data at the second step. Actually, the iteration at the first step also included traffic simulations as shown in Fig. 2, but these were done without the probe data.

3.3. Data

3.3.1 Detector data: In total, 408 detectors were installed in the subject network; that is, on average for every 300-600 m on the expressways under MEX and at least one between every on/off-ramps (about 5~10 km) on the expressways under NEXCO Central and East. With these detectors, we obtained traffic volume and average spot speeds aggregated once every 5 minutes for two categories of vehicle types (i.e., passenger cars and heavy vehicles). Several types of detectors were used at different sites, for example, inductive loop detectors, ultrasonic detectors, and video image processor detectors. From them, we excluded detectors with errors and missing records, and the detectors that seemed inaccurate when comparing traffic counts with upstream and downstream detectors in the data cleansing process.

3.3.2 ETC-OD matrix: As briefly mentioned in section 2, the ETC-OD matrix was the OD matrix of ETC users that specified the traffic volumes between the onramps and off-ramps during each time intervals. This matrix was calculated in each of the three expressway companies (MEX, NEXCO East, and NEXCO Central) by aggregating the records of times when vehicles passed through the tollgates located at onramps, off-ramps, or boundary junctions between different expressways with the ETC on-board units (including ETC 2.0 on-board units that are explained in 3.3.3).

In this research, we first combined these matrices into one matrix in order to make the ETC-OD matrix
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in the whole subject network with the aggregation intervals of 15 minutes for each type of vehicles (passenger cars or heavy vehicles). Here, several assumptions were made about diverging and merging volumes at boundary junctions where expressways under different companies intersect. Then, we approximately converted it into the OD matrix of all vehicles by multiplying the elements by the inverse of the average percentage of ETC users in the expressway companies according to their destination off-ramps. The ETC system in Japan has been in operation nationwide since 2001, and the percentage of ETC users is currently almost 90% among all expressway users.

The OD matrix obtained in the above procedure was used for the initial OD matrix in Fig. 2. Since this procedure was done with several simplifications, the initial OD matrix would not be accurate enough for estimating dynamic traffic conditions. That is why the optimization was further carried out to update it as shown in Fig. 2.

3.3.2 Probe data: Probe data was obtained from the ETC 2.0 system. The ETC 2.0 system was a vehicle-infrastructure cooperative system using the DSRC (Dedicated Short Range Communications) between ETC 2.0 on-board units and roadside units. The system has been deployed nationwide by the Ministry of Land, Infrastructure, Transport and Tourism since 2011. While the ETC system was only for electric toll collection, the ETC 2.0 system had additional functions of dynamic route guidance, safe driving assistance, and probe data collection.

In the probe data collection of the ETC 2.0 system [14], time and position (longitude and latitude) information of each probe vehicle is recorded and accumulated in its on-board unit every 200 m or when its direction changed 45 degrees or more. Then, the accumulated data is uploaded when probe vehicles passed by roadside units, which are generally set every 10~15 km on intercity expressways and 4 km on urban expressways on average. The roadside units send the data to the central server, and finally the central server connects the data of each probe vehicle downloaded by different roadside units to make continuous trajectories of probe vehicles.

Although the use of the ETC 2.0 system is gradually increasing year by year, it is still limited in total traffic volume. On average, we can collect probe data from about 2% to 3% of all vehicles traversing the subject expressways.

3.4 Traffic simulation

In the main part of the estimation process, we simulated traffic with the existing simulator, namely SOUND (Simulation On Urban road Network with Dynamic route choice; [15], [16]), which had been developed by i-Transport Lab. Co., Ltd., by adding a special function for assimilating probe data. Fig. 3 shows the general flowchart. SOUND is a mesoscopic traffic simulator dealing with discrete vehicles with 1-second update intervals. In this simulation, vehicles are generated according to the OD matrix, and their movements are simulated by the traffic flow model and route choice model in the following way.

3.4.1 Traffic generation: Traffic was randomly generated at every time step (i.e. 1 second) from onramps according to a 15-minute OD matrix. Here, the OD matrix was updated during the
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optimization step as explained in subsection 3.5.

Fig. 3 Flowchart of traffic simulation

3.4.2 Traffic flow model: SOUND estimates the number of vehicles and the positions of individual vehicles on each link at every time step according to the fundamental diagram. Here, a simple fundamental diagram is assumed as shown in Fig. 4. It is defined by link capacity $q_c$ and jam density $d_j$. In a free-flow regime (blue line in Fig. 4), forward wave speed, which is the angle from the horizontal axis, decreases from free-flow speed $v_f$ to critical speed $v_c$ as density increases. In a congested flow regime (red line in Fig. 4), backward wave speed $w$ is calculated as follows.

$$w = \frac{q_c}{k_j - \frac{q_c}{v_c}}$$  \hspace{1cm} (1)

In SOUND, expressways are segmented into links on which vehicles are conserved (no entry and exit exist). Then the number of vehicles on each link is first calculated by applying Newell’s simplified kinematic wave theory [17]. After that, with the given boundary of the cumulative number of vehicles at the downstream end of each link, the positions of individual vehicles inside the link are calculated one by one from the downstream to upstream by applying Daganzo’s variational theory [12]. Since not only the downstream end of links but also the observed vehicle trajectories of probe vehicles can be regarded as boundaries, we could assimilate probe data in this simulation. Fig. 5 illustrates how to estimate the position of the following vehicle based on the leading vehicle trajectory.

The parameters for determining a fundamental diagram are traffic capacity $q_c$, jam density $k_j$, free-flow speed $v_f$ and critical speed $v_c$. Usually they need to be calibrated especially at bottlenecks based on empirical analysis, so that congestion phenomena can be reasonably represented. However, since this approach requires a large amount of empirical data, these parameters were uniformly set according to Table 1 in this research. Instead of calibrating these parameters, probe data was assimilated for representing congestion.
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![Fig. 4 Fundamental diagram](image1)

![Fig. 5 Impact of a probe vehicle trajectory](image2)

Table 1 parameters of the links

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(a) MEX</th>
<th>(b) NEXCO East and Central</th>
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<tbody>
<tr>
<td>$q_c$ [pcu/h/lane]</td>
<td>2200</td>
<td>2200</td>
</tr>
<tr>
<td>$k_j$ [pcu/km/lane]</td>
<td>2000</td>
<td>2400</td>
</tr>
<tr>
<td>$v_f$ [km/h]</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$v_c$ [km/h]</td>
<td>60</td>
<td>70</td>
</tr>
</tbody>
</table>

3.4.3. Assimilation of probe data: Specifically, in this simulation, we controlled the speeds of some vehicles so that they could precisely track the observed trajectories of probe vehicles. Then, the speed reduction of a probe vehicle influenced the following vehicles as explained in 3.4.2. As a result, this triggered congestion in the simulation.

If the number of probe vehicles is not so small, most of the traffic congestion is captured by this approach. Furthermore, although it is outside the focus of this paper, by using this approach, it becomes possible to grasp the congestion caused by not only fixed bottlenecks but also some temporary incidents (i.e., traffic crashes or falling objects on roads) that cannot be calibrated in advance. This is the great advantage of assimilating probe data, especially for further development of a real-time traffic monitoring system.

3.4.4 Route choice model: SOUND assumes that road users have perfect information and choose their routes dynamically based on updated travel time and tolls of their alternative routes every fifteen minutes. Thus, users’ route choice probability is formulated by the logit model as follows.

$$ p_j = \frac{\exp(-\theta c_j)}{\sum_{k=1}^{J} \exp(-\theta c_k)} \quad (2) $$

$$ c_j = \alpha \times time_j + \beta \times \frac{distance_j}{v_{fj}} \quad (3) $$

Where, $p_j$: probability to choose route $j$, $J$: total number of available routes, $c_j$: cost of route $j$, $time_j$: expected travel time of route $j$ based on link travel time of the current time step (every fifteen minutes), $distance_j$: distance of route $j$, $v_{fj}$: free-flow speed of route $j$, $\theta$: route choice sensitivity parameter and $\alpha$ and $\beta$: coefficients.
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Coefficients $\alpha$, $\beta$ and $\gamma$ were set as listed in Table 2. These coefficients were estimated based on the observed trajectories of the ETC 2.0 probe vehicles and route travel times from the detector data by the maximum likelihood method. The data used for this estimation was observed during June of 2016 and 2017, which contains the trajectories of 1,034,542 vehicles in total (380,370 vehicles in 2016 and 654,172 vehicles in 2017). Here, please note that the impact of tolls was not incorporated in this model, due to the limitation of the observed data.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Passenger cars</th>
<th>Heavy vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weekday/end</td>
<td>Weekday</td>
<td>Weekend</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.240</td>
<td>0.242</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.330</td>
<td>0.311</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.064</td>
<td>0.064</td>
</tr>
</tbody>
</table>

3.5. Optimization of OD matrix using detector data

The OD matrix was optimized using detector data as shown in Fig. 2. That means the OD matrix was iteratively revised in order to minimize the sum of errors in estimated link traffic volumes from the observed volumes in detector data.

For this optimization, we used the mathematical model, which had been proposed by Kobayashi et al. [18] and applied by Hanabusa et al. [13]. The advantage of this approach was that the number of iterations could be drastically reduced. This was important since it took time to run traffic simulation.

This model minimizes the sum of errors in estimating link traffic volume $E$, which is expressed by the following equation.

$$ E = \sum_i \sum_t (q_{i,t} - \bar{q}_{i,t})^2 $$

Where, $q_{i,t}$: the estimated traffic volume of link $i$ in time step $t$ in the simulation, $\bar{q}_{i,t}$: the observed traffic volume of link $i$ in time step $t$ from detectors.

In the above equation, although $q_{i,t}$ cannot be generally obtained without running the simulation, it is mathematically expressed with the relation to OD traffic volumes under some assumption.

4. Validation

This section introduces a verification to see whether the simulated results can reasonably represent actual traffic conditions or not. Link speeds and link traffic volumes were the most fundamental outputs of the traffic estimations, which could be used for other indices such as the total delay. Therefore, in order to verify the simulated results, these estimated values were compared with the ones observed by detectors.

4.1. Link speed

Fig. 6 and Fig. 7 are examples of the speed contours that show 5-minute link speeds on sections of the E1 expressway and the E4 and S1 expressways where congestion often occurred. The speeds in the
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upper figures (a) were observed by detectors and the ones in the lower figures (b) were estimated by the simulator.

We found that congestion, where the link speeds were lower (indicated by reddish colour in the speed contours), could be represented in the simulation mostly at the same location and time with the observed data. For example, in Fig. 6, congestion that happened from the mainline tollgate and the JCT for the C2 expressway in the morning and evening hours was indicated in both observation and estimation. However, speed reductions were overestimated especially after the beginning of the congestion from the JCT for the C2 expressway in the morning. This happened because sometimes one lane was congested while the other was not congested depending on which direction these lanes were connected. Because such differences in traffic conditions by lane could not be considered in the traffic flow model applied in the simulation, if one probe vehicle was driving on a congested lane, the speed reduction was reflected in the cross-section even though the other lane was not congested. Such kinds of overestimations of speed reductions were also found in other sections, typically around merging and diverging sections.

On the other hand, the beginning of the congestion in the evening in Fig. 6 delayed about 10 minutes in the simulation from the observation. For another example, in Fig. 7, speed reductions in the morning from the JCT for the C2 expressway were underestimated. One of the reasons of these examples was because speed reductions in this simulation were triggered by those of probe vehicles only. Therefore, congestion did not occur in the simulation until a probe vehicle reached the actual congested section, and speed reductions might be less reflected if there were few probe vehicles.

In addition, in Fig. 7, we found that the estimated link speeds during uncongested periods did not
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agree with the observed speeds in many sections on the S1 expressway (the upper part of the figure). This was because the free-flow speeds were simply inputted as listed in Table 1, and not calibrated considering the geometry and other influencing factors of each link. As a whole network, Fig. 8 shows the distributions of the estimated link speeds according to the observed link speeds for every 10 km/h in all links. As shown in Fig. 8, link speeds were overestimated in many links, especially when the observed speeds were low. This implied that congestion and speed reductions were not sufficiently represented in the simulation because of the reasons mentioned above.

![Fig. 8 distributions of estimated link speeds by range of observed ones on 5th June 2017](image)

4.2. Link traffic volume

Fig. 9 shows the scatter diagram of the observed and estimated link volumes. We found that traffic volumes were well estimated in general although there were still some links with over- and underestimations.

![Fig. 9 comparison of estimated and observed link traffic volumes on 5th June, 2017](image)

![Fig. 10. Correlation coefficient between observed and estimated link traffic volumes by time of day](image)
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Fig. 10 shows the correlation coefficients between the estimated and observed link traffic volumes by time of day of the two scenarios on Monday, 6th June 2016 and Monday, 5th June 2017. The result showed that the estimated link traffic volumes were highly correlated with the observed volumes in all the time units, but actually, there were some fluctuations. Analysis in more detail needs to be conducted to identify the reasons in order to improve the accuracy of the estimated results.

5. Conclusion
In this research, we developed the framework to estimate traffic conditions by assimilating probe and detector data into traffic simulations, and applied it on the Tokyo Metropolitan Expressway Network. By comparing the estimation results with the detector data, it was confirmed that the estimation showed a good accuracy in terms of link traffic volumes. Traffic congestion at the typical bottlenecks could be reasonably represented to some extent. However, the speed reduction were sometimes overestimated especially at merging and diverging bottlenecks, but also underestimated in many cases. Against this issue, more analysis in detail in each bottleneck needs to be conducted in order to identify the causes of low accuracy considering the impact of the number of prove vehicles and make necessary improvement. After these validation and improvements, we would like to conduct case studies to evaluate the operational measures.

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