TRAFFIC SIMULATION FOR EXPRESSWAY TOLL PLAZA BASED ON SUCCESSIVE VEHICLE TRACKING DATA

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INTRODUCTION

This paper describes about the modelling concept of traffic flow at expressway toll plaza. Nowadays, Electric Toll Collection (ETC) system has been rapidly popularized in Japan, as shown in Figure 1. Many road authorities expect that more than 80 percent of running vehicles will equip on-board ETC units within a couple of years. Under such high proportion of ETC vehicles, the road authorities have to revise the design of toll plaza in order to prevent undesirable near-miss by increasing the number of ETC exclusive lanes, modifying the geometry or enlarging the area of the plaza.

From the sake of road authorities, the traffic simulation model which can consider the interaction between traffic conditions and the design of toll plaza is to be developed. Traffic conditions should be evaluated in terms of not only LOS but also in safety. As there was less knowledge of the driving behaviour of ETC vehicles in toll plaza, we had to start with the precise survey of vehicle trajectories in the plaza in advance of the modelling.

In the subsequent chapters, let us, at first, introduce the outline of successive vehicle tracking with plural video cameras. Then, the modelling concept of the traffic simulation for toll plaza based on the tracking data will be explained. The model was implemented as an extension module of AVENUE (Horiguchi et al., 1996), a micro-scopic traffic simulation model, and was validated. In the final chapter, the case study using this simulation model will be described as well as the implications through the study.
SUCCESSIVE VIDEO SURVEY OF VEHICLE TRAJECTORIES

Outline of survey

In order to quantify the vehicle movements in toll plaza, traffic survey with precise vehicle tracking technique using plural video cameras (Akahane and Hanakenaka, 2004) was conducted at Narashino Toll Plaza of Higashi-Kanto expressway on 20th February 2004.

The size of the toll plaza is approximately 500 meters in longitude. As it is difficult to cover a whole section of this size with one video camera, we arranged five cameras on the top of the light towers besides the toll gate and cover each portion of the plaza, as shown in Figure 2. Those cameras are synchronized their frame rate with external time code from GPS signal. Furthermore, the positions of cameras and road surface markings are precisely measured with laser surveying instrument. Therefore, if the trajectory of one vehicle is tracked on each video image, those trajectories in video coordination system can be projected onto the real coordination system with complete time consistency.

Simple projection of those trajectories may include the positioning error caused by the unmeasured height of tracking point. The method developed by Akahane corrects this error by estimating the height of tracking point and unite each projected trajectory into one successive trajectory in real space. In the unification process, Kalman smoother to implement the kinematics of vehicle motion estimates not only the vehicle position but also speed and acceleration at every 0.1 second. Although some part in the plaza such as toll gate section under roof was not taken by the cameras, this method can estimate vehicle trajectories according to the vehicle kinematics.
Survey result

Trajectories
The survey was executed at 10:50 – 12:30 on 20th February 2004, of which the traffic condition was relatively light, in order to capture the lane choice behaviour of a vehicle with less restriction from others.
near by. Through the survey during 100 minutes, the trajectories of 1349 vehicles including 344 ETC vehicles were extracted. Figure 4 illustrates part of the vehicle trajectories projected onto real coordination system by overlaying aerial photograph of the toll plaza. There are two ETC toll gates at the centre and one at the left side. Other six gates are for normal (ie. non-ETC) vehicles. Only the ETC vehicles passing through the two gates at the centre were tracked to the downstream of the toll gates.

![Figure 4. Vehicle trajectories arriving from the most left lane at the upstream of toll plaza.](image)

**Speed and Acceleration**

Figure 5 and Figure 6 illustrate the speed and the acceleration changes on ETC exclusive lanes and normal lanes respectively. Over the individual plots, the average and the standard deviations at every 5 meters are plotted as well. From those figures, we can read the tendency those for;

- An ETC vehicle arriving at the upend of the toll plaza runs at around 80 km/hr and gradually slow down with about 1 m/sec² deceleration up to the 60 meters before the gate.
- A normal vehicle arriving at the upend runs at around 70 km/hr and keep the speed up to 150 meters before the gate. Then gradually slow down.
- The passing speed at ETC gate is approximately at 36 km/hr. Bounded by the gate, a vehicle changes deceleration to acceleration, which is more intense than deceleration.

Since those vehicle behaviours were captured under light traffic condition, we may regard they represent the drivers’ desires for the speed and the acceleration on ETC exclusive lanes, which will be used in the modelling stage.
Headway and capacity
Figure 7 shows the histogram of headway distribution at ETC toll gate measured by the vehicle sensor at the gate. Since the headway relatively smaller than the most frequent value are considered as in car following situation, a curve approximates the left part of the peak may represent the headway distribution at high level traffic flows. From the figure, the gamma distribution of which mean value is 4.5 seems well approximate the left part, we may regard this value is the critical headway to give the capacity of ETC toll gate as 800 [veh/hr].
MODELLING OF TRAFFIC FLOW IN TOLL PLAZA

Flow modelling

There are dozens of microscopic simulation models to employ various car-following models which consider drivers’ characteristics, such as response delay, desire speed, target headway, etc. However, some of their important parameters seem to be difficult to directly obtain from traffic survey data. We sometimes have difficulty to find clear relationship between those model parameters and road capacity achieved by the simulation model. Furthermore, those drivers’ characteristics in the simulation model may be less affected by the location on road, while they vary in real as shown in the previous chapter.

In order to overcome those difficulties and to fully utilize the result of the video survey, we have taken those basic modelling strategies as for;

- Car-following behaviour is modelled as first order status equation, i.e. headway spacing and speed (S-V) relationship of which the average can be derived from macroscopic observation.
- Average S-V relationship of the car-following behaviour is determined by the position in the toll plaza.
- Individual behaviour is given by randomly scaling the average S-V relationship at each position according to normal distribution of which the variance can be obtained from macroscopic observation.

In this study, we assume simple S-V relationship, Greenshield’s Formula. The formula can be parameterized with desired free flow speed and capacity at each position in the plaza, which can be obtained through the video survey (Figure 8).

![Figure 8. Spacing-Speed (S-V) relationship varying with the position in the toll plaza.](image)
With the car following behaviour based on S-V relationship, the speed of each vehicle can be calculated with the following simultaneous equations. With this modelling, we can expect the consistency between the observed capacity and the simulated capacity which accumulates individual vehicle movements (Yoshii and Kuwahara, 1995).

\[
\begin{align*}
S_i(t + 1) &= f(V_i(t)) \\
S_i(t) + V_{i-1}(t)dt &= S_i(t + 1) + V_i(t)dt
\end{align*}
\]  
(Eq.1)

where 
\( f \): S-V relationship derived from macroscopic flow characteristics,  
\( S_i(t) \): headway distance of vehicle \( i \),  
\( V_i(t) \): Speed of vehicle \( i \),  
\( dt \): unit time interval.

According to the survey result, capacity and desired speed at each location of both ETC and normal lanes are determined as shown in Figure 9 and Figure 10 respectively.

![Capacity settings in the toll plaza](image1.png)

**Figure 9. Capacity settings in Narashino Toll Plaza.**

![Desired speed settings in the toll plaza](image2.png)

**Figure 10. Desired speed settings in Narashino Toll Plaza.**
Lane choice behaviour modelling

Lane choice behaviour in Narashino Toll Plaza
Inside the toll plaza, a driver may dynamically choose the lane towards the target toll gate, according to the vehicle position, lane operations (ETC exclusive, closure, etc.), queue length, etc. It is expected from the extracted vehicle trajectories that drivers’ lane choice behaviour is identified. For the readers’ convenience, the lane configuration in the upstream section of Narashino Toll Plaza is illustrated in Figure 11. The main expressway that has 3 lanes leads vehicles to the upstream end of the toll plaza at 270 meters before the toll gates. There are three ETC exclusive lanes but they are split. Lateral position of each gate and lane is numbered by increasing from left to right as shown in the figure. Gate #0 is located in front of the right side lane of main expressway.

The choice probability of arrival lane at most upstream end of the main expressway is given to each vehicle type as a boundary condition. As the lane choice model described later will be calibrated for ETC and normal (non-ETC) vehicles respectively, this model requires the proportion of ETC and non-ETC traffic at each lane.

Figure 11. Lane configuration in the upstream section of Narashino Toll Plaza.

Figure 12 and Figure 13 illustrates the toll gate choice probabilities of ETC and normal (non-ETC) vehicles at different positions in the toll plaza. Each column means the percentage of selected gate in the number of vehicles running at the position on each lane. For an instance, from the top-left figure in Figure 12, we can read the fact that 80% of the vehicles running on the centre lane at 270m selected gate #0, which means such vehicles may change their lane to the right at least once.
Figure 12. Choice probabilities of ETC toll gates at different position in the toll plaza

Figure 13. Choice probabilities of normal toll gates at different position in the toll plaza.
From those figures, some tendencies of choice behaviour are implied as for:

(i) For the split configuration of ETC gates, a driver first determines either left or right side of toll gates at the upstream end of the toll plaza. Once a vehicle determines the split side, it will not change the side.
(ii) Lateral range of the selected toll gates is wider at far position from toll gate than near position.
(iii) The centre of the selected toll gates is shift to the left side, because the shape of the toll plaza is expanded to the left side. The amount of the shift is larger at far position than near position.

Basic structure of lane choice modelling
In order to cope with the tendencies above, three steps of choice models are invented as shown in Figure 14. The split side choice model is applied at most once at the upstream end of toll plaza, if the selectable lanes for a vehicle are in split configuration. Once a vehicle enters the toll plaza, it select one of selectable lanes according to the lane choice model, of which parameter may vary with the vehicle position. After a vehicle selects its target lane, it selects one of possible paths to guide the vehicle towards the lane. Those two selections are iteratively applied during a vehicle runs in the toll plaza.

![Flow chart of lane choice modelling.](image)

Split side choice model and its calibration
Split side choice model is described with the following equation. This will take balance of the choice probability of the left split lane groups to the right in the comparison of lateral offset of the left lanes to the right. The parameters $w_1$ and $w_2$ are the weights to take balance, and $\theta$ means the sensitivity. Figure 15 shows the result of parameter calibration to fit the survey result.

$$P_L = \frac{1}{1 + e^{-\theta(\|v_l - \gamma_l\| - \|v_r - \gamma_r\|)w_2}}  \quad (Eq.2)$$
where $P_L$: the choice probability for left split lanes.
\( \delta_L, \delta_R \): the lateral offset in lane position from vehicle’s arriving lane to the centre lane of left / right split lanes.
\( \eta_L, \eta_R \): the lateral offset in lane position from vehicle’s discharging lane at downstream end to the centre of left / right split lanes.
\( \theta, w_1, w_2 \): parameters to be calibrated.

Lane choice model and its calibration
Once a vehicle enters toll plaza, it selects one of the selectable lanes according to the following equation.

$$P_k = \frac{1}{1 + e^{-\theta(k-\delta)}} \quad \text{(Eq. 3)}$$

where $k$: lateral offset from the current lane of vehicle.
\( P_k \): cumulative choice probability of lane $k$ from the most left side.
\( \delta, \theta \): parameters to be calibrated.

As illustrated in Figure 16, $\theta$ represents the lateral range of desirable lanes. If $\theta$ becomes larger, the curve determined by the Eq.3 gets steeper and the lateral range becomes narrower. The parameter $\delta$ means the lateral offset to the centre of desirable lanes. If $\delta$ becomes larger, it biases the choice probability curve more left. Based on the implications from the result of lane choice analysis, $\theta$ will be smaller at the far position from toll gate than the near position, and $\delta$ will be larger at the far position than the near position.

Figure 15.  Calibrated split lane choice model for Narashino Toll Plaza.

![Choice Probability of left side split lanes.](image)

0%  10%  20%  30%  40%  50%  60%
Arrive at left lane  Arrive at centre lane  Arrive at right lane
Survey  Model estimation

$\theta = 0.22$
$w_1 = 2.5$
$w_2 = 2.0$

Figure 16. Parameters used in the lane choice model.
The lane choice model is calibrated for ETC vehicles and normal (non-ETC) vehicles respectively. Figure 17 compares the choice probability of survey result and the calibrated model for normal vehicles at the positions of 120, 210 and 270 meters to the toll gate. Getting closer to the toll gate, the slope of the model curves gets steeper and the centre of the curve gets closer to offset zero as expected.

In the simulation model, $\theta$ and $\delta$ are to be identified at each position in the toll plaza. Therefore, the interpolate function for each parameter are identified as shown in Figure 18. The equations of those functions are described as below in terms of relative distance to the gate in toll plaza upper section, which means ‘$x=0$’ is the gate position and ‘$x=1$’ is the upstream end of toll plaza.

\[
\begin{align*}
\theta &= 4.27e^{-1.14x} \\
\delta &= -0.56x \\
\end{align*}
\]  
(Eq.4)

\[
\begin{align*}
\theta &= 4.00e^{-1.50x} \\
\delta &= -2.68x \\
\end{align*}
\]  
(Eq.5)

where $x$: relative distance to the gate in toll plaza upper section.

Figure 17. Calibrated lane choice model for normal vehicles at each position.
Interpolation of the model parameters at each position

\[ \theta = 4.2685\exp(-1.135x) \text{ (ETC)} \]

\[ \theta = 3.9954\exp(-1.4914x) \text{ (normal)} \]

\[ \delta = 0.5556x \text{ (normal)} \]

\[ \delta = -2.6763 \text{ (ETC)} \]

Consideration of queue length at toll gate

The implemented lane choice model bases on (Eq.3) and modified to consider the queue length in front of each toll gate. As shown in Figure 19, if all the queue lengths are zero or equal to each other, the horizontal axis, i.e. lateral offset of lane, is divided with same band width. However, when the queue lengths are unequal, the band width for the gate with short queue will be wider and with long queue will be narrower, according to (Eq.6). As the wider band width increases the choice probability and vice-versa, this mechanism may work to equalize the queue length of each gate.

\[ b_i = \frac{l_i^{-1}}{\sum_j l_j^{-1}} \quad \text{(Eq.6)} \]

where \( b_i \): band width of lane \( i \).
\( l_i \): queue length of lane \( i \).

Figure 18. Interpolation of model parameters at each position in toll plaza.

Figure 19. Consideration of queue length by changing band width of lane choice model.
Planning for lane changing path
After a vehicle determines its target toll gate, it needs to plan on its lane changing path to reach the toll gate. It seems, however, difficult to identify drivers' decision making model only from the revealed vehicle trajectories. In this study, we do not take conventional behaviour modelling approach. Instead, we take data oriented approach that uses observed vehicle trajectories as the choice set of the path plan. This is based on the idea the drivers' behaviour with some decision making might be indirectly represented in the real data set. Here, all observed trajectories are embedded in the toll plaza, and a vehicle at any position in the plaza can pick up one of the trajectories which pass through the position and towards the target gate of the vehicle, as illustrated in Figure 20. In this modelling, a vehicle in advance to the others always can change its lane and the followers will give their way by decelerating speed.

Figure 20. Lane changing path selection based on observed vehicle trajectories.

VALIDATION AND CASE STUDIES

Model validation
The simulation model explained in the previous chapter was implemented onto existing traffic simulation software, AVENUE (Horiguchi, et al., 1996), as its extension module. Here, the implemented model is validated in terms of lane choice behaviour, speed on each lane, and counts of ‘near-miss’ opportunities.

Reproducibility of lane choice behaviour
Figure 21 is the comparison of simulation and observation results of lane choice probabilities for ETC vehicles. The simulation result well reproduces the observation except for the vehicles arriving from most left lane. The reason is some of those vehicles change the lane to centre or right lanes during they run on main expressway and enter the toll plaza not from the left lane but from centre of right lanes.

Figure 22 is the same comparison for normal vehicles. The magnitude of choice probability from each lane in the simulation is almost the same as observation. However, the lane position of peak probability in the simulation seems to be shifted to the left. This is considered that the model calibration stands on static idea. Namely, the lane choice at certain position is regarded as independent from other choices at different positions. On the other hand, simulation stands on dynamic framework. One vehicle may repeatedly choose lane at every interval. It is considered that the characteristic tend to choose lanes at relatively left side will be amplified by the iterative apply of the lane choice model.
Figure 21. Comparison of simulation (left) and observation (right) results in lane choice probability of ETC vehicles at 270m before the toll gate.

Figure 22. Comparison of simulation (left) and observation (right) results in lane choice probability of normal vehicles at 270m before the toll gate.

Figure 23 illustrates the vehicle counts at every 10 meters on each lane. We may see vehicles are diffusing in the toll plaza at around 230 meters to the gates. Figure 24 shows the paths which are taken by ETC vehicles. As expected, most of ETC vehicles decide to take which split side at far position and do not across the toll plaza at near position.

Figure 23. Spatial distribution of vehicle counts in toll plaza (direction: right to left).
Validation of speed
Figure 25 compares the average vehicle speeds at ETC toll gate. As the desired speed at toll gate position is given as a parameter, it is reasonable for the simulation to reproduce vehicle speed at free flow condition. Figure 26 shows the spatial distribution of vehicle speed at every 10 meters on each lane. In this case of light traffic, no slow down sections are found except the near position to the normal gate.
Count of ‘near-miss’ opportunities
Adding to the normal data output features of AVENUE, the extension module records the average speed and traffic counts at every 10 meters sections on each lane in the toll plaza. Furthermore, the counts of ‘near-miss’ opportunities at every positions are recorded as well. Here, we defined ‘near-miss’ opportunity with the conditions listed in below.

- Two vehicles were running at free flow speed of each position at the previous time.
- One of them decelerates and the headway between them is less than 1 second at current time.
- At least one of them changes its lane from the previous time.

Although this definition is an expedient and does not consider the degree of danger, it may represent some extent of pressure that driver feels from other vehicles changing their lanes.

Figure 27 illustrates the spatial distribution of ‘near-miss’ opportunities. Although the differences are small because of light traffic condition, we may see the small tendency that more ‘near-miss’ will happen at far positions to the gates than near positions.

Case studies
For the purpose of planning optimal design of toll plaza under high penetration of ETC vehicles, we had executed numbers of case studies. In this paper, the results of three case studies listed in Table 1 are described.

Traffic demand is set to the same level as 30th hourly traffic volume from annual statistics at Narashino Toll Plaza. The portion of ETC vehicles is set to 80%, that is about 2400 ETC vehicles arrive in an hour. Since the capacity of ETC toll gate was estimated as 800 [veh/hr] in the video survey, three ETC exclusive lanes in the current configuration would be very tight for the demand. Under heavy traffic conditions, many lane changes may happen and affect on the capacity of toll plaza. Therefore, in Case-80-2 and Case-80-3, one ETC exclusive lane is added to the current lane configuration.
Table 1. Settings of case studies.

<table>
<thead>
<tr>
<th>Case</th>
<th>Traffic demand</th>
<th>ETC vehicles</th>
<th>ETC exclusive lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-80-1</td>
<td>3100 [veh/hr]</td>
<td>80%</td>
<td>Lane#-8, 0, 1 (same as present)</td>
</tr>
<tr>
<td>Case-80-2</td>
<td>3100 [veh/hr]</td>
<td>80%</td>
<td>Lane#-8, -7, 0, 1</td>
</tr>
<tr>
<td>Case-80-3</td>
<td>3100 [veh/hr]</td>
<td>80%</td>
<td>Lane#-8, 0, 1, 2</td>
</tr>
</tbody>
</table>

Case-80-1

In this case, traffic condition in the toll plaza gets jam, although the capacities of ETC toll gates (#-8, #0 and #1) are not fully utilized as shown in Figure 28. From the speed distribution in Figure 29, it is found that the section 160m – 220m gets mostly slow down. This implies that the interference between the vehicles changing their lanes will decline the capacity of this section less than the capacity of ETC gate. Therefore, we may conclude three ETC lanes are not enough for the case of 80% ETC vehicles.

Figure 30 shows the number of ‘near-miss’ opportunities. Since we defined ‘near-miss’ is counted only in free flow condition and this case gets jam condition in toll plaza, less ‘near-miss’ opportunities would be recorded.

Case-80-2

Figure 31 and Figure 32 show the vehicle counts and speeds on each lane. In this case, the traffic jam in the toll plaza is less severe than Case-80-1 but the speed in the plaza slightly slows down, although the capacities of ETC gates are not fully utilized. Especially, the speed of the section 60m – 100m is slower than the speed at gate position, which implies the lane changes in this section affect traffic flow. The ‘near-miss’ counts in Figure 33 supports this idea that there are many ‘near-miss’ opportunities along this section, as well as the upstream section around 200m. Same situation of ‘near-miss’ counts is found...
in the left side of the toll plaza.

Figure 31. Spatial distribution of vehicle counts in toll plaza (Case-80-2).

Figure 32. Spatial distribution of vehicle speeds in toll plaza (Case-80-2).

Figure 33. Spatial distribution of ‘near-miss’ opportunities in toll plaza (Case-80-2).

Case-80-3

Figure 34 and Figure 35 show the vehicle counts and speeds on each lane. This case also does not fully use the capacity of ETC gate. The slow section on ETC lane of this case becomes longer than Case-80-2, but never spill over the toll plaza section. The ‘near-miss’ counts are less than Case-80-2 as less counts are recorded in the left side of the toll plaza.

Figure 34. Spatial distribution of vehicle counts in toll plaza (Case-80-3).

Figure 35. Spatial distribution of vehicle speeds in toll plaza (Case-80-3).
Summary of case studies

The results of those case studies are summarized in Table 2. Regarding with the efficiency, Case-80-2 shows the best result in this case. However, Case-80-3 results less number of ‘near-miss’ than Case-80-2, which means there might be in less pressure to the drivers. Since the average travel times of Case-80-3 is almost the same level as Case-80-2, this case may be considerable for the future plan.

Table 2. Summary of case studies.

<table>
<thead>
<tr>
<th>Case</th>
<th>Case-80-1</th>
<th>Case-80-2</th>
<th>Case-80-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time [veh*hr]</td>
<td>72.48</td>
<td>30.19</td>
<td>36.72</td>
</tr>
<tr>
<td>Average TT for ETC vehicles [sec]</td>
<td>77.5</td>
<td>36.7</td>
<td>38.8</td>
</tr>
<tr>
<td>Average TT for normal vehicles [sec]</td>
<td>73.3</td>
<td>44.8</td>
<td>45.8</td>
</tr>
<tr>
<td>Number of ‘near-miss’</td>
<td>585</td>
<td>926</td>
<td>786</td>
</tr>
</tbody>
</table>

Those case studies give us some useful implications for the improvement of toll plaza design and operation, those for;

(i) Capacity bottleneck may appear not at the ETC gate position but at 50 to 100 meters upstream to the ETC gate because of the merging of ETC vehicles.

(ii) Near-miss opportunities are increasing not only at the bottleneck position near the toll gate but also at far position from the toll gate where the congested section reaches.

(iii) If we add one ETC gate to improve the capacity of the toll plaza, it is better to replace one normal gate near the road centre to ETC exclusive than the left side, in terms of less ‘near-miss’ counts.

CONCLUSION

In this paper, the development of the simulation to evaluate the design of ETC toll plaza was described. In advance of the modelling stage, the precise survey with video image processing had been conducted in Narashino Toll Plaza on Higashi-Kanto Expressway. Based on the findings from the survey, the simulation model was designed so as to utilize the data which can be obtained the normal traffic survey, such as speeds, headways, lane choice, etc. The flow model and the lane choice model proposed here were calibrated and validated by applying to the survey result. Case studies for high ETC penetration situation had been evaluated and some important implications were obtained through this simulation application.

In this paper, we only explain the case studies for toll barrier type, but the model parameters identified here may not be universal. Further studies for different types of toll plaza are also targeted in our scope.
REFERENCES

