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.

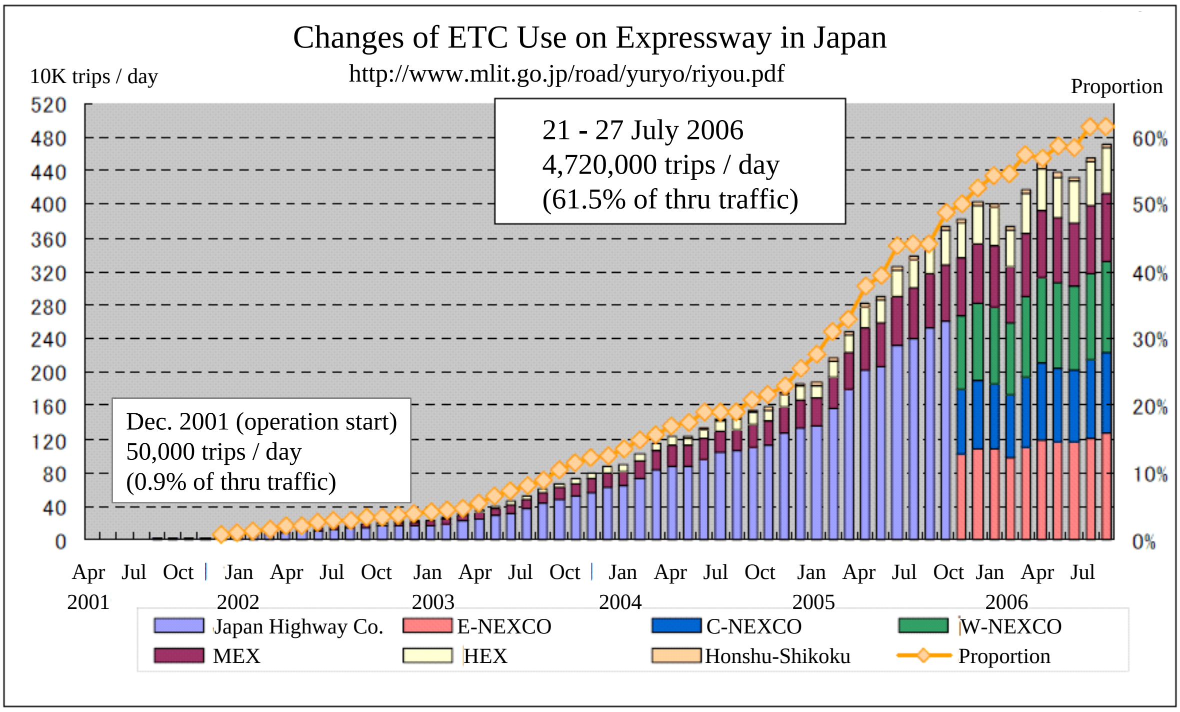

Figure 1. Changes of ETC use on expressways in Japan.

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.

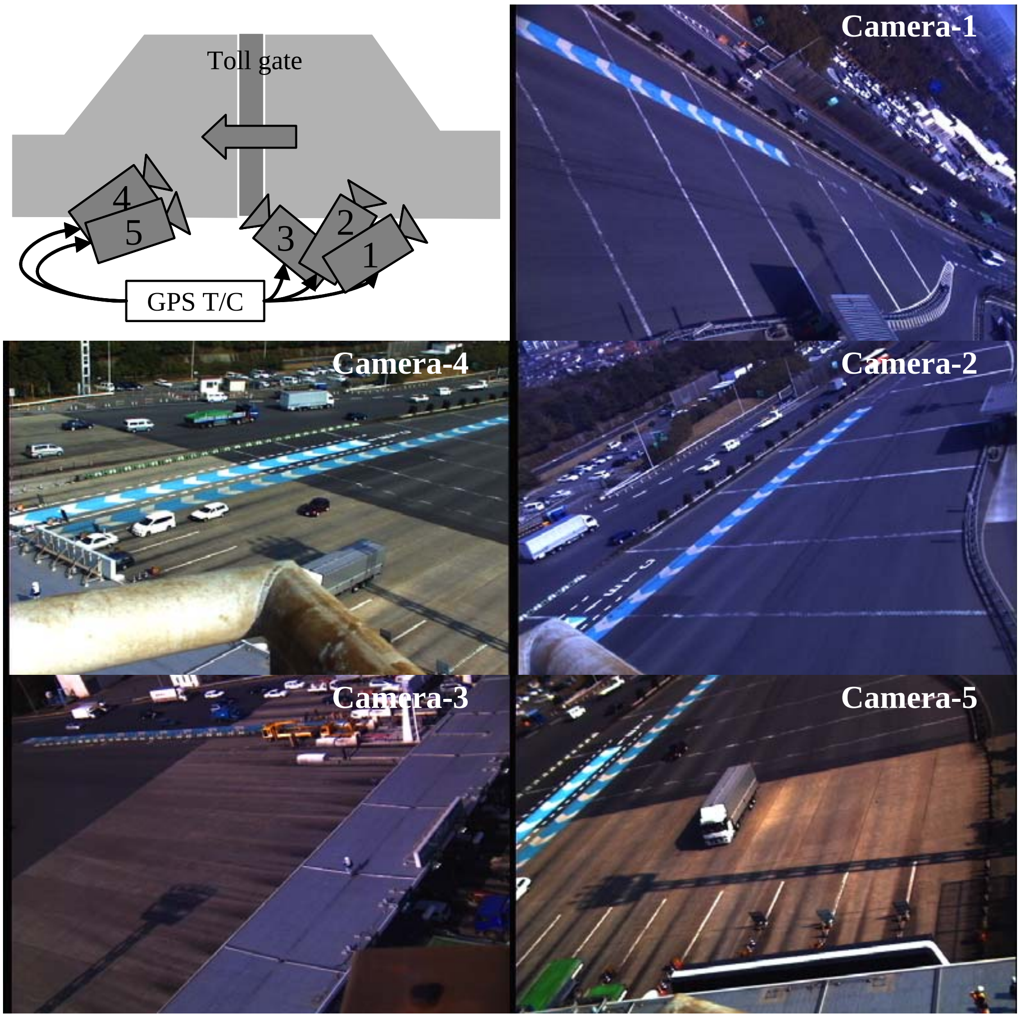

Figure 2. Arrangement of plural video cameras in the survey at NarashinoToll Plaza.

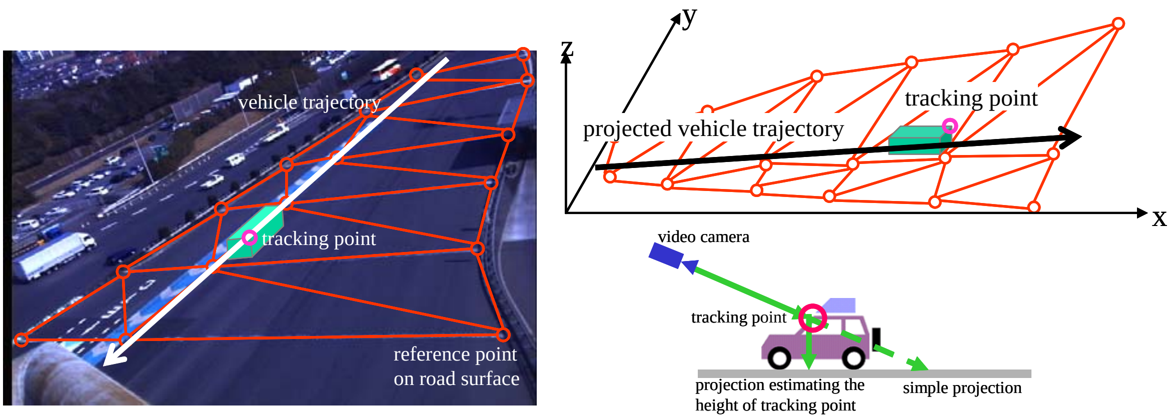

Figure 3. Projection of vehicle trajectory by estimating the height of tracking point.

Survey result

<u>Trajectories</u>

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.

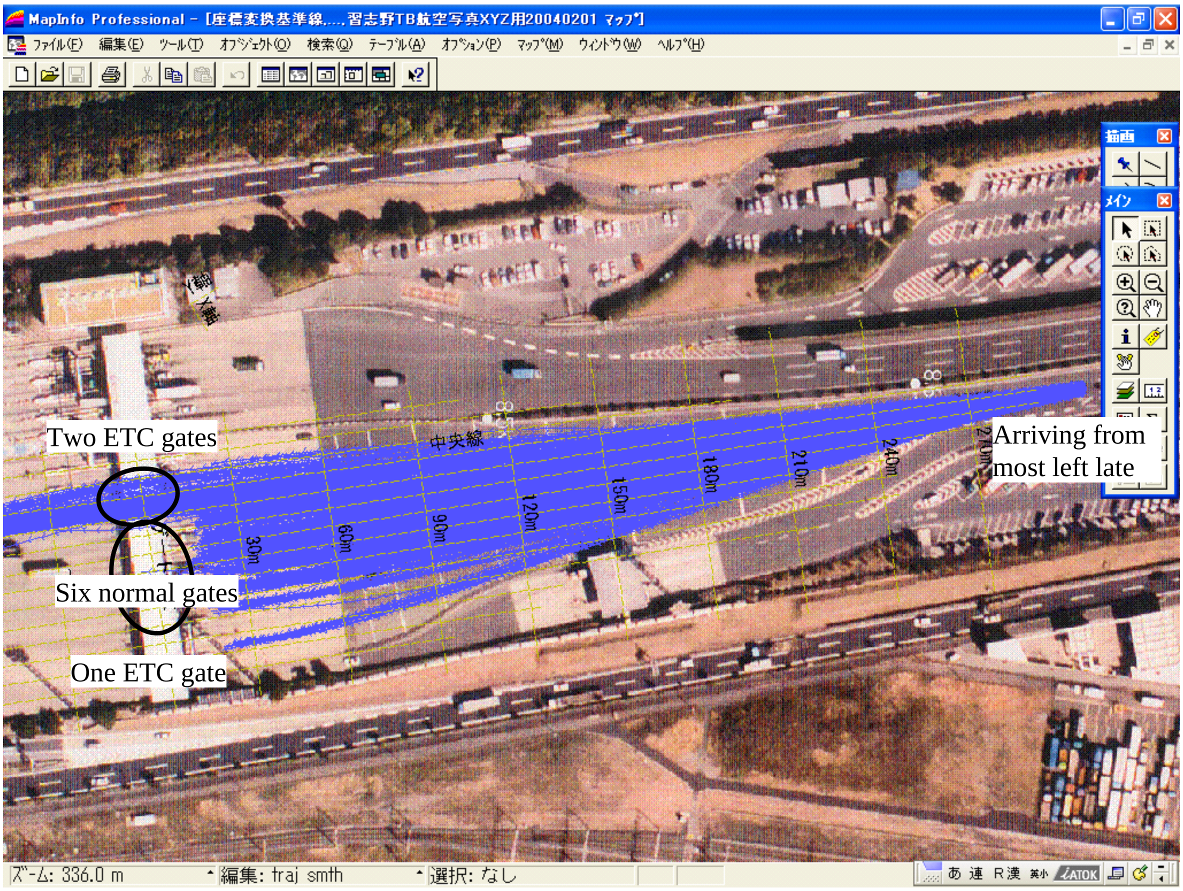

Figure 4. Vehicle trajectories arriving from the most left lane at the upstream of toll plaza.

<u>Speed and Acceleration</u>

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/sec^2 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.

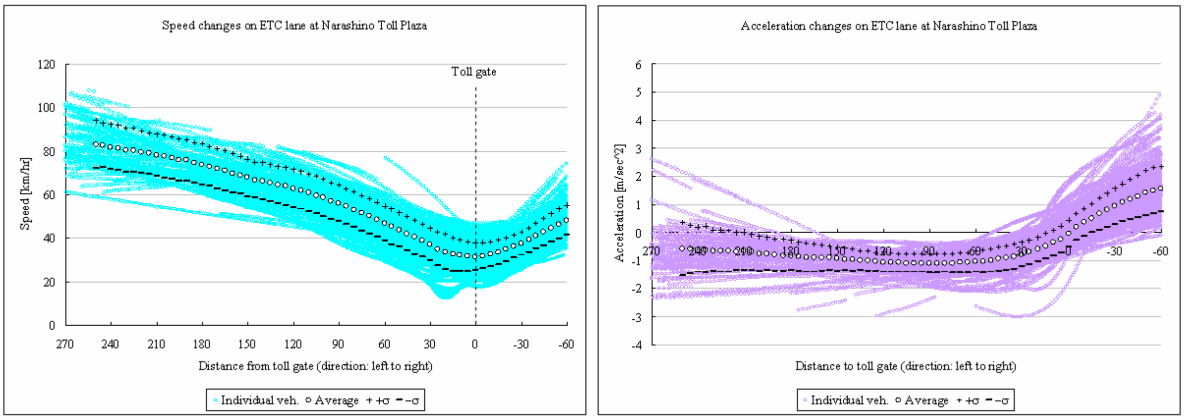

Figure 5. Speed and acceleration distribution on ETC exclusive lane.

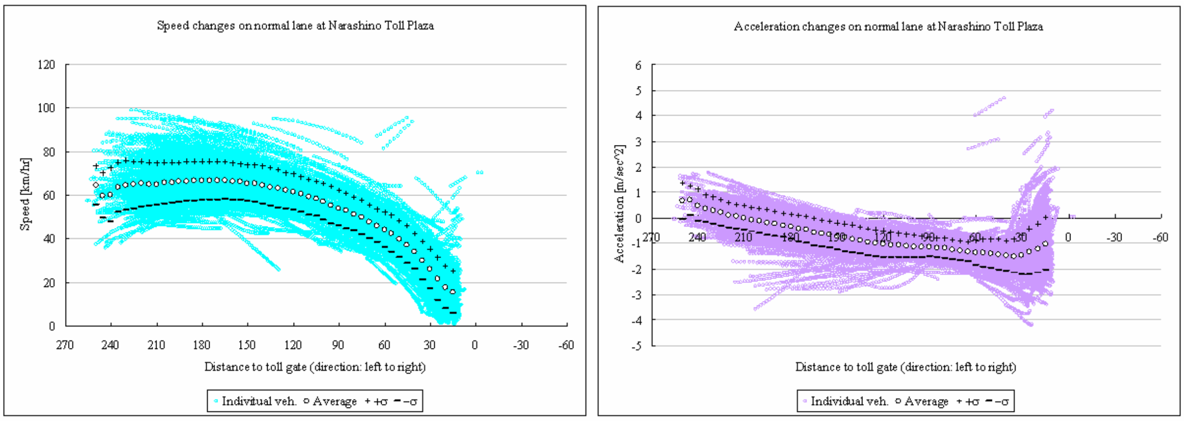

Figure 6. Speed and acceleration distribution on normal lane.

<u>Headway and capacity</u>

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].

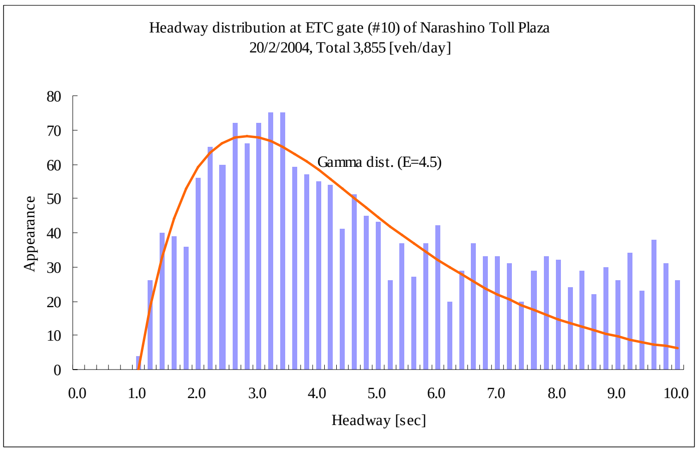

Figure 7. Headway distribution at ETC toll gate.

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, ie. 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).

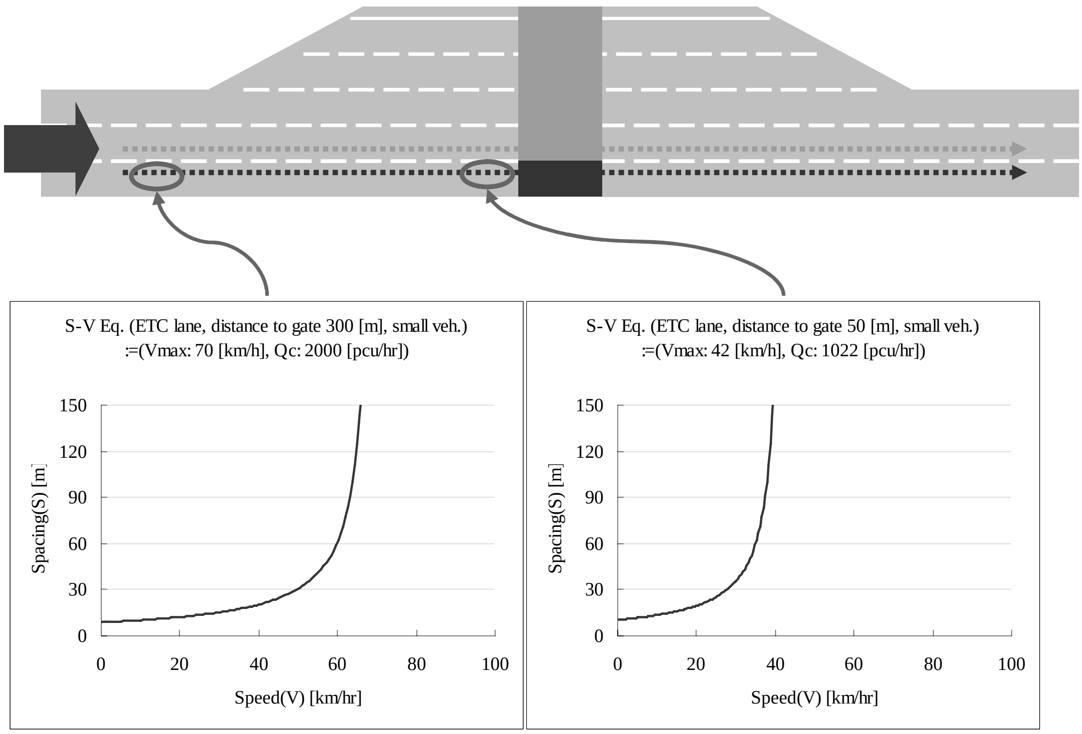

Figure 8. Spacing-Speed (S-V) relationship varying with the position in the toll plaza.

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).

$$\begin{cases} S_i(t+1) = f(V_i(t)) \\ S_i(t) + V_{i-1}(t)dt = S_i(t+1) + V_i(t)dt \end{cases} \qquad \text{(Eq.1)}$$

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.

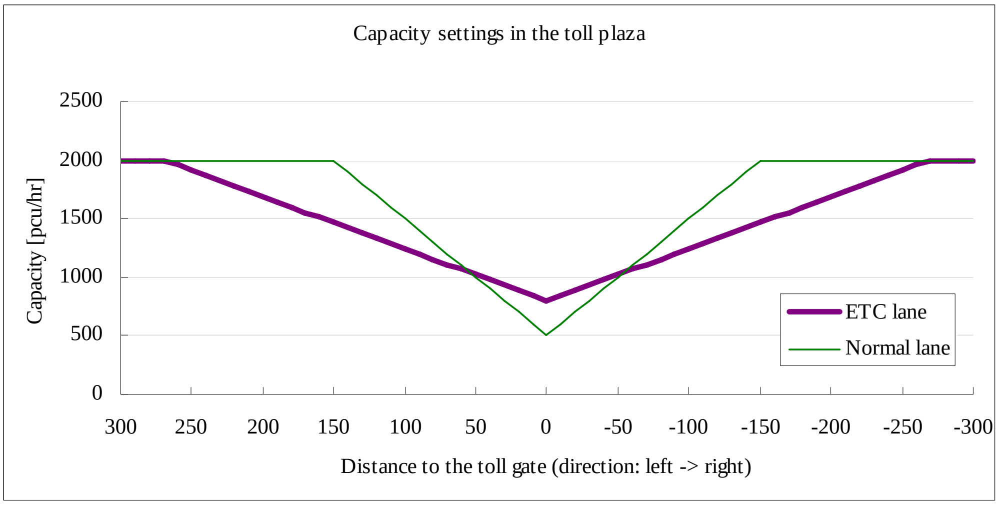

Figure 9. Capacity settings in Narashino Toll Plaza.

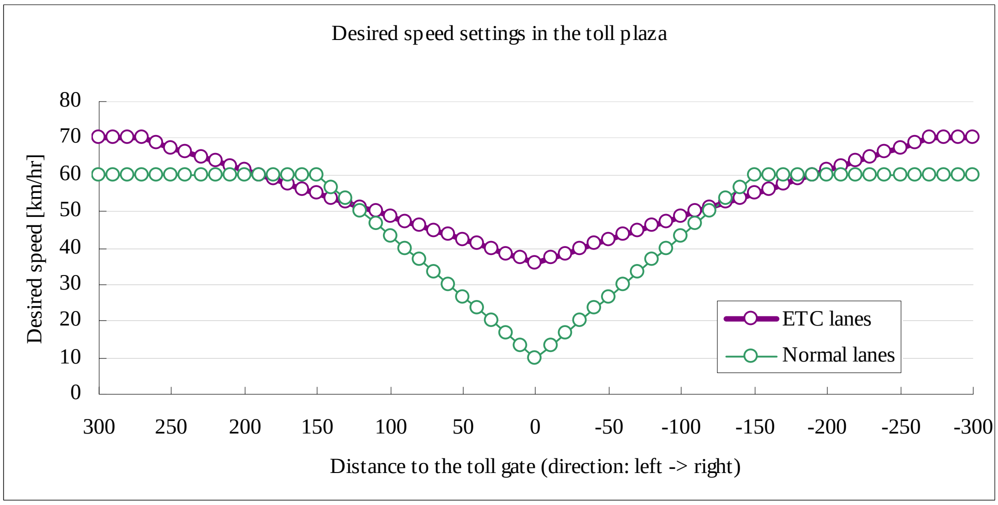

Figure 10. Desired speed settings in Narashino Toll Plaza.

Lane choice behaviour modelling

<u>Lane choice behaviour in Narashino Toll Plaza</u>

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.

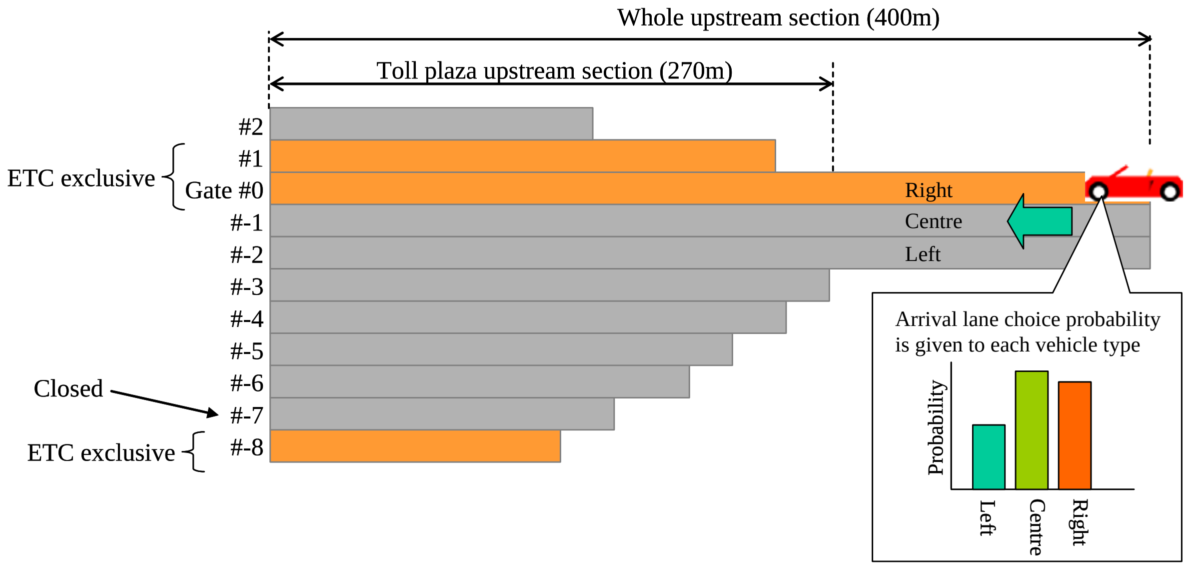

Figure 11. Lane configuration in the upstream section of Narashino Toll Plaza.

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.

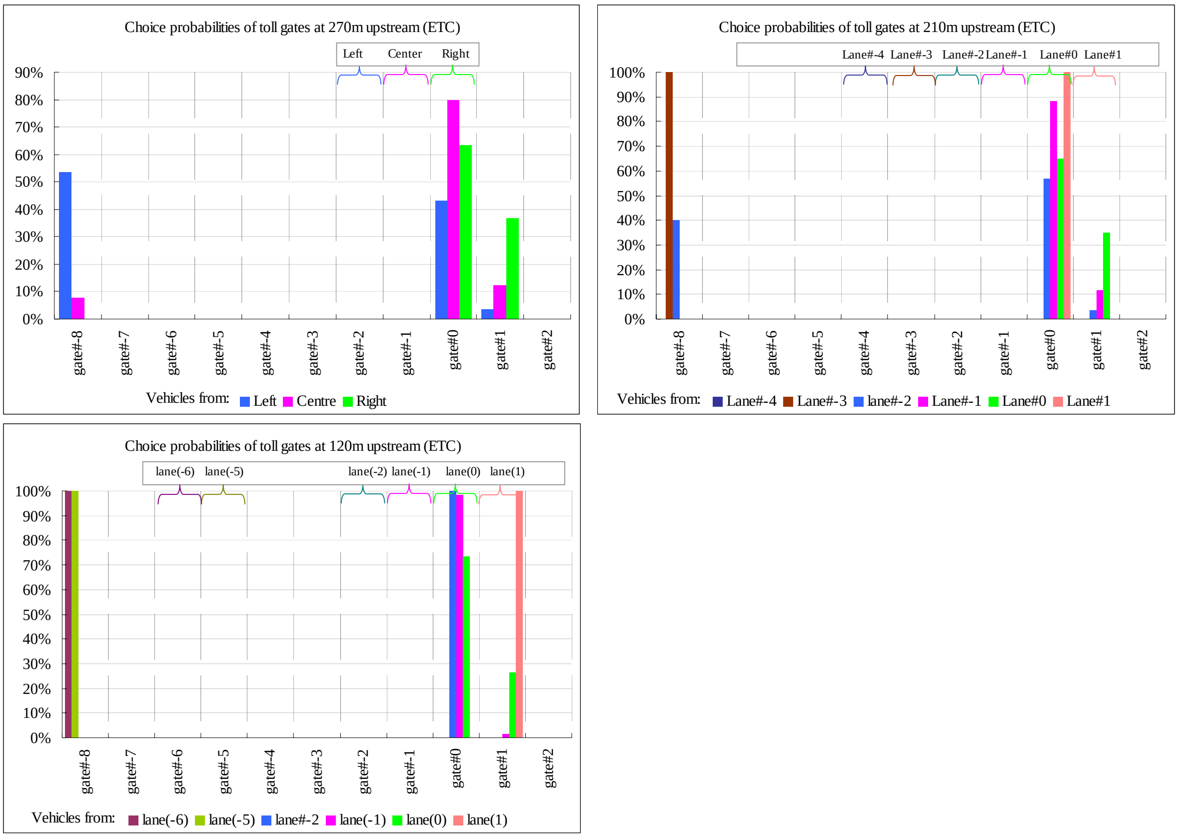

Figure 12. Choice probabilities of ETC toll gates at different position in the toll plaza

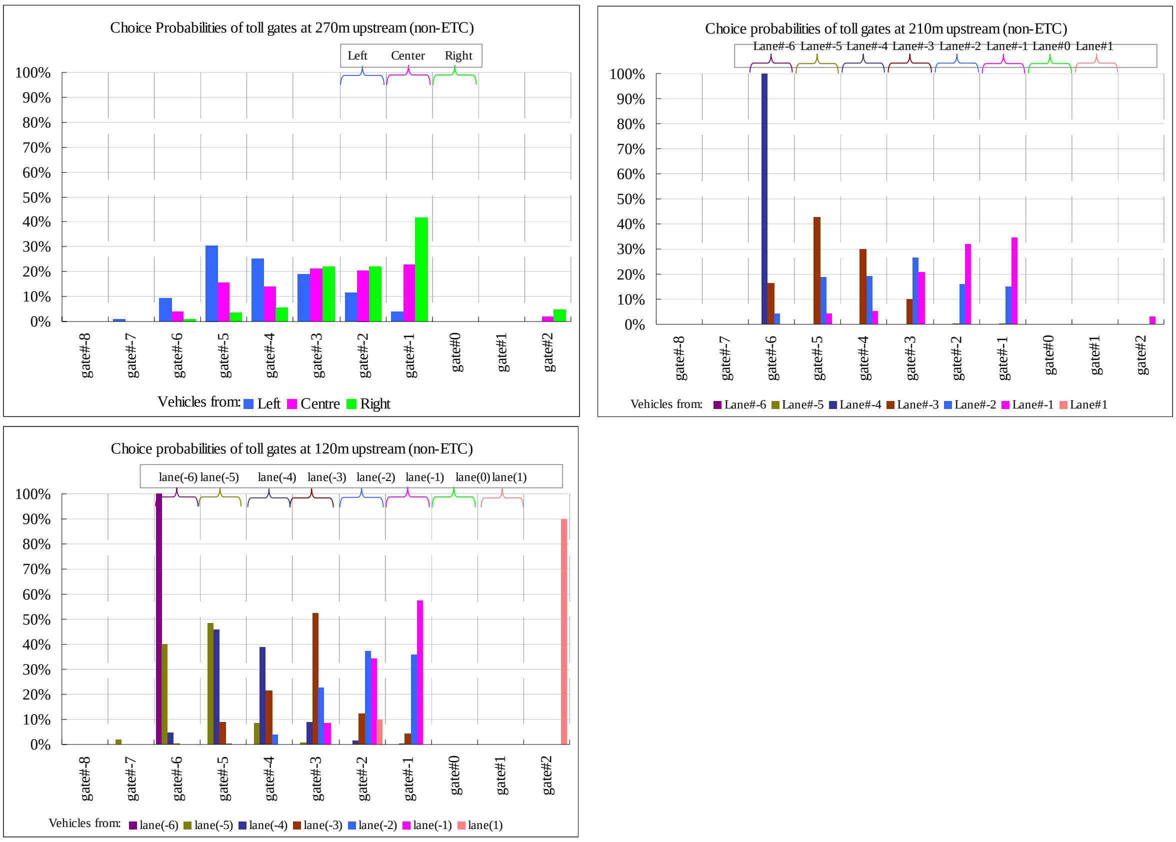

Figure 13. Choice probabilities of normal toll gates at different position in the toll plaza.

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.

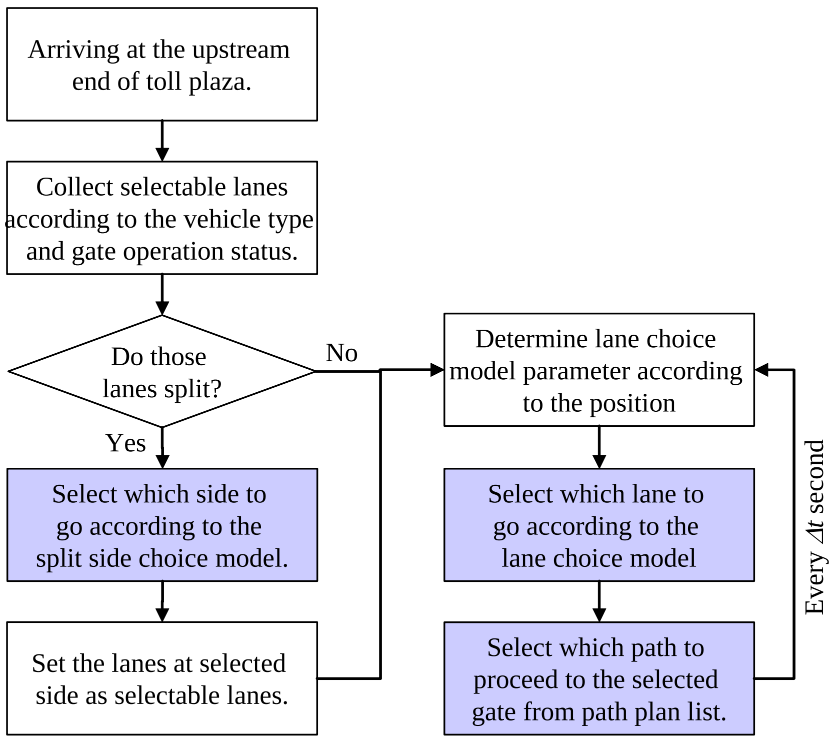

Figure 14. Flow chart of lane choice modelling.

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 θ means the sensitivity. Figure 15 shows the result of parameter calibration to fit the survey result.

$$P_L = \frac{1}{1+e^{-\theta(|\delta_L-\eta_L|w_1-|\delta_R-\eta_R|w_2)}} \quad \text{(Eq.2)}$$

where P_L : the choice probability for left split lanes.
δ_L, δ_R : the lateral offset in lane position from vehicle's arriving lane to the centre lane of left / right split lanes.
η_L, η_R : the lateral offset in lane position from vehicle's discharging lane at downstream end to the centre of left / right split lanes.
θ, w_1, w_2 : parameters to be calibrated.

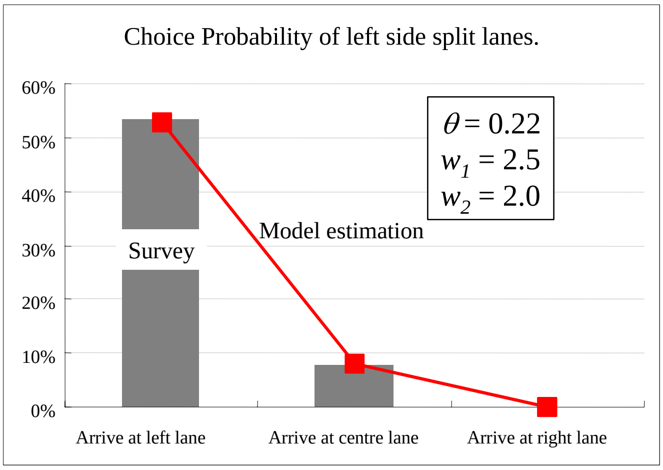

Figure 15. Calibrated split lane choice model for Narashino Toll Plaza.

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.
δ, θ : parameters to be calibrated.

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

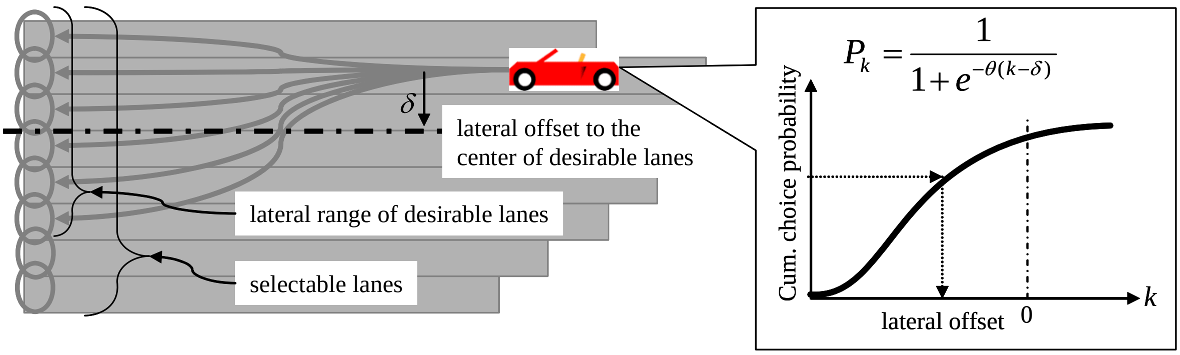

Figure 16. Parameters used in the lane choice model.

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, θ and δ 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.

$$\begin{cases} \theta = 4.27e^{-1.14x} \\ \delta = -0.56x \end{cases} \quad \text{(for ETC vehicles)} \qquad \text{(Eq.4)}$$

$$\begin{cases} \theta = 4.00e^{-1.50x} \\ \delta = -2.68x \end{cases} \quad \text{(for normal vehicles)} \qquad \text{(Eq.5)}$$

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

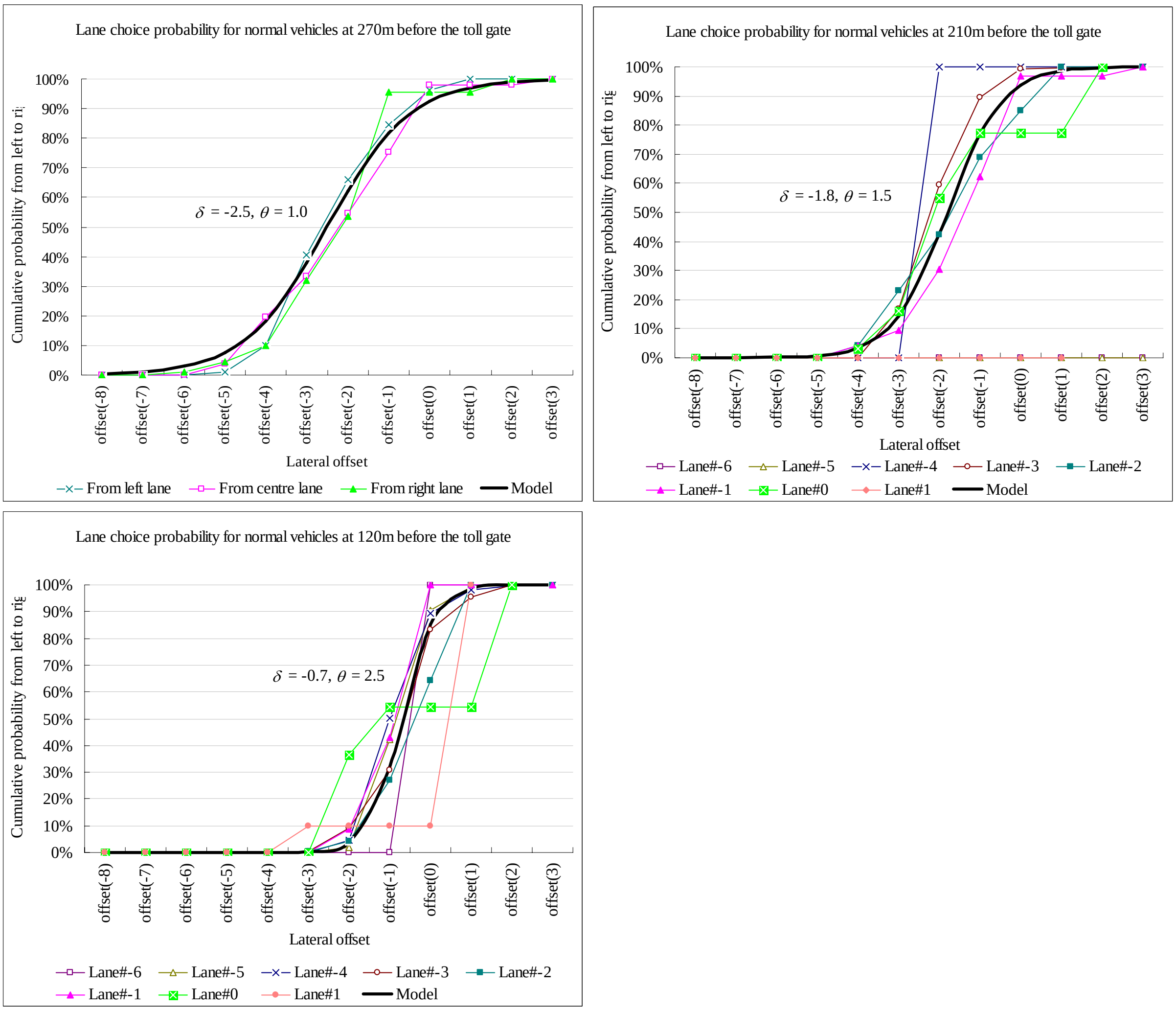

Figure 17. Calibrated lane choice model for normal vehicles at each position.

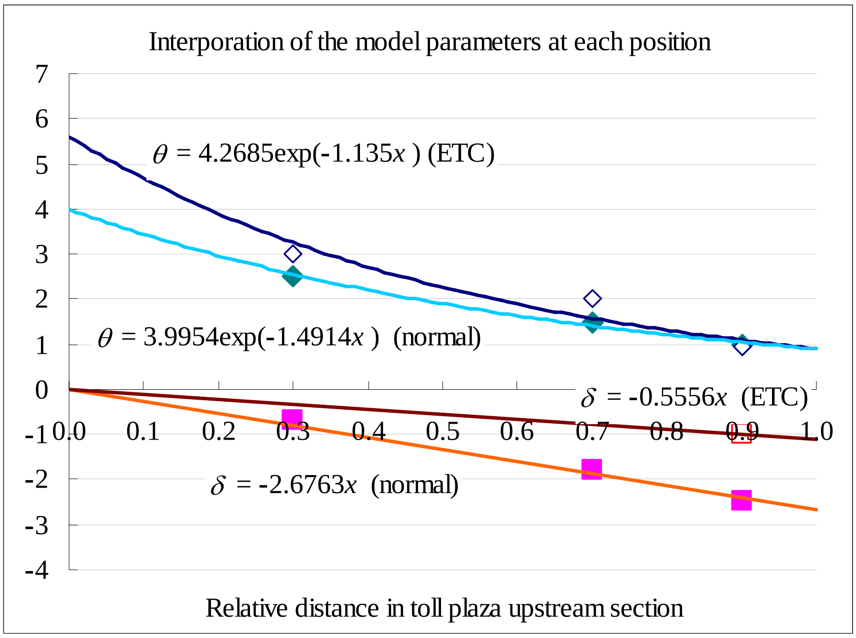

Figure 18. Interpolation of model parameters at each position in toll plaza.

<u>Consideration of queue length at toll gate</u>

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, rf all the queue lengths are zero or equal to each other, the horizontal axis, ie. 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.

$$b_i = \frac{l_i^{-1}}{\sum_j l_j^{-1}} \qquad \text{(Eq.6)}$$

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

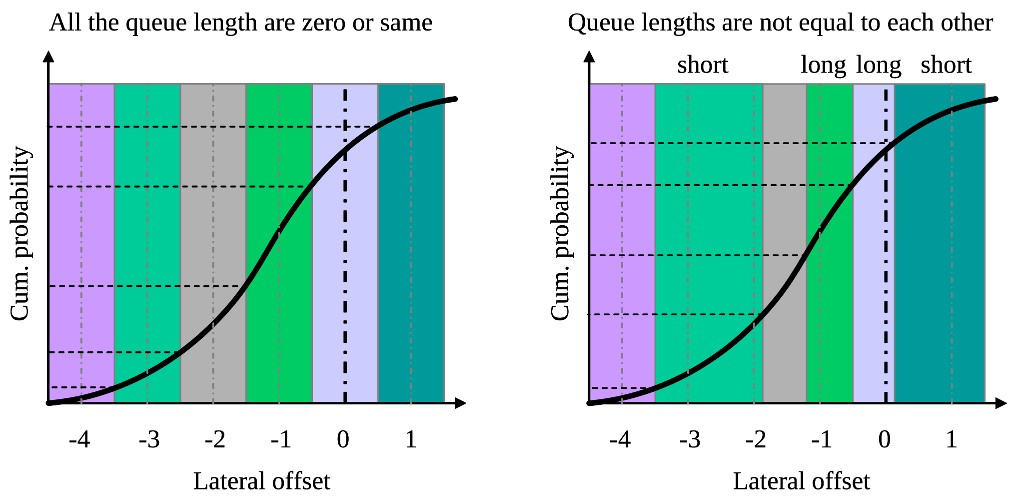

Figure 19. Consideration of queue length by changing band width of lane choice model.

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.

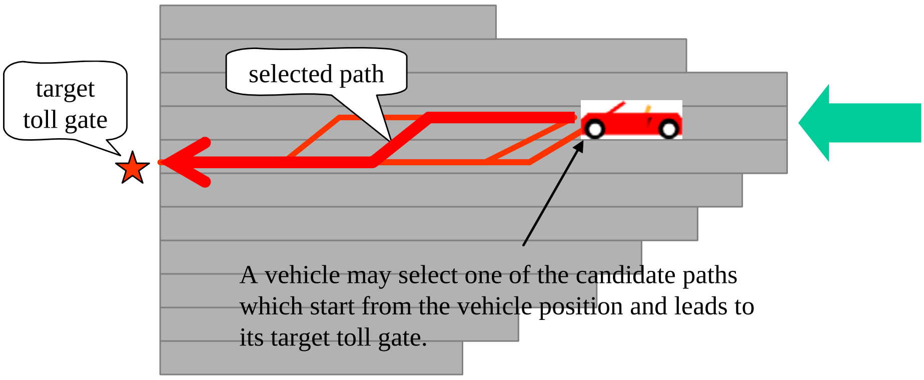

Figure 20. Lane changing path selection based on observed vehicle trajectories.

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.

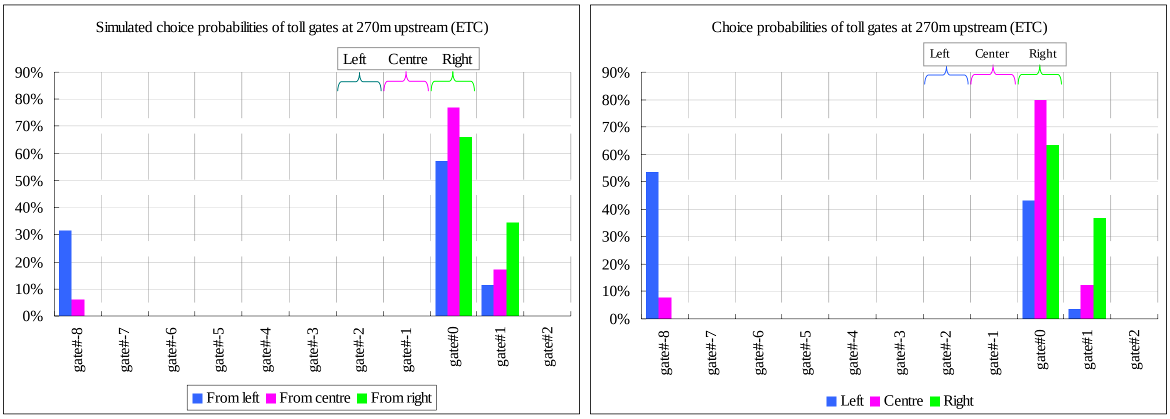

Figure 21. Comparison of simulation (left) and observation (right) results in lane choice probability of ETC vehicles at 270m before the toll gate.

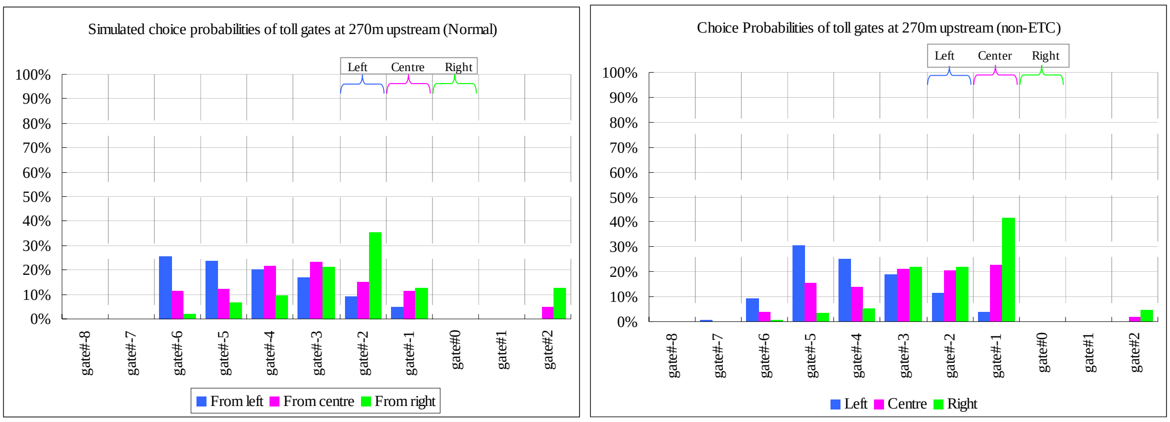

Figure 22. Comparison of simulation (left) and observation (right) results in lane choice probability of normal vehicles at 270m before the toll gate.

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.

断面交通量→	882	882	882	883	884	885	885	884	884	884	884	883	884	883	883	882
車線	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m
2	36	36	36	36	36	34	34	34	14	14	6	6	6	5	5	-1
1	52	52	52	52	43	32	32	30	40	40	38	38	39	32	32	19
0	147	147	147	147	156	165	165	167	122	122	109	109	109	101	101	98
-1	57	57	57	53	52	53	53	55	105	105	131	134	134	157	157	193
-2	113	113	113	110	107	108	108	104	103	103	127	129	129	148	148	178
-3	127	127	127	130	129	133	133	138	133	133	127	127	127	150	150	181
-4	124	124	124	125	129	133	133	134	139	139	150	150	150	157	157	154
-5	105	105	105	107	105	100	100	98	117	117	116	112	112	106	106	60
-6	97	97	97	99	102	102	102	100	86	86	61	60	60	29	29	2
-7	0	0	0	0	0	0	0	25	26	26	20	19	19	-1	-1	-1
-8	24	24	24	24	25	25	25	-1	-1	-1	-1	-1	-1	-1	-1	-1

断面交通量→	882	881	881	881	881	881	881	881	881	880	880	880	880	878	878	878	878
車線	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
1	19	16	16	16	16	14	14	5	5	0	0			-1	-1	-1	-1
0	98	118	118	105	105	115	115	161	161	193	193	192	192	189	189	189	189
-1	193	180	180	238	238	285	285	345	345	323	323	389	389	391	391	390	390
-2	178	185	185	206	206	261	261	309	309	311	311	304	304	306	306	307	307
-3	181	178	178	205	205	195	195	66	66	59	59			-1	-1	-1	-1
-4	154	152	152	109	109	15	15			-1	-1	-1	-1	-1	-1	-1	-1
-5	60	56	56	6	6			-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-6	2	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-7	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-8	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

Figure 23. Spatial distribution of vehicle counts in toll plaza (direction: right to left).

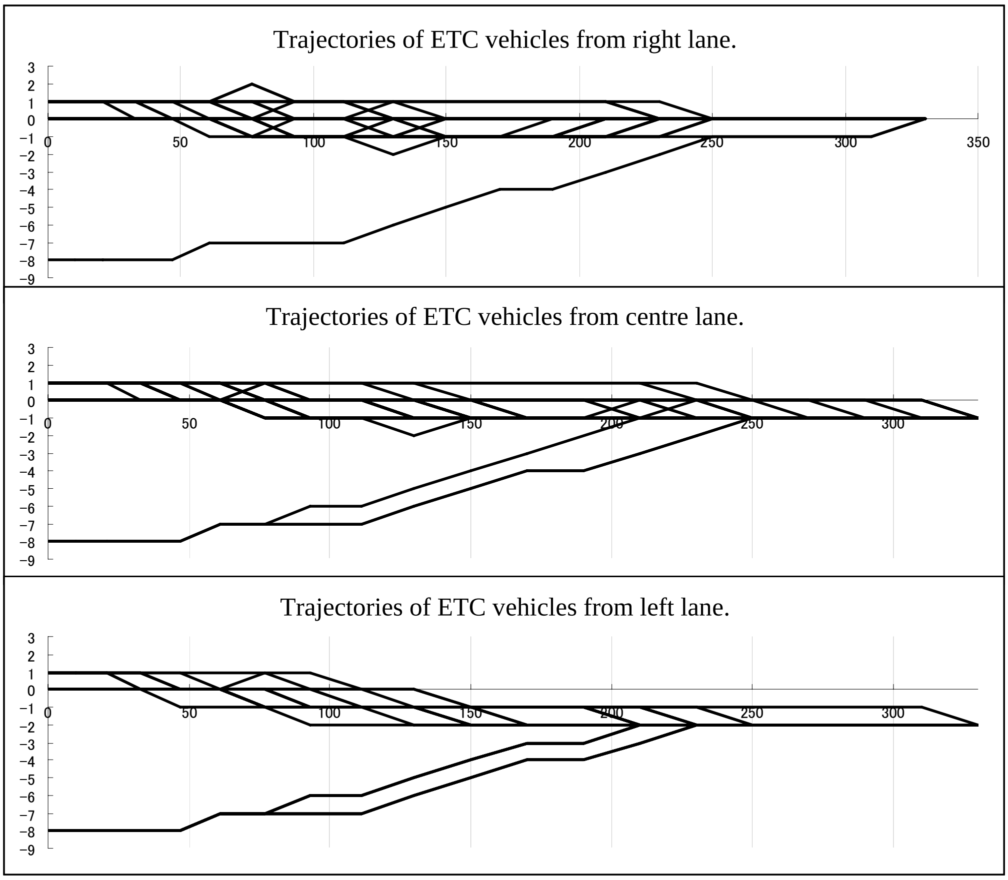

Figure 24. Paths of ETC vehicles in the toll plaza.

<u>Validation of speed</u>

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.

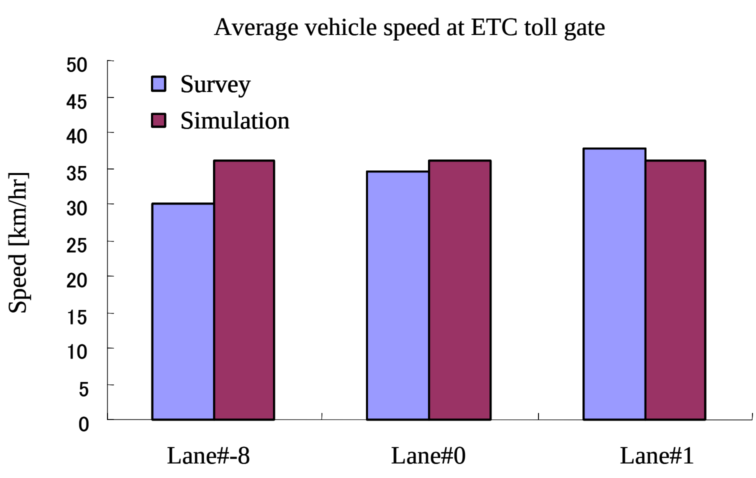

Figure 25. Comparison of average vehicle speeds at ETC toll gate.

車線		0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2		10	20	31	36	41	46	46	51	57	57	62	67	67	72	72	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
1		36	36	36	44	45	52	52	51	57	57	64	64	68	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	72	-1	-1	-1	-1
0		36	37	37	43	45	52	52	54	57	57	60	60	68	71	71	71	71	71	71	71	71	70	70	64	64	71	71	71	71	72	72	72	72
-1		10	20	30	36	41	46	46	50	54	54	59	65	65	72	72	71	71	72	72	70	70	69	69	67	67	70	70	69	69	71	71	71	71
-2		6.2	18	28	33	40	45	45	51	54	54	59	63	63	68	68	69	69	72	72	68	68	67	67	70	70	67	67	69	69	71	71	72	72
-3		6.2	19	29	36	40	45	45	50	52	52	57	66	66	72	72	70	70	70	70	70	70	72	72	72	72	72	72	72	72	-1	-1	-1	-1
-4		8.7	19	28	35	41	45	45	51	56	56	58	64	64	72	72	72	72	72	72	72	72	72	72	72	72	-1	-1	-1	-1	-1	-1	-1	-1
-5		6.8	19	28	33	36	44	44	51	56	56	58	67	67	72	72	72	72	72	72	72	72	72	72	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-6		5.4	18	28	36	40	43	43	51	50	50	58	67	67	72	72	72	72	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-7		10	20	31	36	41	46	46	49	57	57	62	67	67	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-8		36	40	40	42	48	52	52	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

Figure 26. Spatial distribution of running speed in toll plaza (direction: right to left).

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.

車線		0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			-1	-1	-1	-1
0		0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0
-1		0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
-2		0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	2	2	2	2	0	0	4	4	0	0	0	0	0	0
-3		0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0			-1	-1	-1	-1
-4		0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0			-1	-1	-1	-1	-1	-1	-1	-1
-5		0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0			-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-6		0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-7		0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
-8		0	0	0	0	0	0	0	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

Figure 27. Spatial distribution of ‘near-miss’ opportunities in toll plaza (direction: right to left).

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.

Case	Traffic demand	ETC vehicles	ETC exclusive lanes
Case-80-1	3100 [veh/hr]	80%	Lane#-8, 0, 1 (same as present)
Case-80-2	3100 [veh/hr]	80%	Lane#-8, -7, 0, 1
Case-80-3	3100 [veh/hr]	80%	Lane#-8, 0, 1, 2

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.

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	126	126	126	126	126	124	124	122	72	72	34	31	31	28	28																		
1	717	718	718	701	589	463	463	379	350	350	354	354	339	319	319	347	347	383	383	442	442	555	555	614	614	637	637	524	524				
0	697	696	696	713	807	813	813	634	477	477	437	437	428	419	419	433	433	501	501	481	481	424	424	404	404	403	403	522	522	977	977	917	917
-1	22	22	22	21	41	162	162	430	614	614	581	490	490	424	424	417	417	353	353	333	333	295	295	279	279	275	275	297	297	570	570	953	953
-2	48	48	48	48	47	50	50	48	100	100	223	360	360	567	567	606	606	535	535	472	472	470	470	582	582	578	578	573	573	1143	1143	822	822
-3	59	59	59	60	60	61	61	64	65	65	81	170	170	132	132	147	147	229	229	414	414	575	575	566	566	791	791	773	773				
-4	83	83	83	80	82	78	78	78	93	93	180	129	129	126	126	211	211	211	211	247	247	227	227	235	235								
-5	89	89	89	90	89	90	90	100	195	195	167	144	144	228	228	261	261	449	449	275	275	126	126										
-6	108	108	108	110	113	135	135	223	182	182	214	212	212	409	409	232	232																
-7	0	0	24	25	88	201	201	559	493	493	375	346	346																				
-8	676	676	676	653	591	457	457																										

Figure 28. Spatial distribution of vehicle counts in toll plaza (Case-80-1).

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	6	18	29	35	40	45	45	50	51	51	62	67	67	70	70																		
1	33	25	25	20	15	16	16	24	32	32	40	40	51	48	48	50	50		47	24	24	14	14	13	13	13	13	23	23				
0	35	28	28	27	21	13	13	7	5	5	6	6	6	8	8	9	9	8	8	7	7	6	6	5	5	6	6	8	8	26	26	21	21
-1	10	20	31	36	23	16	16	12	10	10	8	6	6	5	5	5	5	4	4	4	4	4	4	3	3	3	3	4	4	14	14	25	25
-2	10	20	30	34	41	45	45	47	21	21	15	16	16	15	15	12	12	9	9	8	8	8	8	11	11	10	10	13	13	38	38	21	21
-3	9	19	29	35	40	45	45	51	53	53	62	63	63	67	67	37	37	25	25	22	22	25	25	29	29	44	44	56	56				
-4	9	19	30	35	41	45	45	51	57	57	58	57	57	63	63	64	64	66	66	58	58	71	71	70	70								
-5	7	18	28	35	40	45	45	48	45	45	44	45	45	61	61	57	57	63	63	64	64	70	70										
-6	6	19	29	35	40	36	36	35	27	27	25	34	34	53	53	59	59																
-7	10	20	7	32	11	12	12	23	19	19	20	31	31																				
-8	36	22	22	20	14	15	15																										

Figure 29. Spatial distribution of vehicle speeds in toll plaza (Case-80-1).

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0																		
1	0	0	0	7	8	4	4	4	2	2	0	0	1	1	1	0	0	0	0	0	0	1	1	0	0	3	3						
0	1	0	0	1	5	12	12	4	1	1	1	1	2	2	2	3	3	1	1	1	1	1	1	0	0	0	0	11	11	15	15	5	5
-1	0	0	0	0	0	1	1	0	3	3	0	1	1	3	3	1	1	0	0	2	2	3	3	1	1	2	2	4	4	2	2	21	21
-2	0	0	0	0	0	0	0	0	0	0	0	2	2	4	4	3	3	2	2	2	2	2	2	1	1	3	3	9	9	84	84	6	6
-3	0	0	0	0	0	0	0	0	1	1	0	0	0	1	1	0	0	2	2	1	1	4	4	1	1	1	1						
-4	0	0	0	0	0	0	0	0	0	0	2	1	1	1	1	2	2	0	0	1	1	0	0										
-5	0	0	0	0	0	0	0	0	3	3	1	2	2	1	1	1	1	10	10	0	0												
-6	0	0	0	0	0	0	0	2	0	0	2	1	1	2	2	0	0																
-7	0	0	0	0	0	2	2	2	6	6	0	0	0																				
-8	0	0	0	0	2	0	0																										

Figure 30. Spatial distribution of 'near-miss' opportunities in toll plaza (Case-80-1).

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.

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	54	54	54	54	54	52	52	49	34	34	16	10	10	6	6																		
1	750	748	748	695	598	500	500	380	226	226	164	164	146	102	102	91	91	100	100	108	108	128	128	147	147	188	188	103	103				
0	677	678	678	696	760	794	794	803	750	750	724	724	689	638	638	609	609	624	624	628	628	740	740	904	904	984	984	1105	1105	1154	1154	1168	1168
-1	57	57	89	81	109	163	163	268	494	494	601	658	658	751	751	797	797	805	805	868	868	939	939	1009	1009	916	916	931	931	995	995	1008	1008
-2	73	74	76	71	71	84	84	94	95	95	107	122	122	167	167	256	256	300	300	469	469	560	560	554	554	577	577	838	838	851	851	825	825
-3	99	99	99	100	100	106	106	110	115	115	142	143	143	201	201	322	322	373	373	428	428	382	382	339	339	333	333						
-4	104	104	106	117	122	121	121	126	139	139	158	212	212	325	325	429	429	392	392	318	318	227	227										
-5	109	109	113	106	105	118	118	138	184	184	319	326	326	419	419	337	337	400	400	175	175												
-6	102	102	149	158	190	236	236	299	406	406	419	448	448	382	382	150	150																
-7	573	576	576	547	583	637	637	721	545	545	338	338	235																				
-8	379	374	374	357	291	175	175																										

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

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	9	19	30	36	40	45	45	50	55	55	62	67	67	72	72																		
1	35	28	28	21	20	23	23	29	39	39	47	47	61	62	62	68	68	69	69	71	71	68	68	62	62	60	60	72	72				
0	36	27	27	26	24	22	22	19	19	19	20	20	23	31	31	43	43	53	53	55	55	55	55	52	52	58	58	63	63	60	60	63	63
-1	8	19	19	34	23	24	24	24	27	27	35	41	41	43	43	45	45	47	47	43	43	40	40	38	38	37	37	49	49	60	60	62	62
-2	10	19	30	34	38	40	40	43	47	47	53	58	58	58	58	60	60	59	59	57	57	54	54	57	57	59	59	65	65	67	67	67	67
-3	7	19	28	34	37	43	43	51	50	50	60	61	61	61	61	63	63	60	60	59	59	61	61	67	67	71	71	63	63				
-4	10	19	29	32	39	44	44	50	50	50	52	53	53	57	57	57	57	60	60	64	64	70	70	67	67								
-5	9	19	30	33	37	40	40	39	35	35	39	45	45	56	56	62	62	65	65	68	68	65	65										
-6	8	19	11	23	23	25	25	25	23	23	32	45	45	62	62	67	67																
-7	12	13	13	14	20	24	24	23	19	19	23	23	47																				
-8	35	33	33	31	33	39	39																										

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

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0																		
1	2	2	2	13	8	6	6	3	0	0	1	1	2	2	2	0	0	0	0	0	0	0	0	0	0	3	3						
0	1	5	5	9	9	13	13	12	11	11	3	3	4	14	14	3	3	6	6	4	4	5	5	7	7	3	3	22	22	8	8	5	5
-1	0	0	0	0	0	0	0	0	2	2	2	7	7	7	7	7	7	11	11	20	20	28	28	19	19	8	8	17	17	4	4	7	7
-2	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	2	2	5	5	12	12	12	12	3	3	6	6	6	6	3	3	5	5
-3	0	0	0	0	0	0	0	0	1	1	1	1	1	2	2	2	2	4	4	6	6	4	4	2	2	0	0						
-4	0	0	0	0	0	0	0	0	1	1	0	1	1	4	4	8	8	4	4	1	1	0	0										
-5	0	0	0	0	0	1	1	0	0	0	6	4	4	4	4	1	1	2	2	0	0												
-6	0	0	0	0	1	1	1	1	3	3	5	6	6	2	2	0	0																
-7	0	2	2	3	4	10	10	12	7	7	5	5	0																				
-8	2	3	3	7	2	0	0																										

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

<u>Case-80-3</u>

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.

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	595	581	581	506	392	268	268	211	96	96	44	44	37	19	19																		
1	583	597	597	620	573	529	529	439	387	387	341	341	292	240	240	216	216	210	210	214	214	237	237	250	250	288	288	125	125				
0	661	662	662	656	754	786	786	773	708	708	719	719	706	705	705	721	721	742	742	740	740	810	810	888	888	916	916	1131	1131	1152	1152	1183	1183
-1	58	58	115	115	178	306	306	464	688	688	752	808	808	833	833	841	841	856	856	887	887	866	866	852	852	833	833	867	867	1002	1002	1000	1000
-2	94	94	94	87	85	89	89	86	97	97	144	170	170	276	276	374	374	390	390	463	463	571	571	823	823	804	804	800	800	819	819	791	791
-3	88	89	92	93	91	95	95	104	125	125	133	152	152	165	165	182	182	206	206	301	301	412	412	143	143	129	129	48	48				
-4	111	112	111	107	117	121	121	119	118	118	143	140	140	153	153	239	239	248	248	312	312	64	64	14	14								
-5	81	81	81	91	88	91	91	102	115	115	107	124	124	217	217	298	298	311	311	48	48	7	7										
-6	84	84	83	85	89	94	94	123	138	138	238	239	239	349	349	90	90																
-7	72	72	104	102	116	151	151	524	476	476	330	287	287																				
-8	509	508	508	478	458	412	412																										

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

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2	15	16	16	17	22	29	29	43	51	51	63	63	66	72	72																		
1	14	17	17	18	19	23	23	29	43	43	45	45	56	57	57	61	61	63	63	63	63	55	55	57	57	55	55	69	69				
0	35	25	25	22	19	15	15	12	11	11	12	12	13	15	15	17	17	21	21	23	23	27	27	32	32	52	52	62	62	56	56	63	63
-1	10	20	19	35	22	22	22	22	21	21	22	22	22	21	21	22	22	23	23	24	24	23	23	24	24	29	29	45	45	60	60	62	62
-2	10	20	30	34	41	45	45	44	46	46	43	43	43	46	46	48	48	59	59	53	53	52	52	56	56	54	54	58	58	64	64	63	63
-3	8	19	29	34	40	44	44	50	51	51	59	63	63	71	71	69	69	59	59	61	61	66	66	61	61	72	72	72	72				
-4	9	20	28	32	40	45	45	45	53	53	58	64	64	68	68	65	65	64	64	71	71	72	72	72	72								
-5	10	19	29	34	38	43	43	48	52	52	57	55	55	67	67	68	68	69	69	65	65	72	72										
-6	10	19	29	33	38	40	40	43	35	35	39	56	56	67	67	70	70																
-7	9	19	18	31	23	28	28	39	34	34	35	55	55																				
-8	36	26	26	25	26	35	35																										

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

Lane	0m	10m	20m	30m	40m	50m	60m	70m	80m	90m	100m	110m	120m	130m	140m	150m	160m
2	1	6	6	10	5	1	1	3	0	0	0	0	0	0	0		
1	1	6	6	16	9	6	6	5	4	4	3	3	2	1	1	1	1
0	3	5	5	8	12	18	18	14	7	7	5	5	5	4	4	4	4
-1	0	0	0	0	0	0	0	1	3	3	1	5	5	6	6	3	3
-2	0	0	0	1	0	1	1	1	0	0	0	0	0	1	1	3	3
-3	0	0	0	1	0	0	0	0	1	1	0	1	1	0	0	1	1
-4	0	0	1	0	0	0	0	1	0	0	2	1	1	0	0	3	3
-5	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0
-6	0	0	0	0	1	0	0	1	0	0	2	2	2	1	1	0	0
-7	0	0	0	0	0	1	1	4	3	3	3	0	0				
-8	1	0	0	0	2	0	0										

Lane	170m	180m	190m	200m	210m	220m	230m	240m	250m	260m	270m	280m	290m	300m	310m	320m
2																
1	0	0	1	1	1	1	0	0	6	6	0	0				
0	6	6	3	3	6	6	3	3	2	2	37	37	3	3	3	3
-1	10	10	11	11	16	16	5	5	11	11	16	16	10	10	7	7
-2	3	3	5	5	8	8	8	8	11	11	8	8	8	8	3	3
-3	3	3	4	4	4	4	2	2	0	0	0	0				
-4	1	1	0	0	0	0	0	0								
-5	1	1	0	0	0	0										
-6																
-7																
-8																

Figure 36. Spatial distribution of 'near-miss' opportunities in toll plaza (Case-80-3).

<u>Summary of case studies</u>

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.

	Case-80-1	Case-80-2	Case-80-3
Total travel time [veh*hr]	72.48	30.19	36.72
Average TT for ETC vehicles [sec]	77.5	36.7	38.8
Average TT for normal vehicles [sec]	73.3	44.8	45.8
Number of 'near-miss'	585	926	786

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

Akahane, H. and Hatakenaka, S. (2004). Successive observations of trajectories of vehicles with plural video cameras, *International Journal of ITS Research*, **Vol.2**, No.1.

Horiguchi, R., Kuwahara, M., Katakura, M., Akahane, H. and Ozaki, H. (1996). A network simulation model for impact studies of traffic management 'AVENUE Ver. 2', *Proceedings of 3rd World Congress on Intelligent Transport Systems*, Orlando (CD-ROM).

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