PROCESS SIMULATION APPROACH TO DESIGN AND EVALUATION OF TOLL PLAZA WITH ETC GATES

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ABSTRACT

The study proposes a process simulation-based approach to traffic jam issues in toll plaza of expressways with ETC gates. First, the paper describes overview of ETC system around the world as well as in Japan, and clarifies the issue of traffic jams, which occurs in toll plaza of Japanese expressways and prohibits the progress of ETC system. Then the paper describes the process simulation model which has been developed in this study, and also shows its internal procedures to simulate the traffic jams. The result of simulation provides two kinds of solution to traffic jam issues. One is to determine the appropriate time in gate change for combination gates. The other one is to study the layout redesign of toll plaza to achieve more efficient performance. Using the result of simulation, feasibility of the approach will be discussed. Since the goal of the study is to propose a practical solution to the traffic jam issues which prohibits the progress of ETC system, this paper also shows the results of simulation of a case study and discusses what the simulation-based approach can provide.

INTRODUCTION

Electrical Toll Collection (ETC) system was started at Tokyo Metropolitan Expressway in the year of 2001, which was the beginning of ETC systems in Japan. Since then, the number of toll plaza equipped with ETC gates has been increased gradually and steadily, by additional construction of ETC gates or updating conventional toll gates to ETC gates. By the end of fiscal 2003, ECT gate will be available at every 1,300 toll plazas of expressways around the country. As a part of Intelligent Transportation System (ITS) in Japan, ETC system is expected to provide several great advantages; improvement of usability for vehicle drivers, drastic counter-measures to reduce traffic jams, a solution to environmental issues such as air pollution or noise pollution by reducing traffic jams, a crucial technologies to realize integrated toll collection system, an important infrastructure for smart intersections to enhance regional activities, and so on.

As one of the promising advantage, ETC system is expected to make great contribution to drastically reduce traffic jams over toll expressways, which are mainly derived from the conventional toll collection at toll gates, where each vehicle is required to stop to pay toll fees. According to the survey, 30% of traffic jams in expressway is occurred around the toll plaza, which means that non-stop toll payment of ETC system can drastically eliminate the traffic jams. However, advantage of ETC has not been fully utilized so far for several reasons. If vehicle drivers do not encounter any traffic jams in a less traffic volume condition, ETC vehicles can enjoy the advantage of non-stop driving to go through toll gates. Since some numbers of toll gates are assigned specific to ETC vehicles in each toll plaza, the number of available toll gates for non-ETC vehicles has been reduced. However, relatively decreased number of non-ETC toll gates does not give any disadvantages over non-ETC vehicles, although non-ETC vehicles remain the same as before the introduction of ETC system. In the mean time, if the traffic volume becomes higher, the situation changes worse. On one hand, ETC vehicles need to go through heavy traffic jams towards one of the available ETC gates at the end of toll plaza. On the other hand, less number of available toll gates for non-ETC vehicles makes traffic jams worse. Furthermore, non-ETC vehicle drivers are discouraged by the fact that an open way to ETC gate is not available for non-ETC vehicles. As a result, overall total travel time for both ETC/non-ETC vehicles around toll plaza becomes longer because of the introduction of ETC systems.

Simulation-based approach has been applied to various areas related to transportation systems and its feasibilities have been reported (Abbas-Turki et al., 2001; Fernandes et al., 1998; Gale et al., 2002; Krajzewicz, et al., 2002; Lucjan et al., 1999). Based on a simulation-based analysis of traffic jams at toll plaza with ETC gates (Horiguchi et al., 2000), the study focuses on two issues to consider counter-measures to fully utilize the advantages of ETC system; Estimation of gate change timing for combination gate and redesign of toll plaza. For one thing, most of the toll plaza had already been designed and operated before the introduction of ETC system. Some gates were replaced with ETC gate, or some ETC gates were

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additionally installed in toll plaza, both of which were based on the conventional layout design of the plaza. Considering the non-conventional flow of traffic which is generated in combination with ETC and non-ETC vehicles, various kind of layout design of toll plaza could be studied using a simulation-based analysis (Ito, 2004; Ito and Hiramoto, 2004). Because of the high construction cost, however, redesign of toll plaza is not always possible. Therefore, some gate converted to be used as combination gate for both ETC and non-ETC vehicles, where gate change timing is very critical but it is not always easy to determine the most appropriate time for gate change in actual situations. The simulation model also helps to determine the appropriate time of gate change.

Outlining the ETC systems around the world as well as in Japan, the paper describes the process simulation model which has been developed in this study, and also shows its internal procedures to simulate the traffic jams. The result of simulation provides two kinds of solution to traffic jam issues. One is to determine the appropriate time in gate change for combination gates. The other one is to study the layout redesign of toll plaza to achieve more efficient performance. Using the result of simulation, feasibility of the approach will be discussed. Since the goal of the study is to propose a practical solution (Biacandi et al., 2000; Schwentke, 2000) to the traffic jam issues which prohibits the progress of ETC system, this paper also shows the results of simulation of a case study and discusses what the simulation-based approach can provide.

ETC SYSTEMS IN THE WORLD

More than 30 countries have introduced electrical toll collection system practically or tentatively, in most case, to collect a flat fee. In Europe, ETC was started in Norway in 1987, followed by Italy, France, Spain, and Portuguese in 90's. Germany made an experimental trial of ETC between 1994 and 1995 to collect fees from large vehicles. Since the introduction of ETC in Texas in 1989, most of the toll ways have been equipped with ETC system in US, which is one of the most ETC prevailing countries in the world. More than 70% of vehicles in commuting time enjoy the benefit of ETC in New York area, sweeping away the traffic jams. Canada and Mexico are also introducing ETC systems just like US. ETC was introduced in Hong Kong in 1993, followed by Malaysia in 1995.

In some countries, ETC system is not compatible each other among neighboring countries, which gives an obstacle to prevail ETC system. International standardization may need to be considered in the nearest future. As for Japan, the history and its current situation has been described in the previous section, to collect non-flat fees.

Electrical Toll Collection (ETC) system was started at Tokyo Metropolitan Expressway in the year of 2001, which was the beginning of ETC systems in Japan. Since then, the number of toll plaza equipped with ETC gates has been increased gradually and steadily, by additional construction of ETC gates or updating conventional toll gates to ETC gates. By the end of fiscal 2003, ECT gates have become available at every 1,300 toll plazas of expressways around the country. The average penetration rate of ETC vehicles in Japan is gradually increasing and now reaches to 12.5% as of January 2004. However, low penetration ratio of ETC vehicles is raising several critical issues to be solved as pointed out in the introduction section.

PROCESS SIMULATION MODEL FOR TOLL PLAZA WITH ETC GATE

This section describes process simulation model and its internal process for traffic jams at expressway toll plaza with ETC gates simulation. The model in this study has been developed based on these modules.

Simulation model development

Using the following 6 modules based on several software modules used in this study, 6 procedures are defined for toll fee payment by vehicles at toll plaza as follows.

CREATE module: to generate entities (objects for simulation) based on a predefined schedule or adequate intervals.

PROCESS module: to represent major processes in simulation, utilizing resources.

DECIDE module: to determine appropriate decision in the model.

ASSIGN module: to set appropriate values into system parameters such as entity properties and types.

RECORD module: to collect statistical values.

DISPOSE module: to represent the final point of simulation. Statistical values are recorded before the destruction of entities.

(1) Generation of vehicles to toll gate: CREATE module generates two types of entities, or general and ETC. ASSIGN module defines toll collection time according to the time and type in each entity generation.

(2) Lane selection: DECIDE module branches the way towards which each entity take based on arbitrary probability, entity type, traffic conditions, etc.

(3) Travel on lane: PROCESS module gives travel time to each entity based on the traffic condition

(4) Gate selection: DECIDE module branches the gate to each entity based on the traffic condition.

(5) Toll collection: Entity is captured by resources based on the predefined time for payment in PROCESS module, the entity is released.

(6) Leave gate: After time stamp by RECORD module, entity is destroyed by dispose module.

Definition of parameters and internal procedure in the model

Figure 1 shows a sample of process simulation model for toll plaza with ETC gate with 3 gates for general vehicles and 1 gate for ETC vehicles, which represents a typical toll plaza of expressway in Japan. The letter A represents generation point for entity, the letter B represents expansion point of drive lane, the letter C represents gate point. Queue.i is defined as waiting queue between A-B points, and Queue.j is defined as waiting queue between B-C points.

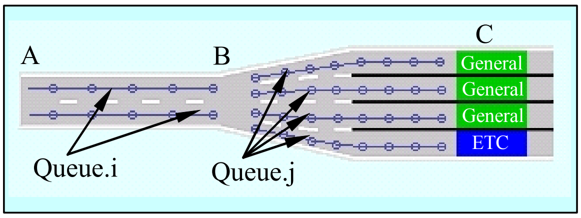

Figure 1: A Process Simulation Model

Number of incoming vehicles per hour is defined as Scheme (1) for non-ETC vehicles and Scheme (2) for ETC vehicles, respectively. ETC mixing ration in overall vehicles is defined as Scheme (3).

$$t_g = \frac{3600}{x_g} \quad (1)$$

$$t_e = \frac{3600}{x_e} \quad (2)$$

$$p = \frac{x_e}{x_g + x_e} \quad (3)$$

t_g : time interval for incoming non-ETC vehicles [sec]
x_g : incoming hourly volume of non-ETC vehicles [no/hr]
t_e : time interval for incoming ETC vehicles [sec]
x_e : incoming hourly volume of ETC vehicles [no/hr]
p : ETC ratio in all vehicles [%]

Entity moves from point A to point C on the queue lines at a certain time interval as defined in Scheme (4).

$$T_d = [L - (q_i + q_j)l - L_s]S_c + L_s S_s \quad (4)$$

T_d : time delay for move [sec]
L : distance between start and goal (A-C) [m]
q_i : number of vehicles in Queue.i
q_j : number of vehicles in Queue.j
l : ave. distance between two vehicles in queue [m]
L_s : distance from speed-down and halt points [m]
S_c : ave. time for unit distance [sec/m]
S_s : ave. time for unit distance at speed-down [sec/m]

T_g and T_e represent required time from the queue-end to toll gate for non-ETC and ETC vehicles, respectively as shown in Scheme (5) and (6).

$$T_g = \frac{q_{ig} t_{pg}}{m} + q_j t_{pg} \quad (5)$$

$$T_e = \frac{q_{ig} t_{pg}}{m} + q_j t_{pe} \quad (6)$$

T_g : time from queue-end to toll gate (non-ETC) [sec]
q_{ig} : total number of non-ETC in Queue.i (i=1,2)
t_{pg} : time to pay at toll gate (non-ETC) [sec]
T_e : time from queue-end to toll gate (ETC) [sec]
t_{pe} : time to pay toll gate (ETC) [sec]
m : number of gate for non-ETC vehicles

The model was developed using process simulation software ARENA (Kelton, R. et al. 1998).

PROCESS SIMULATION AND ITS VERIFICATION BASED ON MATHEMATICAL DATA

To analyze traffic jams at toll plaza with ETC gates, some comparative simulation was conducted using the process simulation model. Feasibility of the model is also studied using layout design consideration around the toll gate plaza. In each simulation, entity generation is started at 500m before the toll gate with 2 driving lanes in Queue.i, with 8 entities in each Queue.j towards 4 gates to drive through. Triangular distribution to calculate required time at toll payment is used for ETC as (3, 4, 5) and non-ETC as (14, 16, 18), respectively. Total simulation time is 1 hour.

Table 1: Conditions in 3 Cases for Simulation

Case	The gate type to be used
Case-1	General gate*4
Case-2	General gate*3 ETC gate*1
Case-3	General gate*3 Combined use gate*1

Basic model

Table 1 shows 3 types case studies in this simulation. All 4 gates are installed with conventional non-ETC in

Case-1, 1 out of the 4 is converted to ETC in Case-2, and the ETC gate is modified to combined gate which can be used for both ETC and non-ETC in Case-3. 10% of ETC penetration rate was used in Case-2 and Case-3. A non-ETC vehicle takes the lane in the shortest queue length when traffic jam is occurred, whereas an ETC vehicle takes the closest lane to ETC gate.

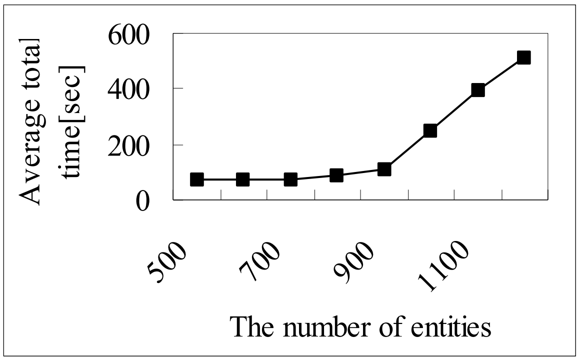

Figure 2: Gate-through Time in each traffic volume

Figure 2 shows the required time to pass the toll gate, or drive-through time in Case-1 according to the hourly traffic volume ranging from 500 to 1200 vehicles per hour. The time stays around 100 seconds up to 900 vehicles, but it drastically increases when the number of incoming vehicles exceeds over 1000, which means that the capacity of toll gates in this simulation is about 900 vehicles per hour.

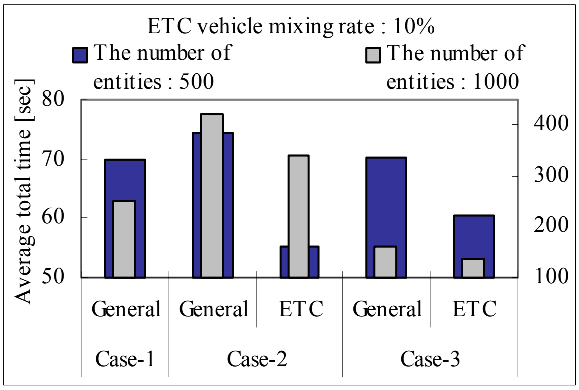

Figure 3: Comparison of Gate-through time for ETC/non-ETC vehicles in Each Case

Introduction of ETC system can provide a solution to solve the problem of traffic jam at toll gates. Figure 3 shows the comparison of drive-through time at toll gates when the hourly traffic volume is 500/1000 vehicles. The drive-through time of ETC vehicle in Case-2 becomes by-far less than that in Case-1, whereas drive-through time of non-ETC vehicle becomes longer. In Case-3, or as a result of combination gate management, drive-through time of non-ETC vehicle becomes the same level of Case-1, although ETC-vehicle takes more time than that in the dedicated ETC toll gate in Case-2. When the traffic volume becomes up to 1000 as shown in the right side-bar scale in Figure 7, traffic jams in Case-2 cannot be taken care of without the management of combination gate in Case-3. The model well represents the current situation of ETC gate traffic as a general case.

Estimation of appropriate time in combination gate management

To estimate the appropriate time of gate change in combination gate management between ETC dedicated use and combination use, Case-2 and Case-3 are compared.

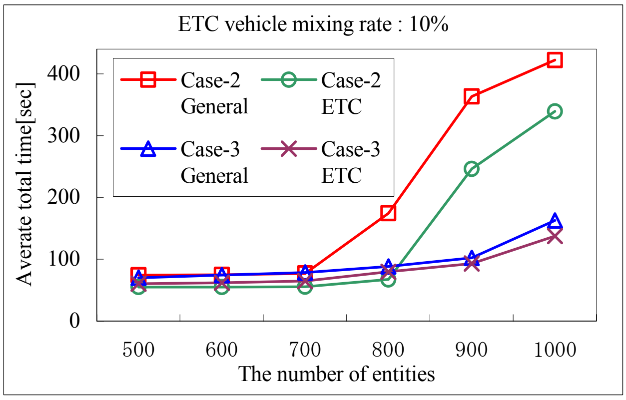

Figure 4: Comparison of Gate-through Time in each Traffic Volume

Figure 4 shows the comparison of average time for the number of entities. Both cases are almost identical if the hourly traffic volume is 800 or less, and the ETC gate provides the highest performance in all of the 4 gates. However, when the traffic volume is increased up to 800 per hour or more, average total time in Case-2 is increased for both ETC/non-ETC vehicles, which means that around 800 would be the capacity of the gates. The results suggests that when the traffic volume reaches this level, it would be the appropriate time of gate change from ETC dedicated use to combination-gate in order to avoid traffic jams, and maintain the high performance of ETC gate.

Study on layout design in toll plaza to achieve higher performance

Management of combination gate may give a solution to traffic jams, however, redesign of toll plaza is sometimes required for consideration to achieve better performance. Process simulation model in this study can also be used to consider and to study those designs. Figure 9 shows 2 types of simple layout examples in different designs, in which Layout-2 is modified on the side of ETC gate to make wider lane before the ETC gate, whereas Layout-1 is identical to the layout used in the basic model as shown in Figure 4. Figure 10 shows the comparison of total average time to pass the toll plaza. As show in Figure 10, performance of

Layout-2 is better than that of Layout-1 when the hourly traffic volume is over 800.

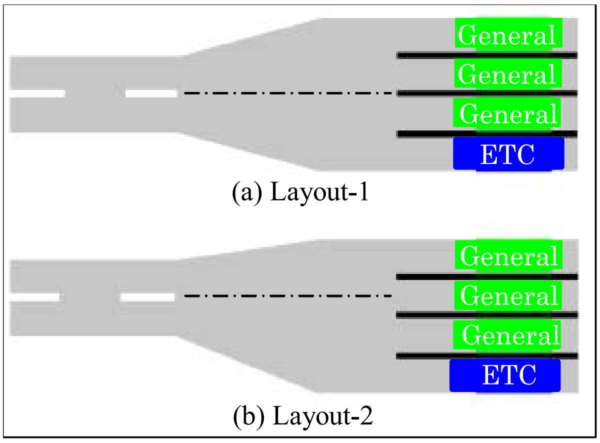

Figure 5: Layout Design Examples

SIMULATION-BASED ANALYSIS AND SOLUTION FOR ACTUAL TOLL PLAZA

Section 3 describes the basic ideas for simulation-based approach based on mathematical data, and shows its feasibility of this approach. Since the goal of the study is to propose an practical solution to traffic jam issues actually occurred in the expressway, we have designed and developed a simulation model for Kochi IC in Japan as a case study. Physical layout data and measured data are applied in this model and internal procedure is defined as well. This section shows the result of verification on the model, and proposes some solutions derived from the simulation of the model, which is on the direction of promoting ETC users.

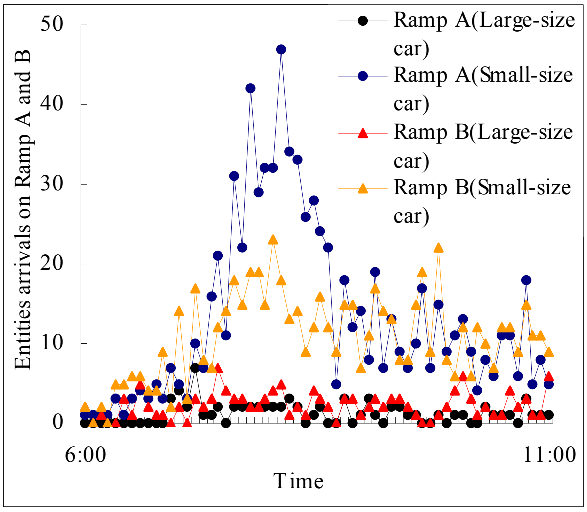

Figure 6: Time Interval Data on Entities Arrivals from Ramp A and Ramp B

Model verification

Quality of simulation model plays a very important role to apply it to actual data. To verify the model which we have developed in this study, several comparison were conducted between collected data and simulated data. The measurement for data collection was carried out between 6:00 am and 11:00 am on a single day at several measurement sites. During the measurement, vehicles were assigned to either small category or large category with or without ETC equipment in the measurement. Figure 6 shows the raw data of entities which came to the Kochi IC toll gate from the Ramp A and Ramp B direction.

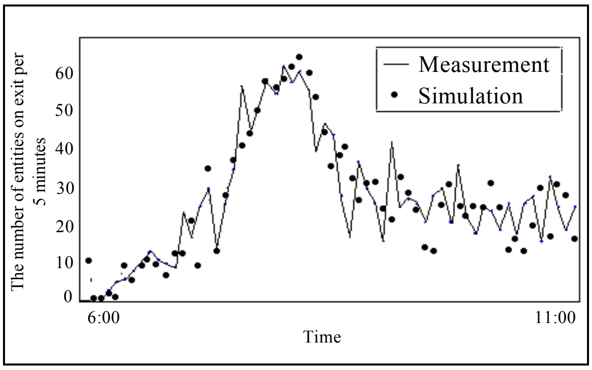

Figure 7: Compasion of Measured and Simulated Data for Out-going Traffic

To verify the model, several kinds of comparison were conducted using measured data and simulated data, including in-coming traffic, out-going traffic, traffic queue time and physical length of the queue, etc. As an example, Figure 7 shows the comparison between measured data and simulated data for out-going vehicles, of which graphs show almost identical results. According to the results of these comparisons, the simulation model in this case study shows good reproducibility.

Solution for actual toll plaza

This section presents some practical solutions which the simulation model can provide in the case of Kochi IC. The model can provide some practical solution to actual problems. For example, the estimation on the effect of combined gate use can be made. According to the simulation uing this model, the traffic of 200 vehicles length is supposed to reach 800 vehicles length if the traffic volume goes up to 20%. As a counter-measure to this traffic, the traffic length can be drastically reduced by the introduction of combined gate use and be remained almost the same level even if the traffic volume goes up to 20%. Although gate management with combined use can provide a shot-term solution, it decreases the benefits of ETC system for ETC vehicles. To study the effect of ETC mixing rate over the traffic jam length, the simulation-based approach can also provide an appropriate reference data. Figure 8 shows that the difference between combined gate use and ETC specific gate use will be almost identical if the mixing rate is increased by 25%. This means that combined gate usage as a counter-measure for traffic jams may not be required if the ETC penetration ratio reaches 12.5% or more from the current level of 10%.

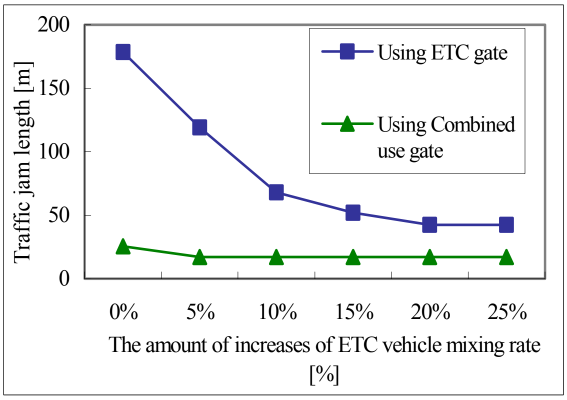

Figure 8: Effect of ETC Mixing Ratio on the Length of Traffic Jams

The result of simulation also indicates that if the number of ETC vehicles increases 5% or more in the Kochi IC case, the gate-through time of ETC vehicles becomes drastically less and it does not matter whether the ETC gate is either combined or dedicated use.

CONCLUDING REMARKS

This paper describes the overview of ETC system in Japan, and pointed out critical issues of traffic jams around expressway toll plaza to be solved to achieve the better performance of toll gates with ETC system. The paper showed the process simulation-based approach, describing the definition and internal procedures, and presented some result of process simulation to analyze the traffic jams which occur in toll plaza of expressways with ETC gates. The paper also showed that the model developed in this study can support estimation of appropriate time in gate change in combination gate, and also consideration of layout redesign of toll plaza to achieve better performance. Since the goal of the study is to propose a practical solution to the traffic jam issue which prohibits the progress of ETC system, this paper also showed the results of simulation of a case study and presents what the simulation-based approach can provide. Conducting much more case studies in actual toll plaza, we would like to work on further studies to increase the quality of the model, and to propose more practical solutions to enhance the progress of ETC systems.

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