MODELING TRAFFIC OPERATIONS AT A TOLL PLAZA USING DISCRETE-EVENT SIMULATION

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The objective of this study is to develop a discrete-event simulation model of traffic operations at a toll plaza to compare the performance measures between the manual and electronic toll collection (ETC) systems. This study also attempts to simulate the scenarios where the number of servers in these systems is reallocated to improve the overall operational performance. The field data were collected at a toll plaza on an expressway on-ramp during a PM peak period via video recording. The collected data were summarized to determine the characteristics of parameters as inputs for the simulation model. The simulation model was developed in EZStrobe, while the results were carried out via STROBOSCOPE. The simulation model was calibrated with the field data prior to making modifications and simulating various scenarios. The results show that, under the existing conditions, switching an electronic tollgate to a manual tollgate reduces the average overall queue delay and queue length by 71% and 78%, respectively. After reallocation, the average queue delays in these systems equalize as the proportion of ETC users reaches 72%. The additional throughput time of 0.4 s/veh in the ETC system is small compensation for the 6.8-second deduction in the average overall throughput time. In conclusion, shortening the queue lengths at the toll plaza by efficiently utilizing the existing tollgates is possible for improving the overall operational performance of the toll plaza without the additional tollgate installation.

Keywords: Tollgate, Toll booth, Simulation modeling, Electronic toll collection, Expressway, On-ramp, EZStrobe, STROBOSCOPE, Queue, Delay.

1 BACKGROUND AND LITERATURE REVIEW

Toll plazas are generally installed on freeways and expressways, which mean for uninterrupted and high-speed flows, for collecting tolls. However, the flow on an expressway on-ramp can be interrupted as queues are formed at the toll plaza when the demand exceeds the capacity, turning the toll plaza into a bottleneck. Electronic toll collection (ETC), a system capable of electronically charging tolls from registered users without stopping vehicles, has been invented to mitigate this problem at toll plazas (Karim et al. 2020, Silveira-Santos et al. 2023).

Queues are a major cause of delay in any traffic systems, especially when vehicles in queues are idling while waiting to be served. As a queue length continues to grow, the average delay of vehicles dwelling in the queue also increases, leading to an increase in the average throughput time of vehicles entering the queue (Srisurin 2013, Srisurin and Singh 2017).

Discrete-event simulation has been an effective tool widely used for modeling queuing problems in transportation to support the decision-making process prior to implementing the
proposed solutions. Various previous studies have adopted discrete-event simulation for modeling and solving problems in both personal and freight transportation (Khoury et al. 2007, Srisurin and Singh 2014b, Safa et al. 2016, Vieira et al. 2019, Talavirya and Laskin 2020, Srisurin et al. 2022).

Recent studies were found to adopt discrete-event simulation for modeling traffic operations at toll plazas for various purposes (Neuhold et al. 2019, Karim et al. 2020, Talavirya and Laskin 2020, Doan 2021, Silveira-Santos et al. 2023). However, an attempt to apply EZStrobe for modeling the operations at toll plazas has not yet been found in the literature.

EZStrobe is a general-purpose discrete-event simulation modeling tool, which relies on activity cycle diagrams, developed by Martinez (2001). Initially, the software has mainly been adopted by researchers to model construction engineering problems (Srisurin and Singh 2014a, Jiradamkerng 2016, Limsawasd and Athisakunagorn 2017, Ioannou and Likhitruangsilp 2020). However, Khoury et al. (2007) applied EZStrobe for modeling airside airport operations. In addition, Safa et al. (2016) suggested that EZStrobe could be possible for optimizing traffic at intersections. Even so, it is still challenging for researchers to attempt modeling complex traffic engineering problems in EZStrobe.

This study aims to develop a discrete-event simulation model of traffic operations at a toll plaza to compare the performance measures between the manual and ETC systems. This study also attempts to simulate various scenarios by reallocating the number of servers in each system to improve the operational performance, and determine the penetration rate of ETC users which cause equilibrium in queue delay between these systems.

2 SIMULATION MODELING

2.1 Methodology

The Rama IX toll plaza, located at the on-ramp of Sirat Expressway in Bangkok, Thailand, was selected as a case study for developing a simulation model in this study. The field data were collected at the location between 5:30 p.m. and 6:30 p.m. on four weekdays in March 2023 via video recording. This study employed 3,429 vehicular arrivals at the toll plaza as samples. The service time of each manual tollgate entrant was obtained by measuring the stopping duration of each vehicle at the tollgate. Meanwhile, a roadway section of 20-meter long upstream of the barrier gate was used to measure the service times of the electronic tollgate entrants since the vehicles only slowed down while approaching the barriers. The characteristics of the collected data were carried out using ARENA Input Analyzer to determine the statistical distributions of arrival rates, interarrival times, service times, and travel times. EZStrobe was used as a tool to develop the simulation model of the traffic operations (Martinez 2001), while the results were carried out via STROBOSCOPE (Martinez 1996). The simulation model was then calibrated with the field data to ensure that the resultant arrival rates, service times, and travel times were within the five-percent margin of error prior to modifying and simulating various traffic scenarios. Each simulation model was run for a duration of 7,200 seconds. The outputs of these simulation runs were then summarized and compared.

2.2 Simulation Models Development

The toll plaza consisted of four tollgates: two manual tollgates and two electronic tollgates. Tolls at tollgates 1 and 2 were collected manually, while tollgates 3 and 4 operated as ETC, as depicted in Figure 1. Each of the ETC gate was equipped with a barrier gate system controlled by using a sensor. The average peak demand volume observed at the toll plaza was 857 veh/h. The ratio of
vehicles entered manual tollgates to vehicles entered ETC gates was 54 to 46. The average service times in the manual and ETC systems were 10.2 s/veh and 2.8 s/veh, respectively.

Figure 1. Graphic illustration of the traffic operations at the toll plaza.

Figure 2. The EZStrobe model of the existing traffic operations at the toll plaza (2+2 system).

The simulation model of the existing conditions was developed in EZStrobe to replicate the traffic operations at the toll plaza, under the existing PM peak demand and proportion between the manual and electronic tollgate entrants, as shown in Figure 2.

The scenario, where the number of servers in each system was reallocated, was simulated to observe the improvement in the operational performance by switching tollgate 3, which currently operates as an ETC gate, to become a manual tollgate (3+1 system). In addition, seven scenarios
with various penetration rates of ETC gate entrants were simulated to determine the equilibrium in queue delay between these two types of tollgates under the existing operation of the toll plaza.

3 RESULTS ANALYSIS

The outputs of the simulation models are generated via STROBOSCOPE. The results indicate that switching an electronic tollgate to a manual tollgate (3+1 system), under the existing PM-peak demand and proportion between the manual and electronic tollgate entrants, reduces the average overall queue delay by 6.5 s/veh, or a 71-percent reduction. The average queue delay in the manual tollgate system decreases by 12.2 s/veh, corresponding to a deduction of 73%; while the average throughput time of the manual tollgate entrants decreases by 13.4 s/veh, which accounts for a 46-percent deduction, as shown in Table 1.

The results also indicate that the average overall queue length at the toll plaza is shortened by 0.5 vehicle s, or shrunk by 78%, when the 3+1 system is implemented. Similarly, the average queue length in the manual tollgate system is shortened by 0.96 vehicles, which accounts for an 84-percent shrinkage. Obviously, for the shortened queue length of approximately one vehicle, the queue delay is decreased by 12.2 s/veh; which is more or less the average service time.

Both the average queue delay and the average throughput time of the ETC gate entrants increase by 0.4 s/veh as the number of servers is deducted by one, while the average queue length in the ETC system only increases by 0.06 vehicles. Despite these increases, the magnitudes of these changes are relatively small and do not significantly impact the overall traffic operations.

At the existing demand volume during the PM peak hour, the overall peak-hour flow rate at the toll plaza increases by 21%, or 48 veh/h, when the 3+1 system is implemented. This is due to the greater level of service in the ETC system, in which the flow rate increases from 204 veh/h/gate to 393 veh/h/gate, as well as the shortened queues in the manual tollgate system.

Table 1. Comparison of performance measures between the existing and modified formations.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Existing (2+2)</th>
<th>Modified (3+1)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queue Delay (s)</td>
<td>16.6</td>
<td>0.3</td>
<td>9.2</td>
</tr>
<tr>
<td>Throughput Time (s)</td>
<td>27.0</td>
<td>3.1</td>
<td>16.2</td>
</tr>
<tr>
<td>Queue Length (veh)</td>
<td>1.15</td>
<td>0.02</td>
<td>0.64</td>
</tr>
<tr>
<td>Peak-Hour Flow Rate (veh/h/gate)</td>
<td>246</td>
<td>204</td>
<td>225</td>
</tr>
<tr>
<td>Capacity (veh/h/gate)</td>
<td>347</td>
<td>1277</td>
<td>812</td>
</tr>
</tbody>
</table>

* OVR is the weighted-average performance measure based on the number of entrants in the manual and ETC systems.

Upon further analysis, it has been observed that as the penetration rate of ETC gate entrants increases from 46% to 50% under the existing PM-peak demand and proportion between the manual and electronic tollgate entrants (2+2 system), the average queue delay of a manual tollgate entrant plummets from 27.0 s/veh to 19.7 s/veh, which accounts for a 27-percent deduction. The amount of change in the average queue delay of the manual tollgate entrants tends to be relatively gentler as the penetration rate of ETC gate entrants exceeds 50%. On the contrary, the average queue delay in the electronic tollgate system gradually increases as the penetration rate of ETC users increases. The average queue delays in these two systems equalize as the penetration rate of ETC gate entrants reaches 88%, as shown in Figure 3.

In the case of the configuration comprising three manual tollgates and one electric tollgate (3+1 system), the analysis indicates that the average queue delays in these two systems equalize as the penetration rate of ETC gate entrants reaches 72%, as shown in Figure 3.
DISCUSSION AND CONCLUSIONS

This study exhibits that EZStrobe and STROBOSCOPE can effectively be used to simulate traffic operations at toll plazas. The results show that switching an electronic tollgate to a manual tollgate, under the existing demand and proportion between the manual and electronic tollgate entrants, reduces the average overall queue delay and queue length by 71% and 78%, respectively. As a queue length is shortened by one vehicle, the vehicular queue delay can be expected to decrease approximately by the average amount of the service time at the tollgate.

Although the average queue delay, throughput time, and queue length in the ETC system increase as the number of servers is deducted by one, the increases in these quantities are relatively small and do not significantly impact the overall traffic operations at the toll plaza. The additional throughput time of 0.4 s/veh in the ETC system is small compensation for the 6.8-second reduction in the average overall throughput time, which accounts for a 42-percent reduction. Consequently, it turns out that the greater level of service in the ETC system, along with the immensely shortened queues in the manual tollgate system, causes the reduction in the average overall throughput time of vehicles at the toll plaza.

In conclusion, shortening the queue lengths at the toll plaza by efficiently utilizing the performance of the existing tollgates would be possible for improving the overall operational performance of the toll plaza without adding tollgates. The configuration comprising three manual tollgates and one electric tollgate (3+1 system) is more suitable for the traffic operations at the toll plaza under the existing demand and proportion between the manual and electronic tollgate entrants. However, the existing traffic operation plan utilizing two manual tollgates and two electric tollgates (2+2 system) should be implemented when the penetration rate of ETC gate entrants reaches 72%, due to the equalization between the average queue delays in these two systems. Alternatively, it should be adopted when the penetration rate of ETC gate entrants reaches 50%, as the sharply decreased average queue delay compared to the existing conditions.

Since the implementation of the 3+1 system at the location has never been attempted in reality, the results of this scenario could not be validated by using the field data. This study, therefore, assumes that the modified simulation models would reflect real-world scenarios once they have been calibrated. This assumption serves as a limitation of the study. Future research should be conducted to develop a convertible tollgate that can operate in both electronic and manual toll collection systems to accommodate the uncertainty and fluctuation of the demands for both types of users during various times of day.
References


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