CIVIL ENGINEERING

Traffic micro-simulation model for design and operational analysis of barrier toll stations

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Received 25 October 2015; revised 25 May 2016; accepted 31 May 2016

Abstract The objective of this paper was the development of a microscopic traffic simulation model for design, assessment, and operational analysis of toll stations. A simulation software using VB.NET was created to simulate the stochastic nature of traffic arrival, toll collection time, and driver decision making. The developed simulation model was used to analyze different scenarios of traffic volumes, toll booth capacity, driver types, and configuration of toll station. Results showed that volume per toll lane and method of payment significantly affect the average delay and maximum queue lengths of a toll station. Recommendations on number of toll booths are presented in order to process peak traffic hours without excessive delay times or long queues.

1. Introduction

Highway toll stations constitute a unique type of transportation system that requires special analysis. Tolls are used as an instrument to finance new road infrastructure throughout the world. Guidelines on the layout of toll stations and design factors based on experience gained by operators of major existing toll facilities in the UK, European, and American operators can be found in [1,2].

In 1998, a new law was introduced that enabled the Egyptian Ministry of Transport (MOT) to raise revenue from direct road charges. Consequently, several existing roads were converted to toll roads [3]. A study of toll rates for the Cairo Alexandria desert road was presented in [4].

The local basic mechanism of a manual toll collection has remained essentially unchanged since its inception. Manual toll collection is characterized by toll stations comprised of toll lanes which are manned by an attendant for the collection of the road charge. Stops at toll stations, however, impede the smooth flow of traffic and consequently can reduce the level of service provided [5].

The importance of properly designing toll stations cannot be overstated. If improperly designed, these facilities can act as major bottlenecks. Toll stations can act as system bottlenecks that reduce the productivity of these highway resources as well as increase energy consumption and fuel emissions. Consequently, the efficient operation of toll stations is a high priority objective [6].

The Highway Capacity Manual (HCM) currently does not include any guidance for analyzing a toll station and there is no standardized analytical method to evaluate performance of a toll station [7]. Therefore, traffic simulation models are...
used to enhance operation analysis and management of this type of transportation facilities [8,9].

A challenge faced by traffic modelers when developing models of toll stations has been the constraints of the different software packages, which lack a built-in toll station feature or module [10]. Microscopic traffic simulation models have come to the fore with the increasing computational power of nowadays computers and their capability of modeling the complex dynamics of traffic flow and demand. Benefits of micro-simulation over traditional traffic analysis techniques are categorized into three main areas: clarity, accuracy, and flexibility [11,12]. A recent study has used micro-simulation to model toll stations in Istanbul [13]. Results showed that using microscopic simulation to model toll stations can lead to efficiency benefits for all parties and the road users. Therefore, the objective of this paper was the development of a microscopic traffic simulation model for design, assessment, and traffic operation analysis of toll stations.

2. Model description

The Visual Basic.NET (VB.NET) programming language was utilized to build the proposed simulation model. A discussion of data structures and algorithms associated with VB.NET can be found in [14]. The inputs include hourly traffic volume, payment type, driver type, number of toll booths, and duration of the simulation run. Model outputs are delay statistics (average delay time, waiting time in queue), queue statistics (average, quartiles, maximum queue length), and utilization factors for the entire system as well as for each toll booth.

Each vehicle $i$ is represented by a 6-tuple $(i, t, k, d, o, v)$ where $i$ is a vehicle unique identification number, $t$ is arrival time, $k$ is the highway lane in which the vehicle is coming from, $d$ is driver type, $o$ is method of payment, $v$ is the processing time depending on method of paying tolls. Note an $n$-tuple is an ordered list of elements. The output data of a vehicle $i$ is a 4-tuple $(i, ntoll, start, finish)$ where $i$ is the vehicle unique identification number, $ntoll$ is the selected toll lane, $start$ is the start service time, and $finish$ is the departure time. From these detailed outputs, statistics on delay, queue, and resource workload can be calculated. The proposed model includes three main modules: traffic generation, Toll lane selection, and Toll collection processing.

2.1. Traffic generation module

A large number of headway distributions have been developed to represent the different patterns of vehicle arrivals. The most widely applied assumption light-to-medium traffic is that vehicles arrive randomly and the headways follow exponential distribution [15]. Other distributions such as Pearson type III or the Erlang distribution may be used when a limited amount of overtaking is possible [16].

In order to carry out a simulation using random inputs such as headways, probability distributions must be specified. In the proposed simulation model, sequences of random points in time for vehicle arrivals were generated. For instance, the headway times are commonly represented by an exponential random variable with a mean $h > 0$. The following inverse-transform algorithm can be used to generate the vehicular headway times.

$$h = -\frac{1}{\lambda} \ln u$$

$$t_i = \sum_{j=1}^{i} h$$

where $u \sim U(0,1)$ is the distribution function of a uniform random variable having a range [0, 1], $h$ is a generated headway instant in seconds, $\bar{h}$ is the average headway in seconds, and $t_i$ is the arrival time of a vehicle $i$. The reader is referred to [17] for a detailed discussion about simulation models, generating random variables, variance-reduction techniques, and common random numbers. Approaching vehicles are assumed to be uniformly distributed among the basic highway lanes.

2.2. Toll lane selection module

Driver decision making affects the operation of a toll station. Some driving habits for selecting the toll lane at toll stations were reported in [18]. As drivers approach toll facilities, they naturally search for the optimal lane choice. Most drivers enter a toll lane on the same side of the toll station from which they come to the toll station. Once drivers have selected which half of the toll station to enter, they select the lane with the shortest queue on that side. Some other drivers were observed entering the lane with the shortest queue regardless of the side of the toll station from which they come to the toll station. Finally, a small percentage of drivers appeared to randomly choose a toll lane.

The proposed simulation model includes a lane selection algorithm that incorporates four different types of driver behavior as follows:

- **Driver Type 1**: selection criterion is based on random selection.
- **Driver Type 2**: selection criterion is the shortest queue in a half-side of the toll station.
- **Driver Type 3**: selection criterion is the maximum utility score (Toll Lane Desirability, TLD), and
- **Driver Type 4**: selection criterion is the shortest queue in the entire station. Lowest queue index (toll booth number) is selected in the case of tie.

Each driver type has a certain probability where sum of probabilities’ of the four types equals the unity $(P_1 + P_2 + P_3 + P_4 = 1)$. The search space, the feasible region defining the set of all possible solutions, of all drivers is all toll lanes except that of Driver Type 2, in which the search space is limited to half-side of the toll station. Excluding the first driver type, toll booth selection is based on a rational driver’s objective to minimize travel time subject to constraints such as lane changes for the third driver type.

For Driver Type 3, the proposed model assigns vehicles to booths using a “utility score, TLD” to identify the most attractive booths for each vehicle at the current time. The TLD utility score utilizes relative queue length, required number of lane changes, and a driver sensitivity factor. The following equation evaluates TLD for each toll lane relative to the toll lane a vehicle is currently in [19].

$$TLD_j = \frac{\Delta Q}{LC^{ST}}$$
where $TLD$ is toll lane desirability of toll lane $j$, $AQ$ is difference in queue length between vehicle’s current lane and a toll lane, $LC$ is number of lane changes required for vehicle to reach toll lane $j$, and $SF$ is lane change sensitivity factor. The sensitivity factor indicates the driver’s willingness to make a lane change to save one queue space. The input range for this value is $0–1$ with $0$ meaning a driver is very willing to make a lane change and $1$ meaning a driver is less likely to make a lane change.

2.3. Toll collection processing module

The processing time ($\tau$) of toll collection is another source of variability. Human activities introduce significant variability in processing times. The processing time depends on method of paying the highway tolls. The payment method in Egypt for toll facilities is based on the traditional cash where a toll attendant collects a fare physically in the form of currency. This method is considered a time consuming form of fare collection as compared with other forms of toll collections such as automatic coin machines and electronic toll collections. When entering the highway, vehicles must stop to render payment at the collection booth and the driver receives a payment receipt. Near the end of the highway and at the exiting main toll stations, the driver slows down at the toll station to present the payment receipt to the toll attendant and drivers may proceed without making a complete stop.

The model includes two types of payment, namely cash and payment receipt. The processing times were represented by a triangular random variable and the following inverse-transform algorithm was used to generate the processing times. The triangular distribution is used for cases when one estimation of the most likely value for the random variable in addition to its range (lower and upper bounds).

Generate $u \sim U(0, 1)$

$$\tau_{ao} = \begin{cases} 3600/(b_{ao} + \sqrt{u(b_{ao} - a_{ao})(c_{ao} - a_{ao})}) & a_{ao} \leq \tau \leq c_{ao} \\ 3600/(b_{ao} - \sqrt{(1-u)(b_{ao} - a_{ao})(b_{ao} - c_{ao})}) & c_{ao} < \tau \leq b_{ao} \end{cases}$$

where $u \sim U(0, 1)$ is the distribution function of a uniform random variable having a range $[0,1]$, $\omega$ is an index indicator for type of payment where $\omega = 1$ for cash and $\omega = 2$ for payment receipt holders, $a$ is the minimum processing time (which occurs at the maximum capacity of a toll booth), $b$ is the maximum processing time (equivalent to the minimum capacity of a toll booth), and $c$ is the mode processing time. For each payment type, there are corresponding values for $a_{ao}, b_{ao}$, and $c_{ao}$.

3. Model verification and validation

Model verification is the process of examining the conceptual aspects of the model to ensure it works logically [20]. Verification included tracking vehicles to ensure movements follow the logical sequence built in the model. Model validation is considered to the process of determining to what extent the model’s underlying fundamental rules within relevant theories such as the queuing theory. The queuing theory closed-form equations are limited to exponential inter-arrival and service-time rates as well as highly limited in system complexity, which is not the case for the proposed simulation model. The proposed simulation model can handle any combination of distributions for inter-arrival and service time, logic of drivers’ decision making, partial closures for toll booths, and heterogeneity in service times among the toll booths.

To validate the proposed simulation model, it was examined against the queuing theory equations using a 2-s exponentially-distributed inter-arrival times (i.e., arrival rate $= 1800$ vehicles per hour), and a 12-s exponentially-distributed service time (i.e., processing rate $= 300$ vehicles per hour). An $M/M/N$ queue system is described by arrival rate, processing rate and number of servers in the system. An $M/M/N$ system has exponentially distributed inter-arrival times, an exponentially distributed service time and $N$ server [21]. The $M$ denotes Markovian behavior, which signifies an exponential distribution. Different toll booths were considered in order to verify the model at different levels of degree of congestion in terms of volume to capacity ratios.

Thirty (30) simulation runs were conducted and the 95% confidence interval for the true average delay time was calculated for each configuration and revealed that at 95% level of confidence no significant difference exists between the simulation model and the queuing theory for the case of exponential distributions, single type of payment, and lane selection is based on the shortest queue criterion.

To simulate a toll station using the proposed model, essential input data are needed. The primary traffic data include the design hourly traffic volume and number of toll booths. Other input data are average and distribution processing time, distribution of traffic arrivals, number of the highway lanes, percentages of the different driver types, share of payment types, length of the simulation run, number of runs, and warm-up period. Note that the most important aspect when modeling a toll station is to define the process-time profile [22], which includes share of payment types (e.g., 50/50 versus 100/0, cash/receipt), process time of each payment type (e.g., cash versus receipt), and individual toll booths. The triangular parameters for processing times are $(a_1 = 250; b_1 = 350; c_1 = 300)$ and $(a_2 = 500; b_2 = 700; c_2 = 600)$ for traditional cash and payment receipt holders, respectively. Like every micro-simulation program, the proposed model has a set of user-adjustable parameters which enable the analyst to calibrate the proposed model to match locally observed conditions. Calibration of this information using local data will improve the accuracy of the proposed simulation model.

4. Experimental design

The experimental design included input factors and the output performance indicators. In experimental design terminology, factors are the different variables thought to have an effect on the output performance of the system. These variables are controllable in that the practitioner can vary the levels in the simulation model. Main input factors included hourly traffic volumes, capacity of the toll booth, driver type for lane-selection behavior, and number of toll booths. The main output performance indicators are average delay time and maximum queue length. Table 1 summarizes the experimental design factors and input parameters. The experimental design includes three levels of traffic volumes, five levels of percentage of cash-payment drivers, five levels of driver habits for decision making, and ten levels of number of toll booths. For each toll
station configuration (N), there are 75 design points. For each design point, 30 simulation runs were conducted and system performance indicators were calculated. A simulation run represents 65 min of traffic flow including 5 min warm-up period. During the warm-up period, results are not collected in order to reduce bias estimate in model results.

Table 1 summarizes results of the simulation model in terms of average delays and maximum queues. These results can be used to determine savings achieved by vehicles for various percentages of cash drivers over the base case (100% cash drivers) and to estimate the operational benefits of opening extra toll lanes. The operational benefits of opening extra toll lanes varied among the considered scenarios.

5. Results and analysis

After the execution phase of the experimental design has been completed, attention was directed toward the analysis phase of the simulation results. The function of the analysis phase is to provide information necessary to provide decision recommendations with respect to the output performance of the system. Fig. 1 presents contour plots of average delay and maximum queue based on the model results of the experimental design. When a toll station is designed, choosing the right number of toll booths is a critical issue. Fig. 1 and Table 2 can be used to determine number of toll booths in order to process peak traffic hours without long delay times. As the number of the toll booths increases or the processing time decreases, the average delay time decreases.

Table 2 | Summary results of the experimental design (average of 30 runs at each design point).

<table>
<thead>
<tr>
<th>Traffic volume</th>
<th>Average delay (s)</th>
<th>Max. queue length (veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%Cash</td>
<td>0%</td>
<td>25%</td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N = 6</td>
<td>7.5</td>
<td>11.2</td>
</tr>
<tr>
<td>N = 8</td>
<td>7.0</td>
<td>9.4</td>
</tr>
<tr>
<td>N = 10</td>
<td>6.8</td>
<td>8.9</td>
</tr>
<tr>
<td>N = 12</td>
<td>6.7</td>
<td>8.6</td>
</tr>
<tr>
<td>N = 14</td>
<td>6.7</td>
<td>8.6</td>
</tr>
<tr>
<td>N = 16</td>
<td>6.7</td>
<td>8.5</td>
</tr>
<tr>
<td>N = 18</td>
<td>6.7</td>
<td>8.5</td>
</tr>
<tr>
<td>N = 20</td>
<td>6.6</td>
<td>8.4</td>
</tr>
<tr>
<td>N = 22</td>
<td>6.6</td>
<td>8.4</td>
</tr>
<tr>
<td>N = 24</td>
<td>6.6</td>
<td>8.4</td>
</tr>
<tr>
<td>4000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N = 6</td>
<td>264.0</td>
<td>791.9</td>
</tr>
<tr>
<td>N = 8</td>
<td>11.4</td>
<td>138.3</td>
</tr>
<tr>
<td>N = 10</td>
<td>8.2</td>
<td>14.3</td>
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<tr>
<td>N = 12</td>
<td>7.4</td>
<td>10.7</td>
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<tr>
<td>N = 14</td>
<td>7.1</td>
<td>9.6</td>
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<td>N = 16</td>
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<td>N = 22</td>
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<tr>
<td>N = 24</td>
<td>6.8</td>
<td>8.6</td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N = 6</td>
<td>1302</td>
<td>2094</td>
</tr>
<tr>
<td>N = 8</td>
<td>515</td>
<td>1109</td>
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<tr>
<td>N = 10</td>
<td>62.6</td>
<td>520.3</td>
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<tr>
<td>N = 12</td>
<td>11.0</td>
<td>136.9</td>
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<td>N = 14</td>
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<tr>
<td>N = 24</td>
<td>6.9</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Utilization factor > 1 for the highlighted cells.
A toll station should have adequate capacity to effectively process the anticipated traffic without excessive queues and delays. However, unlike roadways and intersections that have unified standards addressing capacity, no such standards exist for toll stations. Each toll agency typically has its own goal as to adequate capacity. For example, the goal could be having a toll station meets two objectives throughout its design horizon of 20 years [23]. The first objective was to keep average delays during the peak hour to approximately half minute or less. The second objective was to keep maximum queues during the peak hour to 20 cars or less. Fig. 2 presents proposed number of toll booths to process peak traffic hours without excessive delay times or long queues. At traffic volume equals 2000 vehicles per hours and 50% cash or more, the number of toll booths should be around 6–10, whereas for traffic volume equals 4000 vehicles per hours, the number of toll booths should be around 14–18.

Fig. 3 shows model results for average delays and maximum queue at different levels of percentage of cash drivers. The average delay and maximum queue length varied among the considered five levels of cash drivers. Output performance indicators of scenarios with percentage of case payment less than 100% are better than the base case (100% cash). Model results can be utilized to estimate the changes in toll station delays due to changes in method of payment. The average delay dropped from about 83 s at a traffic volume equals 300 veh/h/lane with 100% cash drivers to about 7 s at 0% cash drivers.

Fig. 4 presents delay and queue model results by driver type for simulation runs with utilization factor less than 1.0. Differences in delays among the different driver types were statistically tested using Friedman test [24]. The test can be applied to determine whether c treatments (the driver types in this case) have been selected from populations having equal medians. The hypotheses are as follows: H₀: all treatment effects are
zero versus H1: not all treatment effects are zero. Because the calculated $p$-value $= 0.000 < 0.05,$ the null hypothesis is rejected at the $\alpha = 0.05$ level. This shows that driver decision making is a central factor in the design and configuration of toll stations.

### 6. Conclusions

Toll station operation is a critical component of roadway operations, as tolls provide both a means of revenue for expansion and opportunity for demand management. A toll station should have adequate capacity to safely and effectively process the anticipated traffic without excessive queues and delays. However, unlike roadways and intersections that have standards addressing operational analysis, no such standards exist for toll stations.

This paper presented a model that incorporates the complex task of modeling the driver behavior at the toll station as well as the stochastic nature of traffic arrival and toll collection time. The proposed model can be used to assess design changes prior to expensive implementation or provide valuable information that could lead to more efficiency at the toll station, providing benefits for the toll station operating authority and the road users using the tolled facility. The developed simulation model was used to analyze 750 different scenarios. Results showed that manual toll collection (i.e., 100% cash) is inefficient which can easily cause excessive delay to the highway traffic. The reduced lane capacity associated with manual toll collection has an adverse impact of traffic delay. It also necessitates a significantly enlarged footprint for toll collection stations, since many additional lanes were necessary to accommodate the traffic flow. At traffic volume equals 2000 vehicles per hours and 50% cash or more, the number of toll booths should be around 6–10, whereas for traffic volume equals 4000 vehicles per hours, the number of toll booths should be around 14–18. Local efforts should start to investigate the use of electronic toll collection (ETC) in order to maximize vehicle throughput and reduce delay.

Results of the paper fill the gap that designers, planners, operators facing when design, evaluate, operate, or upgrade a new toll station in Egypt since the Egyptian highway design and traffic codes do not have any guideline for toll facilities. Results of the proposed model provide a valuable insight into the potential effects of changing the mix of payment methods, or operational changes in toll booth schedule, or assessment of a proposed toll station design.

### References


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