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TRAFFIC MICROSIMULATION APPROACH TO PLAN, EVALUATE, AND DESIGN TOLL STATIONS

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Abstract

A toll station should have adequate capacity to safely and effectively process the anticipated traffic without excessive queues and delays. This paper presented a proposed microscopic traffic simulation model for design, assessment, and operational analysis of toll stations. The proposed microscopic approach has the potential of providing the traffic engineers and decision makers with a good idea about the delay savings due to the operational changes of toll stations and to assign the appropriate lane staffing plan to efficiently accommodate the incoming design traffic. The proposed model incorporates the complex task of modeling the driver behavior at toll stations as well as the stochastic nature of traffic arrival and toll collection time. The developed simulation model was used to analyze different scenarios. Results showed that the drop in lane capacity associated with manual toll collection has an adverse impact on traffic delays and queues. 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

To create additional revenue that could be spent on maintenance and to address traffic safety the Egyptian Ministry of Transport (MOT) introduced the concept of road tolling. In 1998, a new law was introduced that enabled the Egyptian government

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to raise revenue from direct road charges. Consequently, several existing roads were converted to toll roads [1]. The 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. A study of toll rates for the Cairo Alexandria desert road was presented by [2].

Toll station systems consist of a number of service booths in which vehicles arrive from freeways at certain rates and must come to a stop in order to be processed. In this type of system, vehicles typically join a single queue for each booth and wait to pay the fees where service rates depend on type of payment. Efficient sizing of toll stations, minimizing their cost, and vehicle delay time are critical concerns to many transportation policy makers. The toll station design has evolved over time, always connected with the evolution of technology and the need for improvement in terms of road safety and environmental problems encountered over the past few years. Guidance on the layout of toll stations and design factors can be found in [3, 4], which is based on experience gained by operators of major existing toll facilities in the UK, European, and American operators. 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 and increase energy consumption and fuel emissions. Consequently, the efficient operation of toll stations is a high priority objective. Therefore, the objective of this paper is development of a microscopic traffic simulation model for design, assessment, and traffic operation analysis of toll stations.

2. Model Description

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. These also aid to a great extent in estimating the impacts and benefits of operational strategies in complex transportation networks with a fair degree of accuracy [5]. Guidelines for applying traffic microscopic simulation modeling are included in [6].

2.1 Vehicle Arrival Headways

A large number of headway distributions have been developed to represent the different pattern of vehicle arrivals. The most widely applied assumption light-to-medium traffic is that vehicles arrive randomly and the headways follow exponential distribution]. The following inverse-transform algorithm was used to generating the headway times.

$$h = -\bar{h}\ \ln u$$

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

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*. Approaching vehicles are assumed to be uniformly distributed among the basic highway lanes (i.e., probability (*k*) = 1 / number of basic highway lanes).

2.2 Driver Decision Making

The proposed simulation model included a lane selection algorithm that incorporates the following four different types of driver behaviors.

- 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 optimum (maximum) 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 ties.

Except 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 following equation evaluates *TLD* for each toll lane relative to the toll lane a vehicle is currently in [7]. The *TLD* equation utilizes relative queue length, required number of lane changes, and a sensitivity factor.

$$TLD_j = \frac{\Delta Q}{LC^{SF}}$$

where, *TLD* is toll lane desirability of toll lane *j*, ΔQ is difference in queue length between vehicle‘s current lane and a toll lane *j* , *LC* is number of lane changes required for vehicle to reach toll lane *j*, *SF* is lane change sensitivity factor. The sensitivity factor is a variable that affects a driver‘s willingness to make a lane change to save one queue space. The input range for this value is 0 to 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. Each toll booth is assigned one and only one queue. Vehicles select the toll lane based on the proposed lane selection algorithm. Once a vehicle joins a queue it remains in the same queue until service is completed at the booth (i.e., no queue switching). No lane change occurs if the driver is already in the lane with the shortest queue length.

2.3 Toll Collection Processing Time

The processing time (τ) 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.

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 estimates the most likely value for the random variable in addition to its range (lower and upper bounds).

$$\textit{Generate}\ u \sim U(0,1)$$

$$\tau_\omega = \begin{cases} 3600 \Big/ \left(a_\omega + \sqrt{u(b_\omega - a_\omega)(c_\omega - a_\omega)}\right) & a_\omega \le \tau \le c_\omega \\ 3600 \Big/ \left(b_\omega - \sqrt{(1-u)(b_\omega - a_\omega)(b_\omega - c_\omega)}\right) & c_\omega < \tau \le b_\omega \end{cases}$$

where $u \sim U(0,1)$ is the distribution function of a uniform random variable having a range [0, 1], ω 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 $c \in [a, b]$ is the mode processing time. For each payment type, there are corresponding values for $a_\omega, b_\omega,$ and c_ω.

3. Model verification

Model verification is the process of examining the conceptual aspects of the model to ensure it works logically [8]. Verification included tracking vehicles to ensure movements follow the logical sequence built in the model. Furthermore, the proposed simulation model was examined against the queuing theory equations by using an hourly traffic volume equals 1,800 vehicles per hour and a toll booth capacity equals 300 vehicles per hour. Note that the queuing theory closed-form equations are limited to exponential inter-arrival and service-time rates as well as is 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. Equations of the queuing theory for an *M/M/N* system are described by arrival rate, processing rate and the number of servers in the system. The *M* denotes Markovian behavior, which signifies an exponential distribution. Therefore, an *M/M/N* system has exponentially distributed inter-arrival times, an exponentially distributed service time and *N* server [9]. The arrival rate is denoted by λ vehicles per hour, the service rate is μ vehicles per hour, and ρ is the utilization factor ($\rho = \lambda / (\mu N)$) of the system. The mean inter-arrival time is equal to ($1/\lambda$ = 2 seconds) and the mean processing time is equal to ($1/\mu$ = 12 seconds). To reach a steady state, the toll station service rate (μN) should be greater than the arrival rate (λ). Different configurations ranging from 7 to 12 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 confidence interval for the true average delay time was calculated for each configuration. Table 1 shows the 95% confidence interval (CI) for the true mean delay based on the simulation model as well as the calculated mean delay obtained by applying equations of the queuing theory. Based on the 95% CI, no significant difference exists between the simulation model and the queuing theory.

Table 1. Model Verification Results

No. of toll-booths (N)	Mean delay (sec)	Std Dev (sec)	SE of Mean	95% CI of the true mean delay	Average delay ($M/M/N$)
7	18.757	4.414	0.806	(17.109, 20.405)	19.366
8	14.801	2.138	0.390	(14.003, 15.600)	14.142
9	13.154	1.386	0.253	(12.636, 13.671)	12.784
10	12.466	1.027	0.188	(12.082, 12.850)	12.304
11	12.110	0.828	0.151	(11.801, 12.419)	12.118
12	11.960	0.771	0.141	(11.673, 12.248)	12.045

4. Simulation Experiment, Results, and Discussion

4.1 Simulation Experiment

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. Average delay time is considered the most important indicator [10]. Table 2 summarizes the experimental design factors and input parameters. The experimental design includes three levels of traffic volumes, five levels of percentage of cash drivers, five levels of driver habits for decision making, and ten levels of number of toll booths. The experimental design includes a total of 750 factor combinations. For each toll station configuration, a factorial design with 75 design points was considered. Other input parameters of the proposed simulation model included the processing times for toll collection. The triangular parameters for processing times were $(a_1 = 250; b_1 = 350; c_1 = 300)$ and $(a_2 = 500; b_2 = 700; c_2 = 600)$ for the traditional cash and payment receipt holders, respectively.

Table 2. Factors and Levels Considered in the Experimental Design

Factor	No. of levels	Input Parameters
Factor 1: Hourly traffic volumes	3	$2000, 4000, 6000\ veh/hr$
Factor 2: Payment Type	5	$\%Cash = 100\%, ..., 0\%$ with $\Delta = -25\%$
Factor 3: Driver Type	5	• 100% Driver Type 1 • 100% Driver Type 2 • 100% Driver Type 3 • 100% Driver Type 4 • Mixed: 10% Driver Type 1, 30% Driver Type 2, 30% Driver Type 3, and 30% Driver Type 4.
Factor 4: Number of toll booths	10	$N = 6, ..., 24$ with $\Delta N = 2$

4.2 Simulation Results

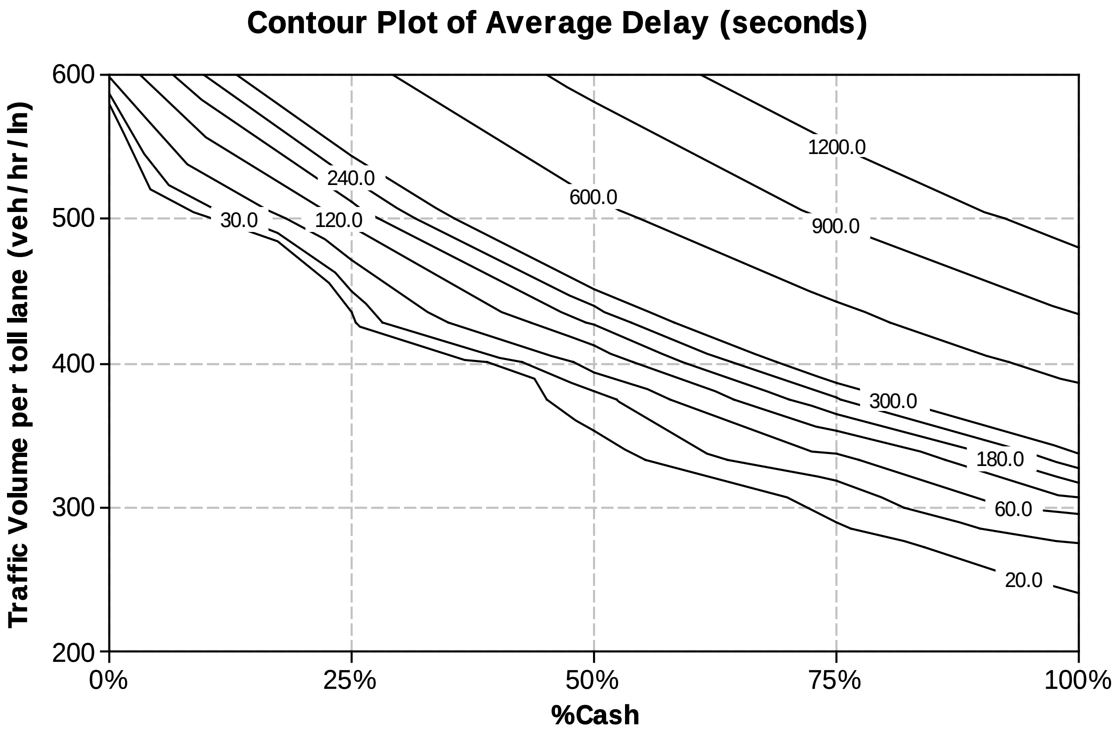
The execution phase of the experimental design included a total of 750 factor combinations, 22,500 simulation runs, and about 97.5 million vehicles. For each of the factor combination, 30 simulation runs were conducted and system performance indicators were calculated. For each simulation run, length of the simulation run was 65 minutes including 5 minutes warm-up period. During the warm-up period, results are not collected in order to reduce bias estimate in model results. Table 4 summarizes results of the simulation model in terms of average delays and maximum queues. As the utilization factor of the toll station increases, motorists experience higher delays and longer queues. If the utilization factor exceeds one (cases are highlighted in Table

4), then the toll station system will not reach a steady state since the system has incoming vehicular traffic more than the system can process.

Table 4. Summary of the Simulation Results

Traffic Volume	%Cash	Average Delay (sec)					Max. Queue Length (veh)				
		0%	25%	50%	75%	100%	0%	25%	50%	75%	100%
2,000	*N* = 6	7.5	11.2	18.0	55.1	289.2	7	12	15	46	85
	N = 8	7.0	9.4	12.1	16.0	22.6	5	8	9	18	24
	N = 10	6.8	8.9	11.0	13.5	16.3	5	6	7	9	10
	N = 12	6.7	8.6	10.6	12.6	14.8	5	7	7	8	7
	N = 14	6.7	8.6	10.4	12.3	14.2	5	5	6	7	6
	N = 16	6.7	8.5	10.3	12.1	14.0	4	5	6	7	6
	N = 18	6.7	8.5	10.2	12.0	13.8	4	4	4	6	6
	N = 20	6.6	8.4	10.2	11.9	13.7	4	5	5	5	6
	N = 22	6.6	8.4	10.2	11.9	13.6	4	5	5	5	5
	N = 24	6.6	8.4	10.1	11.9	13.6	4	4	5	4	6
4,000	*N* = 6	264.0	791.9	1332	1866	2399	153	263	352	386	458
	N = 8	11.4	138.3	534.3	933.2	1331	17	86	169	219	266
	N = 10	8.2	14.3	78.8	377.6	692.3	11	28	70	127	183
	N = 12	7.4	10.7	17.1	53.3	272.1	9	13	21	56	84
	N = 14	7.1	9.6	13.1	19.4	41.6	8	10	19	26	47
	N = 16	7.0	9.1	11.7	15.2	21.3	8	10	12	14	29
	N = 18	6.9	8.9	11.1	13.7	17.3	7	9	8	15	18
	N = 20	6.9	8.8	10.8	13.1	15.8	6	9	8	11	13
	N = 22	6.8	8.7	10.6	12.7	15.0	5	7	9	9	11
	N = 24	6.8	8.6	10.5	12.4	14.5	6	7	10	8	9
6,000	*N* = 6	1302	2094	2882	3675	4471	493	606	676	723	769
	N = 8	515	1109	1699	2294	2893	236	347	431	477	522
	N = 10	62.6	520.1	990.5	1466	1946	76	203	286	333	371
	N = 12	11.0	136.9	520.4	915.2	1315	23	93	170	226	271
	N = 14	8.5	18.1	190.5	523.5	865.2	17	38	113	157	184
	N = 16	7.7	12.2	29.6	234.9	529.6	12	27	43	106	139
	N = 18	7.3	10.4	16.5	48.0	272.6	10	16	30	51	97
	N = 20	7.1	9.7	13.4	21.4	82.6	11	11	19	34	76
	N = 22	7.0	9.3	12.2	16.8	29.0	7	13	16	20	39
	N = 24	6.9	9.0	11.5	14.9	21.1	7	12	12	23	30

When the utilization factor is higher than 0.90, the delay times and queue lengths significantly increase. Data of Table 4 can be used to determine the time savings achieved by vehicles for various percentages of cash drivers over the base case on 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 since it depends on the amount of reduction in the utilization factor due to the increase in the number of toll lanes. Figure 1 presents contour plots of average delay and maximum queue based on the model results of the experimental design.



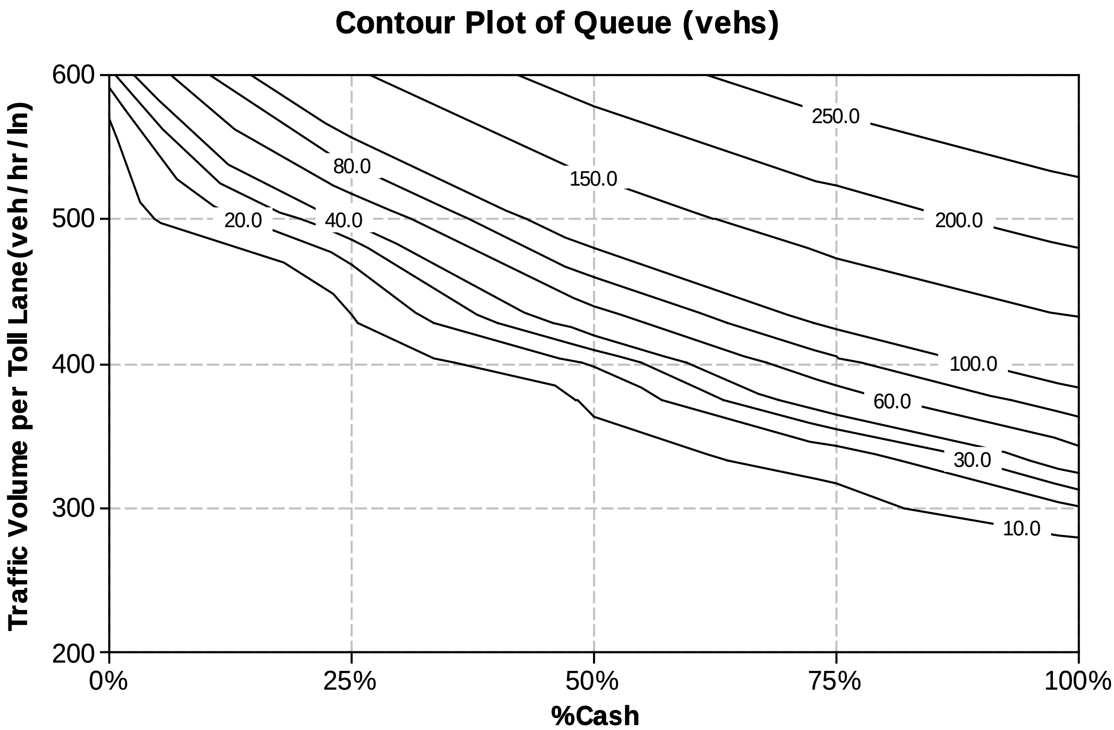


Figure 1. Contour plots of Model Results of the Experimental Design

When a toll station is designed, choosing the right number of toll booths is a critical issue. Figure 1 and Table 4 can be used to determine number of toll booths in order to process peak traffic hours without long delay times. If the number of the toll booths increases or the processing time decreases, the average delay time decreases. A toll station should have adequate capacity to effectively process the anticipated traffic without excessive queues and delays. However, unlike roadways and intersections which 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 [11]. The first objective is to keep average delays during the peak hour to approximately half minute or less. The second objective is to keep maximum queues during the peak hour to 20 cars or less. Figure 2 presents proposed number of toll booths to process peak traffic hours without excessive delay times or long queues.

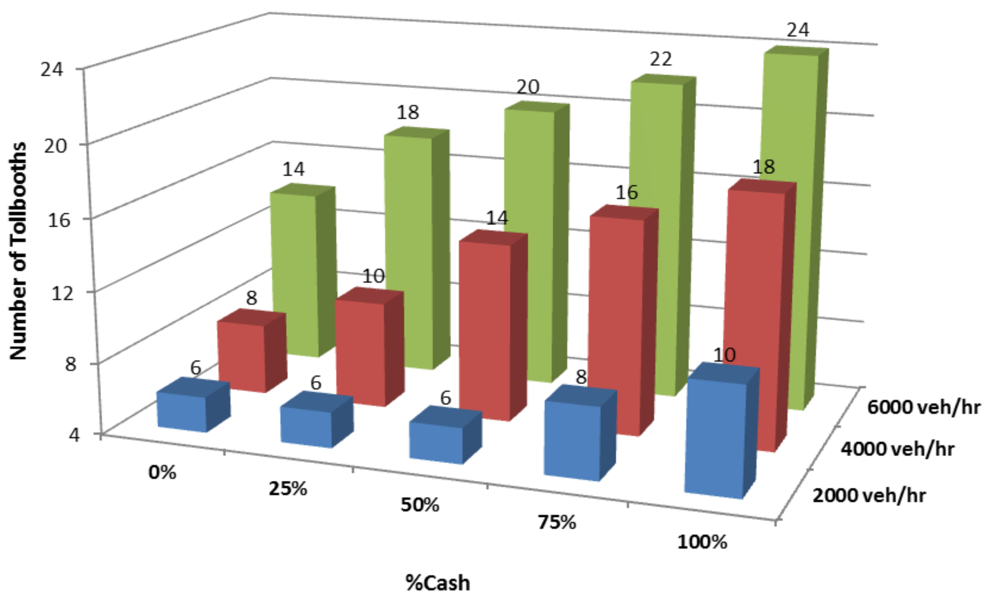


Figure 2. Proposed Number of Toll booths for the Design of a Toll Station

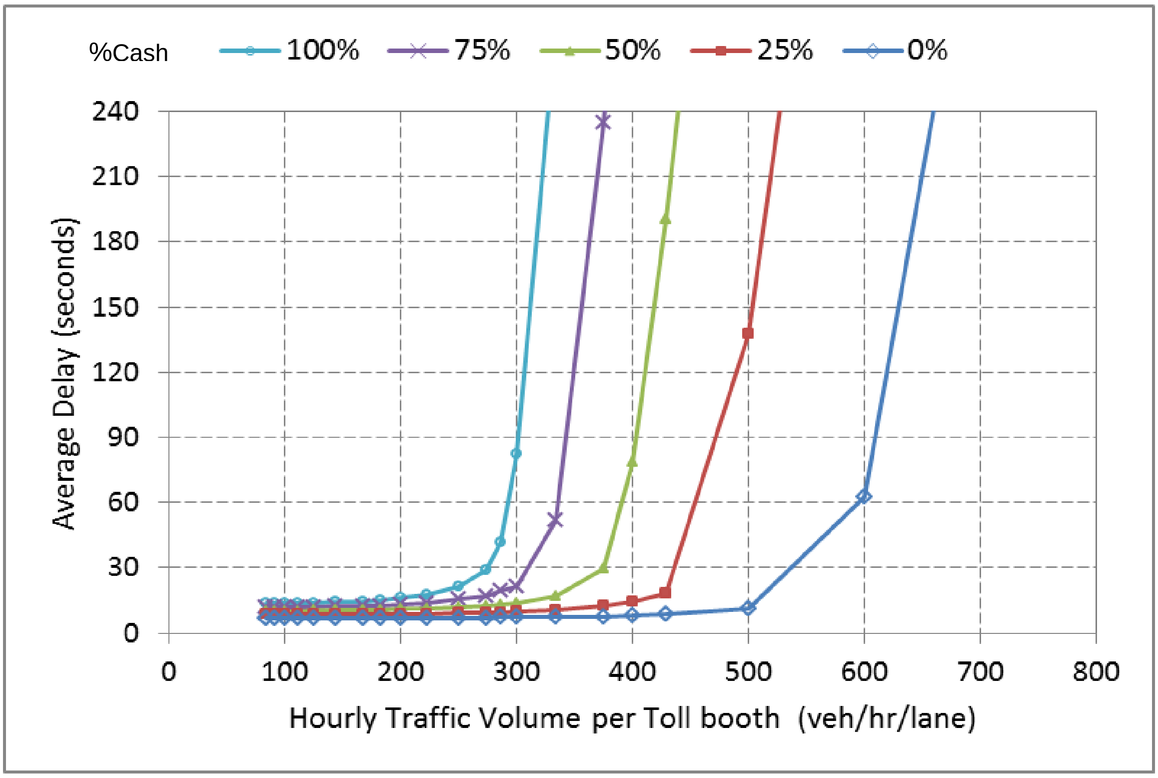
4.3 Discussion

4.3.1 Effect of Payment Type

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. Figure 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 %cash 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 seconds at a traffic volume equals 300 veh/hr/lane with 100% cash drivers to about 7 seconds at 0% cash drivers.

4.3.2 Effect of Driver Type

Figure 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 [12]. Friedman test is a standard nonparametric analysis of a randomized block experiment. 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 idea is to investigate treatment differences while controlling for a blocking factor (utilization factor in this case). The hypotheses are: Ho: all treatment effects are zero versus H1: not all treatment effects are zero. Because the calculated $p\text{-}value = 0.000 < 0.05$, the null hypothesis is rejected at the $\alpha = 0.05$ level.



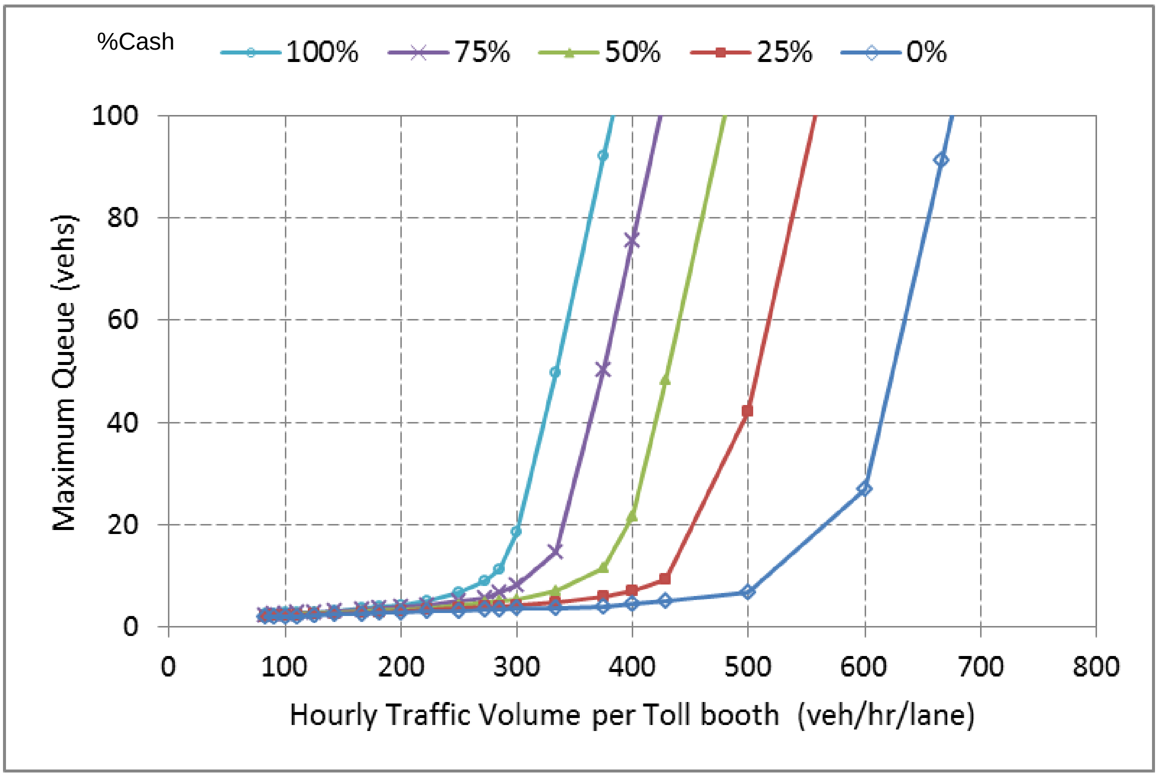


Figure 3. Model results for average delays and maximum queues

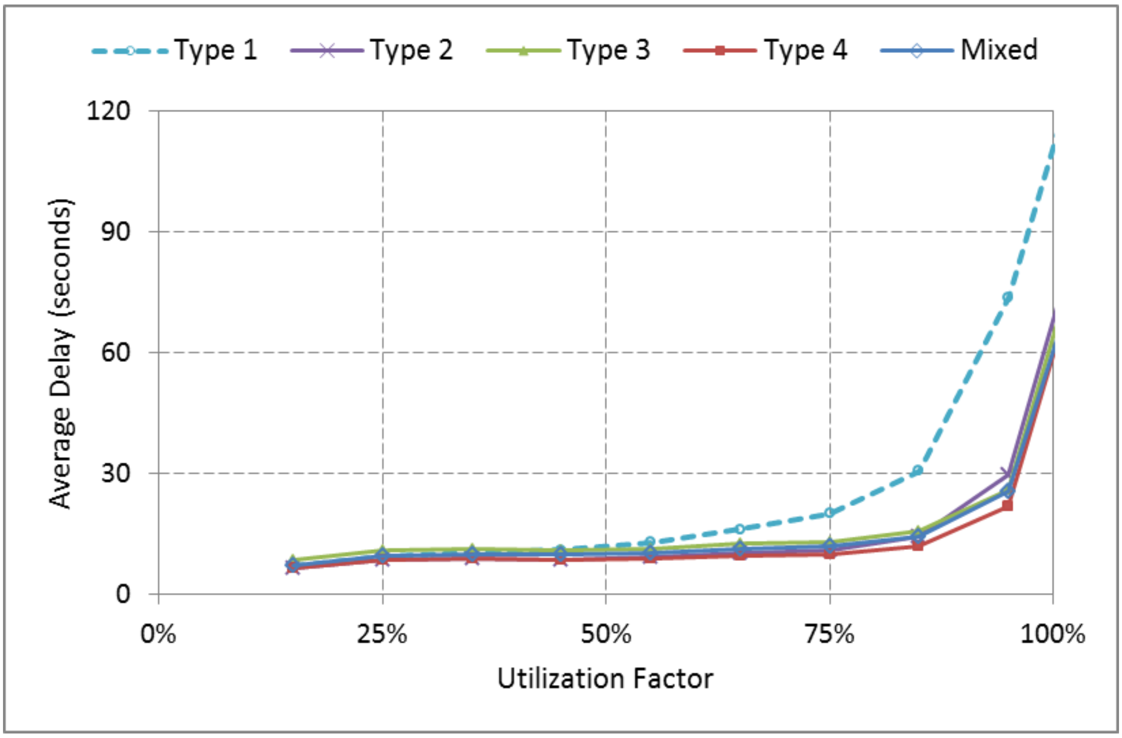


Figure 4. Model results for effect of driver type on average delays

Conclusions

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 which have standards addressing operational analysis, no such standards exist for toll stations. This paper presented a proposed microscopic traffic simulation model for design, assessment, and operational analysis of toll stations. The model 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 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 necessary to accommodate the traffic flow. The proposed microscopic approach has the potential of providing the traffic engineers and decision makers with a good idea about the delay savings due to the operational changes of toll stations and to assign the appropriate lane staffing plan to efficiently accommodate the incoming design traffic.

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