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CONCEPTUALIZATION OF TRAFFIC FLOW FOR DESIGNING TOLL PLAZA CONFIGURATION: A CASE STUDY USING SIMULATION WITH ESTIMATED TRAFFIC VOLUME

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Computer simulation is one of the popular approaches to the design of toll plazas. Toll plaza configurations such as toll collection methods, number of toll booths, and types of vehicles have been studied in the literature. Traffic flow types can be another influential factor when designing toll plazas, especially in case that traffic flow information is not available, but only the estimate of traffic volumes. Few studies have reported the effect of traffic types on toll plaza performances. In this article, a discrete-event simulation method is used to analyze the sensitivity of toll plaza performance for different types of traffic flow. Two traffic patterns, deterministic and probabilistic traffic flow, is considered. This study is based on a proposed project for building a toll bridge in the eastern North Carolina. The estimated future traffic counts for the toll bridge are used to study the difference between the two traffic patterns.

Significance: Appropriate representation of events is essential for a simulation analysis. When modeling toll plazas using a simulation, validity of toll plaza performances such as length of waiting line and waiting time will be dependent upon the accuracy of traffic flow information. This study addresses the sensitivity of toll plaza performances for different traffic patterns.

Keywords: Modeling and simulation, traffic flow types, electrical toll collection, toll plaza, performance measures

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1. INTRODUCTION

Simulation-based approaches have been applied to various system optimization problems in industries. In the literature, some examples include cellular manufacturing processes (Hachicha et al., 2007), preventive maintenance scheduling (Alfares, 2002), risk-based decision making (Cao and Wang, 2003), supply chain diagnostics (Kao and Huang, 2008), flowshop scheduling (Katten and Maragoud, 2008) and toll plaza configurations (Sadoum, 2005). Although simulation approaches are popular and powerful, it should be emphasized that simulation is just one of possible experiments for an interested system. Thus, simulation analysis requires a careful process of designing a conceptual model of a real or proposed system for a given set of conditions (Kelton et al., 2007). It is essential that the functionality of the system as well as associated conditions should represent the system as close as possible in order to produce reliable results from simulation analyses. As discussed by Zhou et al. (2007), designing a conceptual model needs a formalization and representation of knowledge across different domains such as application, simulation, and implementation. Unfortunately, even the same concept usually tends to be expressed differently by each domain. Many practitioners who have expertise in the application domain but not in the simulation and implementation domains are likely to experience some difficulties in formalizing system functions. In addition to the system formalization, representation of characteristics of a given set of conditions such as randomness of events, stochastic processes, or uncertainty is another challenge.

For conceptualizing toll plaza system, Edie (1954) introduced a typical queueing theory-based approach to the analysis of toll plaza performance. A single traffic flow distribution and one type of tollbooth at the toll plaza were assumed to build a queueing model. However, when there are various types of traffic flow patterns for different time periods and not identical tollbooths, the problems become more complex and time consuming to analyze. Due to these drawbacks from the operations research-based methods, simulation-based approach has been introduced for the analysis of toll plaza performance measures in the literature. When applying a simulation analysis to toll plaza performances, conceptual designing factors can be represented with certainty or uncertainty. Some examples of designing factors with certainty may include the distance between diverging area and toll booths, number of approaching lanes, or number of toll booths. Some uncertain designing factors are Electrical Toll Collection (ETC) penetration rates, traffic flow rates, or toll transaction rates. Several studies reported design issues in toll plaza (Ito and Hiramoto, 2004; Ito, 2005), traffic jams at toll plaza with ETC gates (Horiguchi and Kuwahara, 2000), different toll collection methods (Chao, 1999), and determination of the number and different types of toll booths (van Dijk et al., 1999). From the perspective of toll plaza configuration, several payment methods and combinations of different vehicle types (van Dijk et al., 1999) or a combined design of manual gate and ETC gate and ETC penetration rate (Ito, 2005) have been considered to analyze toll plaza performance. For modeling different payments' processing time, an average service time (deterministic) for each service type (Sadoum, 2005), a triangular distribution (Ito, 2005), or an average service time for each service type as well as each vehicle type (van Dijk et al., 1999) have been used.

Conceptualization of traffic flow pattern is one of the influential factors on the traffic simulation modeling. When modeling the traffic flow for toll plaza analysis, typically two patterns of traffic information are used. One is a deterministic traffic volume for a given period, and the other is a probabilistic type. When studies focused on performance measures during a traffic peak time period, they usually assumed fixed traffic counts (van Dijk et al., 1999; Ito, 2005). This assumption would be valid because it can be expected that the time intervals between successive traffic arrivals might be almost constant. However, since the resources are overloaded during the peak period, it would be necessary for the simulation model to run longer than the peak period in order to make the queue "flush-out" to a normal level. Sadoun (2005) demonstrated this issue by comparing the average delay time for different arrival rates during a peak time period and after the period. Since it is generally accepted that characteristics of traffic flow are likely to fit a Poisson process, it would not be unusual to consider a theoretical exponential distribution for the arrival time of traffic when a probabilistic traffic pattern is applied. In reality, however, transportation engineers usually estimate traffic volumes using a traffic counter for a given time period. If we convert a traffic count for the specified time period into an interarrival time between traffic arrivals, which is the conversion of a Poisson distribution to an exponential distribution, the accuracy of the estimated arrival time will be decreased as the time unit of the specified time period is increased. For instance, let's assume that the traffic volume was averaged every 10 minutes for an hour as follows: 20 vehicles for the first 10 minutes, 20 for the second 10 minutes, the same volume up to the fifth 10 minutes, and 500 vehicles for the last 10 minutes. In this case, the specified time period is 10 minutes, and the interarrival time will be estimated exponentially distributed with the average of 0.5 minutes for the first five 10 minutes and is 0.02 minutes for the last 10 minutes. However, if an hour is used for the specified unit time period, the interarrival time would be 0.1 minutes (60 min/600 vehicles). Thus, there would be significantly fewer arrivals during the last 10 minutes when the time period of an hour is applied compared to traffic arrivals when the time period of a 10 minute is applied. Difficulty of conceptualization of traffic flow increases when building a model with future estimated traffic volumes for a proposed system. Practitioners usually project an hourly traffic volume based on previous data sets. In this case, the projected traffic volume can be used either as a deterministic value with certainty or as a probabilistic value with uncertainty. For the probabilistic case, statistical analyses can be applied to infer a probability distribution for the traffic flow. However, when traffic conditions can be represented with a more simplified form, the practitioners will face less burden of simulation modeling.

In this study, a conceptualization of traffic flow is discussed on the basis of the sensitivity of toll plaza performances by two traffic patterns-deterministic and probabilistic traffic flow using a discrete-event simulation method. Estimated future traffic counts for a proposed project for building a toll bridge in the eastern North Carolina are used in the study.

2. REAL-LIFE EXAMPLE

2.1 Traffic Flow

In the eastern area of North Carolina in the United States of America, building a toll bridge has been proposed by the North Carolina Turnpike Authority (NCTA). At the western end of the bridge, a toll plaza will be constructed where traffic moving in both directions will pay a toll. One of the objectives of the project was to configure the toll plaza design to provide a cost effective service. One of the main expectations from the planned toll bridge was to resolve the heavy traffic flow toward the coastal area in the morning and returning traffic in the afternoon during a peak season. For designing the toll plaza, traffic volumes were estimated for both directions, i.e., the eastbound and westbound of the bridge, in Yr 2012 and Yr 2025. Even though it was estimated during the twenty-four period, the time period from 9 AM to 5 PM was considered as a simulation time window in this study because this time period showed the beginning and ending points of high traffic flow rate for the toll plaza.

Based on the hourly forecasted traffic counts for the toll bridge in Yr 2012 and Yr 2025, two different traffic flow patterns, deterministic traffic flow and probabilistic traffic flow, were examined. For the deterministic traffic flow pattern, it was assumed that the number of traffic counts during each hourly window was fixed without any variation over time. Since it was not possible to infer a probability distribution for an hourly period from the traffic count estimates, a variation of traffic counts for an hour period was considered on the forecasted fixed traffic counts to build a probabilistic traffic flow pattern. A symmetric triangular distribution was assumed with 5%, 10%, and 15% of deviation from the hourly estimate. The triangular distribution is commonly used when the exact form of the distribution is not known, but the estimates for the minimum, maximum, and most likely values are available. When it is symmetric, the minimum and maximum values are deviated equally from the center value, that is, the most likely value. Two possible traffic originations such as a southbound of the local highway and a northbound of that highway were considered to coming to the eastbound of the toll plaza with the partition of total traffic volume 90% and 10%, respectively.

2.2 Toll Plaza Configuration

A sensitivity analysis of toll plaza performance was used to evaluate possible alternatives of the toll plaza configuration on the basis of only the number of manual booths. Since there would be reserved lanes for ETC booths in the design plan and processing times at ETC would not influence queue related measures at manual toll booths, ETC penetration rates were used to control traffic volumes for manual booths. The applied ETC penetration rates were 25%, 40%, 50%, 60% or 80%. Up to three toll booths were considered. The capacity of manual toll collection was estimated to be between 400 vehicles per hour and 450 vehicles per hour. Based on this estimation, a symmetric triangular distribution was also assumed for the manual transaction processing time with the minimum of 400 vehicles, most likely 425, and maximum 450 per hour. According to the guidance from the North Carolina Turnpike Authority, lane changing options before approaching to toll booth lanes were applied to various number of toll booths considered. Figure 1 shows the lane changing options for different number of toll booths considered. Traffic from the northbound was not allowed to use the ETC lane.

2.3 Simulation Modeling

A discrete event simulation method was used to measure the average waiting time and average queue length every hour at the manual toll by using the ARENA simulation software (Arena). The flow chart logic of the simulation model was built as shown in Figure 2. For creating vehicles to toll plaza two creation modules, one for the southbound of the local highway and the other for the northbound were used. Each vehicle was directed to either an ETC lane or manual lanes according to the ETC rate. The vehicle directed to manual lanes were able to select a manual toll booth on the basis of lane changing options as shown in Figure 1 and the number of waiting vehicles in each lane. For selecting a toll booth a minimum queue length rule was used. If there was a tie in the queue length, the closest lane (the lower numbered toll booth) was selected. Once the vehicle joined a lane, the waiting time was recorded. After completing the toll transaction the vehicle was disposed. In addition to the average performance measures, maximum values were also collected for the worst traffic case. Table 1 shows the experimental design of scenarios. Each scenario ran 30 replications.

Table 1. Experimental design of scenarios

Traffic flow type	Deterministic or Probabilistic
ETC penetration rate	25%, 40%, 50%, 60% or 80%
Number of manual tollbooth	1, 2, or 3 booths
Traffic deviation rate for probabilistic case	5%, 10%, or 15%

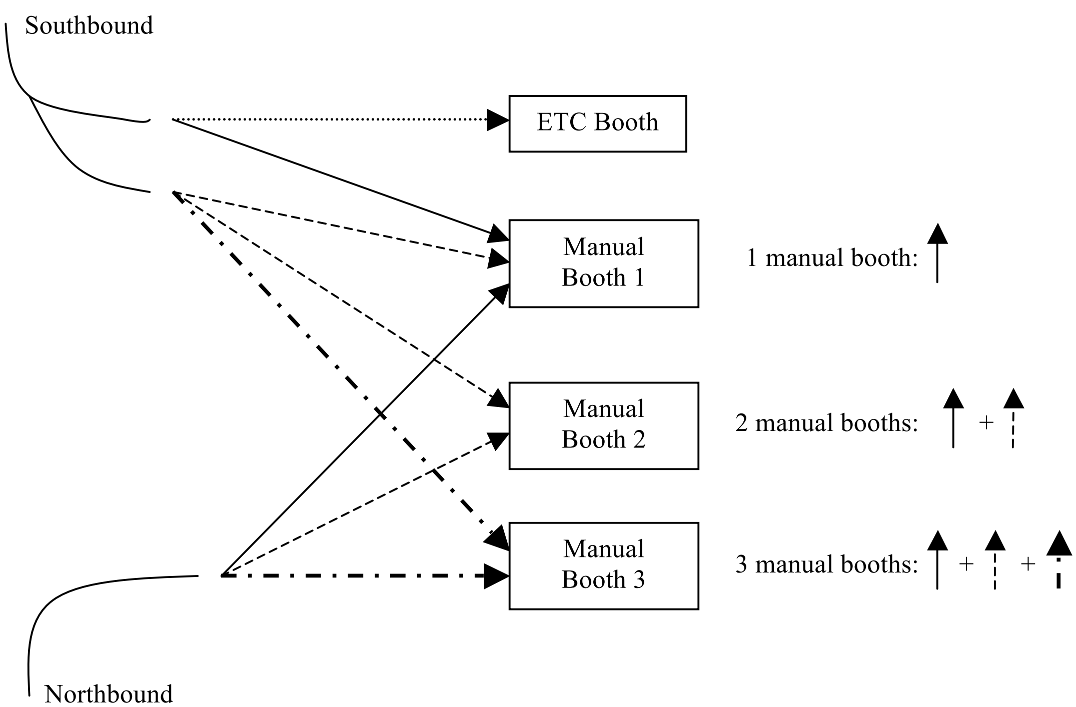

Figure 1. Toll booth approaching options for different number of manual booths

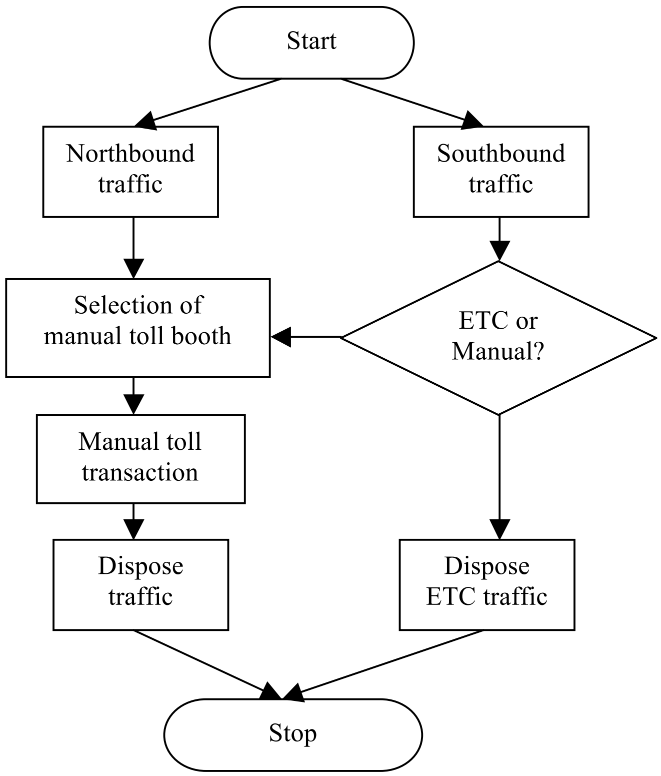

Figure 2. Simulation logic flow

3. RESULTS

Simulation results were summarized in terms of maximum, minimum, and average of queue length and waiting time after 30 simulation runs. In the original simulation results, the queue length was shown by the number of cars. In this study, however, the queue length was converted to a distance in feet. The distance was calculated on the basis of the following criteria generally accepted by the NCTA: the average length of a car 15 feet; the minimum clearance from the front and back of a car 5 feet each; the considered distance for a car 20 feet.

3.1 Deviation Rates in Probabilistic Traffic Flow

Deviation rates for the probabilistic traffic flow did not show a difference on the average performance measures for each time period at the same ETC penetration rate. Also, maximum values of performance measures were not different between traffic deviation rates. Comparisons between deviation rates on the average queue length, waiting time, and maximum values are shown in Tables 2, 3, and 4, respectively. For illustration purposes, the tables show the performance measures for the different number of manual tolls at the lowest ETC penetration rate (25%) and the highest rate (80%) for the eastbound in Yr 2012.

Table 2. Comparison of average queue length between traffic deviation rates

ETC Rate		25%			80%		
Deviation Rate		5%	10%	15%	5%	10%	15%
Time Period	9 ~ 10am	(580, 9,1)**	(567, 9, 1)	(580, 9, 1)	(2, 0, 0)	(2, 0, 0)	(2, 0, 0)
	10 ~ 11am	(1993, 14, 2)	(1953, 14, 2)	(1979, 15, 2)	(2, 0, 0)	(2, 0, 0)	(2, 0, 0)
	11 ~ 12pm	(4350, 27, 3)	(4345, 27, 3)	(4356, 29, 3)	(3, 0, 0)	(3, 0, 0)	(3, 0, 0)
	12 ~ 1pm	(7538, 44, 4)	(7573, 49, 4)	(7560, 51, 4)	(4, 0, 0)	(4, 0, 0)	(4, 0, 0)
	1 ~ 2pm	(11176, 57, 5)	(11221, 67, 5)	(11204, 68, 5)	(4, 0, 0)	(4, 0, 0)	(4, 0, 0)
	2 ~ 3pm	(14975, 61, 5)	(15044, 72, 5)	(15028, 74, 5)	(4, 0, 0)	(4, 0, 0)	(4, 0, 0)
	3 ~ 4pm	(18793, 62, 5)	(18906, 72, 5)	(18897, 77, 5)	(4, 0, 0)	(4, 0, 0)	(4, 0, 0)
	4 ~ 5pm	(22577, 59, 5)	(22719, 68, 5)	(22711, 73, 5)	(4, 0, 0)	(4, 0, 0)	(4, 0, 0)

**: All numbers were rounded to the next integer in feet.*
***: Numbers can be read for (1 tollbooth, 2 tollbooths, 3 tollbooths).*

Table 3. Comparison of average waiting time between traffic deviation rates

ETC Rate		25%			80%		
Deviation Rate		5%	10%	15%	5%	10%	15%
Time Period	9 ~ 10am	(2m 40s, 2s, 0)	(2m 37s, 3s, 0)	(2m 39s, 2s, 0)	(2s, 0, 0)	(2s, 0, 0)	(2s, 0, 0)
	10 ~ 11am	(8m 22s, 4s, 1s)	(8m 10s, 4s, 1s)	(8m 12s, 4s, 1s)	(2s, 0, 0)	(2s, 0, 0)	(2s, 0, 0)
	11 ~ 12pm	(16m 20s, 6s, 1s)	(16m 12s, 6s, 1s)	(16m 14s, 7s, 1s)	(3s, 0, 0)	(3s, 0, 0)	(3s, 0, 0)
	12 ~ 1pm	(26m 2s, 10s, 1s)	(25m 58s, 11s, 1s)	(26m, 11s, 1s)	(3s, 0, 0)	(3s, 0, 0)	(3s, 0, 0)
	1 ~ 2pm	(37m 4s, 12s, 1s)	(37m 4s, 14s, 1s)	(37m 2s, 14s, 1s)	(3s, 0, 0)	(3s, 0, 0)	(3s, 0, 0)
	2 ~ 3pm	(48m 52s, 13s, 1s)	(48m 57s, 15s, 1s)	(48m 52s, 15s, 1s)	(3s, 0, 0)	(3s, 0, 0)	(3s, 0, 0)
	3 ~ 4pm	(1h 1m 8s, 13s, 1s)	(1h 1m 14s, 15s, 1s)	(1h 1m 7s, 16s, 1s)	(3s, 0, 0)	(3s, 0, 0)	(4s, 0, 0)
	4 ~ 5pm	(1h 13m 41s, 12s, 1s)	(1h 13m 47s, 14s, 1s)	(1h 13m 40s, 15s, 1s)	(3s, 0, 0)	(3s, 0, 0)	(4s, 0, 0)

**: All numbers were rounded to the next integer in seconds.*
***: Numbers can be read for (1 tollbooth, 2 tollbooths, 3 tollbooths).*

Table 4. Comparison of maximum values between traffic deviation rates

ETC Rate	25%			80%		
Deviation Rate	5%	10%	15%	5%	10%	15%
Queue Length (ft)	(57150, 925, 300)**	(56875, 1100, 350)	(58650, 1250, 275)	(200, 100, 75)	(200, 100, 75)	(175, 100, 75)
Waiting Time	(3h 13m 10s, 2m 37s, 32s)	(3h 18m 15s, 3m 5s, 41s)	(3h 19m 52s, 3m 1s, 31s)	(1m 6s, 14s, 7s)	(1m, 5s, 14s, 7s)	(55s, 14s, 7s)

**: All numbers were rounded to the next integer*
***: Numbers can be read for (1 tollbooth, 2 tollbooths, 3 tollbooths)*

3.2 Deterministic vs. Probabilistic Traffic Flow

The performance measures were compared between deterministic traffic counts and probabilistic traffic counts for the possible pairs of ETC rates and number of manual toll booths. Since no difference was found between traffic deviation rates, the average from the three deviation rates was used for the case of probabilistic traffic counts. The two different traffic flows showed no difference for each combination of ETC rates and the number of manual tollbooths during each time period. Table 5 and Table 6 show comparisons of average queue length and waiting time, respectively, at the lowest ETC penetration rate (25%) and the highest rate (80%) for the three different manual tollbooths for the eastbound in Yr 2012.

Table 5. Comparison of average queue length between deterministic and probabilistic traffic flows

ETC Rate		25%			80%		
Tollbooth		1	2	3	1	2	3
Time Period	9 ~ 10am	(597, 576)**	(9, 9)	(1, 1)	(2, 2)	(0, 0)	(0, 0)
	10 ~ 11am	(2029, 1975)	(14, 14)	(2, 2)	(2, 2)	(0, 0)	(0, 0)
	11 ~ 12pm	(4400, 4350)	(26, 28)	(3, 3)	(3, 3)	(0, 0)	(0, 0)
	12 ~ 1pm	(7597, 7557)	(42, 48)	(4, 4)	(4, 4)	(0, 0)	(0, 0)
	1 ~ 2pm	(11246, 11200)	(54, 64)	(5, 5)	(4, 4)	(0, 0)	(0, 0)
	2 ~ 3pm	(15078, 15015)	(58, 69)	(5, 5)	(4, 4)	(0, 0)	(0, 0)
	3 ~ 4pm	(18923, 18865)	(59, 70)	(5, 5)	(4, 4)	(0, 0)	(0, 0)
	4 ~ 5pm	(22731, 22669)	(56, 67)	(5, 5)	(4, 4)	(0, 0)	(0, 0)

**: All numbers were rounded to the next integer in feet*
***: Numbers can be read for (deterministic, probabilistic)*

Table 6. Comparison of average waiting time between deterministic and probabilistic traffic flows

ETC Rate		25%			80%		
Tollbooth		1	2	3	1	2	3
Time Period	9 ~ 10am	(2m 45s, 2m 38s)	(2s, 2s)	(0, 0)	(2s, 2s)	(0, 0)	(0, 0)
	10 ~ 11am	(8m 30s, 8m 15s)	(4s, 4s)	(1s, 0)	(2s, 2s)	(0, 0)	(0, 0)
	11 ~ 12pm	(16m 30s, 16m 15s)	(6s, 6s)	(1s, 1s)	(3s, 3s)	(0, 0)	(0, 0)
	12 ~ 1pm	(26m 14s, 26m)	(9s, 10s)	(1s, 1s)	(3s, 3s)	(0, 0)	(0, 0)
	1 ~ 2pm	(37m 15s, 37m 4s)	(12s, 14s)	(1s, 1s)	(3s, 3s)	(0, 0)	(0, 0)
	2 ~ 3pm	(49m 7s, 48m 54s)	(12s, 14s)	(1s, 1s)	(3s, 3s)	(0, 0)	(0, 0)
	3 ~ 4pm	(1h 1m, 1h 1m 10s)	(12s, 14s)	(1s, 1s)	(3s, 3s)	(0, 0)	(0, 0)
	4 ~ 5pm	(1h 14m, 1h 13m 42s)	(12s, 14s)	(1s, 1s)	(3s, 3s)	(0, 0)	(0, 0)

*: *All numbers were rounded to the next integer in feet*
**: *Numbers can be read for (deterministic, probabilistic)*

3.3 ETC Rates and Number of Tolls

Since no difference was found between the deterministic and probabilistic traffic flow as described in the section 3.2, the performance measures with the deterministic traffic flow was applied. For checking the sensitivity of ETC rates and number of tolls on performance measures, the maximum values of queue length and waiting time (the worst case during the simulated time window) were compared. From the perspective of maximum queue length and maximum waiting time, no significant difference was found between 2 manuals and 3 manuals as long as the ETC penetration rate kept above 25%. Table 7 shows the comparison along with the ETC rates and number of manual tolls for the eastbound in Yr 2012.

Table 7. Comparison of maximum queue length and maximum waiting time for ETC rates and number of manual tolls

Performance	ETC Rate	Number of Manual Tolls		
		1	2	3
Maximum Queue Length (ft)	25%	56,400	800	325
	40%	28,150	350	225
	50%	12,150	275	150
	60%	1,425	200	125
	80%	200	100	75
Maximum Waiting Time	25%	3 hrs 12 min	2 min 15 s	36 s
	40%	2 hrs 6 min	59 s	24 s
	50%	1 hr 4 min	44 s	16 s
	60%	8 min	33 s	14 s
	80%	1 min	14 s	8 s

4. CONCLUSION

In this study, conceptualization of traffic flow was investigated using projected traffic volumes for a proposed toll bridge in the eastern area of North Carolina. Toll plaza performance measures such as average queue length, average waiting time, maximum queue length, and maximum waiting time at the tolls were compared between two different types of representations of projected traffic volumes. Some other toll plaza designing factors such as lane selection options, electronic toll collection (ETC) rates, and number of manual tolls were combined with traffic flow to measure the specified toll performances. Finding appropriate values of input parameters for a traffic simulation model is always a challenge to simulation model builders as well as to traffic engineers. The comparison of performance measures between deterministic and probabilistic traffic flow can suggest a convenient way to resolve one of those complex problems. For generating traffic flow in a simulation model, deterministic traffic counts for a time period can be used as an input parameter into the model rather than considering a probabilistic distribution. This simplicity in designing the traffic creation module will be beneficial for users with less expertise in simulation modeling.

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BIOGRAPHICAL SKETCH

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