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

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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

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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 $(i, t, k, d, \omega, \tau)$ 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, ω is method of payment, τ 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 $\bar{h} > 0$. The following inverse-transform algorithm can be used to generate the vehicular headway times.

$$h = -\bar{h} \ln u \tag{1}$$

$$t_i = \sum_{1}^{i} h \tag{2}$$

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].

$$TLD_j = \frac{\Delta Q}{LC^{SF}} \tag{3}$$