MICROSCOPIC MODELING OF LANE SELECTION AND LANE-CHANGING AT TOLL PLAZAS

Sandeep Mudigonda (Corresponding Author)
Graduate Student
Department of Civil and Environmental Engineering
Rutgers University
623, Bowser Road,
Piscataway, NJ 08854
Phone: (732) 445-3162, Fax: (732) 445-0577, Email: sandeepm@eden.rutgers.edu

Bekir Bartin
Research Associate
Department of Civil and Environmental Engineering
Rutgers University
623, Bowser Road,
Piscataway, NJ 08854
Phone: (732) 445-3675, Fax: (732) 445-0577, Email: bbartin@rci.rutgers.edu

Kaan Ozbay
Professor
Department of Civil and Environmental Engineering
Rutgers University
623, Bowser Road,
Piscataway, NJ 08854
Phone: (732) 445-2792, Fax: (732) 445-0577, Email: kaan@rci.rutgers.edu

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ABSTRACT

The microscopic simulation of traffic operations at a toll plaza entails the detailed understanding of the driver behavior. The lane selection behavior of the driver involves complex inter-vehicle dynamics. This study involves the development of a new methodology for the microscopic simulation of toll plaza operations. Different driver dynamics such as the lane selection probability based on the approach and exit ramp of the driver, the queue length at each of the toll booths have been considered. The proposed model involves a utility-based heuristic for each lane at the toll plaza based on the factors stated above. The driver chooses the lane which maximizes his utility. The contribution of each of the factors to the individual driver’s utility is a function of his/her wait time at the toll plaza and the number of decisions the driver has already made to choose his/her target lane. The proposed model is validated for three toll plazas on the New Jersey Turnpike using a detailed vehicle transaction, service time and lane usage data. The novelty of the proposed approach is threefold: (1) the use of a validated toll plaza model developed in Paramics simulation software, (2) the use of the API feature of Paramics to simulate a realistic lane selection process of drivers at the toll plaza using a lane utility model, and (3) the use of actual vehicle demand data obtained from the electronic transaction data.

INTRODUCTION

Evaluation of traffic operations at toll plazas is a challenging task due to drivers' complex lane selection behavior and their interaction with other vehicles. There are several factors that influence drivers' lane selections at a toll plaza such as payment options, queue lengths, toll plaza configuration, etc. Especially, when toll plazas are located at separate locations away from the mainline - unlike barrier toll plazas - there are additional factors that should be considered which would likely influence drivers' lane selections.

Most of the macroscopic models are too aggregate to capture time-dependent changes in traffic patterns and to model various factors that affect drivers' lane changing and lane selection behavior.

Microscopic traffic simulation models have come to the fore with the increasing computational power of present-day 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.

The objective of this study is to investigate the factors that influence vehicles' lane selection at toll plazas. Three toll plazas are selected from New Jersey Turnpike (NJTPK) for our analyses, namely interchanges 13, 15W and 18W. A utility-based heuristic for the drivers' lane selection was developed and implemented in a microscopic simulation software of the selected toll plazas. The variables in the developed lane utility model reflect the location-specific and condition-specific factors that influence drivers' lane choices. The variables observed to be significant
on lane choices are but not limited to: (1) Approach ramp of the vehicle entering the toll plaza, (2) Exit ramp of the vehicle exiting the toll plaza, (3) Queue lengths at each lane at the toll plaza. Variables 1 and 2 are location-specific variables. Variable 3 is condition-specific and believed to influence drivers' lane choices at any given toll plaza. The addition of variable 1 or 2 depends on the geometric design of the toll plaza. It is shown in our analysis that although only variable 3 would be sufficient in the lane utility model to simulate barrier toll plazas (e.g. interchange 18W toll plaza), other type of toll plaza configurations (e.g. interchange 13 and 15W toll plazas) require additional variables (variable 1 or 2) in the utility model to ensure accurate representation of drivers' lane choices.

Paramics micro simulation software was used to develop simulation models of the selected toll plazas and to validate the lane utility model. Paramics is a widely used microscopic traffic simulation tool. The most important feature of Paramics is the ability of overriding or extending the default models such as car following, lane changing, route choice, etc. using its Application Programming Interface (API). This feature helps modelers to incorporate customized functionalities and test their own models.

The novelty of the proposed approach is threefold:

- The use of a validated toll plaza model developed in Paramics simulation software
- The use API feature of Paramics to simulate a realistic lane selection process of drivers at the toll plaza using a lane utility model.
- The use of actual vehicle demand data obtained from the electronic toll collection (ETC) dataset, provided by the New Jersey Turnpike Authority (NJTA).

The outline of the paper is as follows. Section 2 presents the previous studies that focused on toll plaza simulation. Section 3 describes the development of a toll plaza model and how to simulate it using Paramics API. Section 4 presents the simulation analysis and results of the case studies for the three selected toll plazas from NJTPK. The conclusions and future work are presented in Section 5.

LITERATURE REVIEW

Most of the available microscopic simulation software packages, including Paramics, do not have a built-in toll plaza model. Several researchers developed customized toll plaza simulation models. (1-11) A review of the previous studies aimed at developing toll plaza simulation models is described below.

Junga (1) developed a simulation model of a toll plaza in GPSS simulation package to evaluate the automatic vehicle identification technology. The lane selection mechanism was applied by assigning each vehicle to a set of lanes and vehicles would further choose from the lanes in the set based on the payment type of that lane.

Correa et al. (2) implemented an object-oriented simulation model (TOLLSIM) of a toll plaza in MODSIM III simulation language. The lane choice is based on shortest queue at the toll lanes.
Danko and Gulewicz (3) used a spreadsheet to model the toll plaza and calculated the throughput and queue lengths at the toll plaza.

Burris and Hildebrand (4) created a discrete-event microsimulation model to study the toll plaza at A. Murray MacKay Bridge at Halifax, Canada. Traffic demand was generated based on a negative exponential distribution. Vehicles' lane selection was based on a logistical routine that would take into account queue length, traffic volume, and proximity of the preferred payment-type lane. Various lane configuration scenarios were evaluated using this model.

Al Deek et al. (5) developed a toll plaza simulation model for the Holland East toll plaza, Orange County, Florida for different configurations and characteristics. The developed model had various inputs such as approach speed, acceleration, deceleration, etc. It would generate various measures of effectiveness such as throughput, queue length, average queue delay, maximum queue delay and total queue delay and lane utilization. The toll plaza geometry, number of lanes and the width were also a part of the input data. The lane changing percentage was assumed to be 100% in other words, if a vehicle is behind a slower moving vehicle, then that vehicle changes its lane. The reaction time was distributed uniformly between 0.4 s and 1.0 s. The arrival times were collected from field and generated using an empirical discrete distribution.

Astarita et al. (6) developed a much more complete toll plaza model. In addition to the car-following and gap-acceptance based lane-changing model, the authors defined a lower threshold, “hard wall”, at the toll plaza before which all the drivers would make appropriate lane changes to reach their destination toll plaza. The location of the “hard wall” was determined based on the aggressiveness of drivers. They also defined an upper threshold as the distance from the toll plaza below which drivers start their lane changing decision-making. Drivers would attribute some amount of utility for each tollbooth, which was based on the queue length and the number of lanes they had to cross to reach at a particular lane.

Chien et al. (7) studied the removal of toll plazas and changing the collection method for five toll plazas on the Garden State Parkway, New Jersey using a Paramics model to determine an optimal toll plaza configuration. They used the default lane changing behavior provided in the Paramics simulation engine.

Ceballos and Curtis (8) used the microscopic simulation model for toll plazas and parking exit plazas for the analysis of parking exit plazas at four different international airports across United States. VISSIM, a commercial microscopic traffic simulation software, was used for the simulation model. The authors also stated that the advantage of using microscopic simulation models for traffic simulation was that they can be integrated with rest of the network and analyze a more complete and systematic model.

Ozbay et al. (9) and Bartin et al. (10) developed a toll plaza model in Paramics that is integrated with the freeway model of NJTPK. It was shown in Ozbay et al. (9) that the default Paramics lane selection at toll plazas was substantially insufficient. Therefore, the default lane selection at toll plazas was improved using Paramics API. The authors developed a path-based lane choice model which takes into account the destination of the driver. The destination influences the lane choice of the driver in order to avoid unnecessary weaving after crossing the toll plaza. This information is known only at the entry toll plazas from the NJTPK transaction data.

Nezamuddin and Al-Deek (11) developed a toll plaza model for Holland Toll
Plaza on SR408, Orlando, Florida using Paramics Microsimulation software. The authors used the default features available in Paramics to model the toll plaza and validated the delays for the year 1998 and 2004. The toll plazas simulated for their study were barrier toll plazas.

Discussion

From the previous sub-section it can be observed that various researchers developed toll plaza simulation models which were developed either as a standalone model or built the model in commercial microscopic simulation software. In the standalone models the lane selection was based on queue length at the toll plaza, proximity of the preferred payment type, number of lane changes to be made, etc. The models built in commercial microscopic simulation software used a number of parameters provided by the default simulation engine in the software. However all of the developed models represent barrier-type toll plazas only.

In the case of NJTPK, as mentioned before, most of the toll plazas are not barrier toll plazas. They are connected to several ramps from different directions, thus increasing the complexity of the lane choice behavior. Moreover, since there is no built-in toll plaza model in any of the commercial simulators, the lane choice and driver behavior will be based only on the default lane-changing and car-following mechanisms. These default mechanisms can surely be modified using various parameters provided, but the drivers’ natural decision making process cannot be accurately captured.

As an extension of Ozbay et al. (9) and Bartin et al. (10) this study enhances the modeling of the decision making process of the drivers at the toll plaza. By the use of API feature of Paramics, positives from both the standalone models (natural decision making process) and the microscopic simulators (detailed car-following and gap acceptance models) are combined. As mentioned in the Introduction section of this paper, there are several variables that have to be taken into account in order to replicate drivers’ lane selection accurately in the simulation model. Most important variables are:

1. Approach ramp of vehicles at toll plaza: Drivers tend to use the closest toll lanes with respect to their current lanes. Depending on which ramp they approach the toll plaza from, the possibility of reaching a toll lane that is far from their current lane is lower. Figure 1 shows the schematics of the interchanges chosen for analyses in this study. For example, in Figure 1 vehicles coming from the north are likely to choose lanes that are on the right side of the toll plaza. Similarly, vehicles from the south are likely to stay on the left side of the toll plaza, where conditions permit. This stems from the fact that drivers try to avoid excessive weaving at the toll plaza entrance where vehicles access the plaza from different directions.
Figure 1. Schematics of Selected Toll Plazas in NJTPK

(2) Exit ramp of vehicles after exiting toll plaza: Drivers tend to select lanes that are close to their exit locations to avoid excessive weaving at the downstream of the toll plaza. However, this is not as significant a variable as the approach ramp probability, because drivers have a better view of the relative position of other vehicles when they leave the plaza as opposed to approaching the plaza from different ramps.

(3) Queue Lengths at toll plaza: It could be claimed that drivers choose shorter queues to reduce their wait times at the toll plaza. They could possibly change their decisions based on the perceived wait times.

All of these variables, aside from the usual parameters such as next lanes, mean target headway, mean reaction time, etc., have been incorporated into the current model.

1 Lane numbers start at 1 at the top, and are in the increasing order to the bottom
DEVELOPMENT OF THE ENHANCED TOLL PLAZA MODEL

Toll Plaza Model Inputs
The inputs required to model the toll plaza in Paramics are described below.

Toll Plaza Geometry
Satellite images available on the Internet were used as overlays to procure the information about the number of lanes in the toll plazas and the geometry of each toll plaza area.

Toll Plaza Configuration
There are only two user and lane types at the NJTPK, namely E-ZPass and manual (cash) toll payment. The number of lanes dedicated to each payment type was obtained from the NJTA.

Origin-Destination Demand Matrix
The ETC dataset provided by the NJTA were used to create origin-destination (OD) demand matrix.

It should be noted that NJTPK is a closed system tolled highway. Vehicles enter the mainline through an entry toll plaza at an interchange located separately from the mainline. Similarly, they exit the highway through an exit toll plaza, each interchange therefore has entry and exit toll lanes.

The ETC dataset consists of the individual vehicle-by-vehicle entry and exit time data. It also consists of the information regarding the lane through which each vehicle was processed (both E-ZPass and Cash users). From this dataset the number of E-ZPass and Cash users was available from January 2004 to June 2008.

Types and Classes of Vehicles
Table 1 shows a representative (for Interchange 13) breakdown of daily volume based on vehicle classes and payment types. Vehicle class 1 defines a passenger car, vehicle classes 2 to 6 define trucks with increasing axle-numbers and B2 and B3 define buses with 2-axles and 3-axles, respectively. It can be seen that the overall E-ZPass market share for a typical day was 70%. Each payment type under a vehicle class was considered as a different vehicle type.

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Volume</th>
<th>Cash</th>
<th>E-ZPass</th>
<th>E-ZPass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34,650</td>
<td>10,726</td>
<td>23,924</td>
<td>69.0%</td>
</tr>
<tr>
<td>2</td>
<td>2,080</td>
<td>476</td>
<td>1,604</td>
<td>77.1%</td>
</tr>
<tr>
<td>3</td>
<td>1,019</td>
<td>219</td>
<td>800</td>
<td>78.5%</td>
</tr>
<tr>
<td>4</td>
<td>351</td>
<td>46</td>
<td>305</td>
<td>86.9%</td>
</tr>
<tr>
<td>5</td>
<td>4,034</td>
<td>1,132</td>
<td>2,902</td>
<td>71.9%</td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>5</td>
<td>31</td>
<td>86.1%</td>
</tr>
<tr>
<td>B2 &amp; B3</td>
<td>324</td>
<td>14</td>
<td>310</td>
<td>95.7%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>42,494</td>
<td>12,618</td>
<td>29,876</td>
<td></td>
</tr>
</tbody>
</table>
Lane Probabilities based on the Approach and Exit Ramps

As mentioned earlier, drivers' lane selection depends heavily on which ramp (northbound or southbound direction) from which they are approaching the toll plaza as well as which direction they are headed to after the toll plaza.

Lane probabilities based on the approach ramp can be obtained from the ETC dataset. Since each vehicle's entry and exit interchanges were available in the ETC dataset, at any given toll plaza we could extract vehicles' origin interchanges. The NJTPK is a closed system in such a way that there is only one path between any two interchanges. Thus the knowledge of vehicles origin, payment type (Cash or E-ZPass) and their lanes at the toll plaza enables the determination of the proportion of vehicles of a payment type choosing a particular lane based on which ramp (northbound or southbound) they are approaching the toll plaza from. For example, Table 3a shows the drivers' probability of selection of each lane based on their approach direction for interchange 13.

It should be noted that within each column of Table 3a, the sum of lane selection probabilities for cash lanes and E-ZPass lanes is equal to 1.0 separately. For example, if a cash vehicle is coming from the northbound direction, its probability of selecting lane 1 is 0.072, whereas its probability of selecting lane 10, which is closer, is 0.138. The probabilities for all cash lanes (lane#1,2,5,6,7,10,11,12,13) add up to 1.0 for each direction. Similarly, for an E-ZPass vehicle, probability of selecting lane 9 is higher than the probability of selecting lane 3, located on the opposite side of the plaza.

Lane probabilities based on the exit direction, on the other hand, are not readily available from the ETC dataset. This is because vehicles are out of the NJTPK system after crossing the toll plaza and the information as to which exit ramps they choose are not revealed in the transaction data. Therefore, the authors collected the percentage of vehicles heading towards either of the exit ramps from each lane for the interchange in question.

Service Times

Data collected from the exit toll plaza at interchange 16E on June 20, 2006, June 27, 2006 and July 5, 2006 were used to collect the exit service time data at the toll plaza. It is assumed that the Interchange 13 would have similar service time distribution as Interchange 16E. Toll processing time of 177 exiting passenger cars and 44 exiting trucks and buses were extracted. Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) goodness-of-fit tests show that toll processing times follow a lognormal probability distribution for $\alpha = 0.05$. Table 2 shows the summary of goodness of fit analysis. These service times were incorporated into the toll plaza model using the API capability in Paramics, thus obtaining a more representative toll plaza model.

Since each vehicle's entry and exit interchanges were available in the ETC dataset, at given toll plaza we could extract their origin, thus determine which ramp (northbound or southbound) they are approaching the toll plaza from.
Table 2 Goodness of Fit Results for Exit Toll Service Times

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>Mean (sec)</th>
<th>Std Dev (sec)</th>
<th>KS Test Statistics</th>
<th>AD Test Statistics</th>
<th>Reject Lognormal at α = 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars 177</td>
<td>17.90</td>
<td>12.69</td>
<td>0.0491</td>
<td>0.6153</td>
<td>No</td>
</tr>
<tr>
<td>Trucks &amp; Buses 44</td>
<td>27.57</td>
<td>11.85</td>
<td>0.0894</td>
<td>0.4401</td>
<td>No</td>
</tr>
</tbody>
</table>

**Paramics Implementation of the Toll Plaza Model**

As mentioned earlier, Paramics does not have a default model for toll plaza operations. Although the geometry of a toll plaza can be generated in Paramics, the complex lane changing and selection behavior at these locations cannot be modeled using Paramics’ default models. However, Paramics allows users to customize vehicles’ behavior using its API feature. In other words, using the C++ programming language, users can modify the lane changing, car following and other dynamics of traffic flow.

This section explains the use of Paramics API to enforce a more realistic lane selection based on a lane utility model. The lane utility model explained in this section is an extension to the authors’ earlier work on toll plaza simulation (9, 10).

There are three significant variables that influence drivers’ lane choices, where applicable: (1) Approach ramps they come from (2) The exit ramps they select after the plaza and (3) Queue lengths at the toll plaza.

Therefore, the utility of a given lane $i$ can be modeled as a linear function shown below:

$$U_i = \alpha^e p^e_i + \alpha^x p^x_i + \alpha^q p^q_i,$$  

Where, $p^e_i$, $p^x_i$, $p^q_i$ are the probabilities of choosing lane $i$ depending on the approach ramp ($e$), exit direction ($x$) and the queue conditions ($q$) respectively, and $\alpha^e$, $\alpha^x$, $\alpha^q$ are the weights for each variable where $\alpha^e + \alpha^x + \alpha^q = 1$.

When a vehicle approaches the toll plaza, the driver makes a decision about which lane to choose based on the lane utilities and selects the lane which maximizes his utility, $\max(U_i)$ where $i = 1, ..., n$ lanes. Then, s/he makes the next lane decision with this lane as the target lane. As for the weights, the default values for $\alpha^e$, $\alpha^x$, $\alpha^q$ were assumed as 0.4, 0.5 and 0.1, respectively. As mentioned earlier, drivers were assumed to give more weight to the direction they are coming from than the direction they are headed to after the toll plaza.

The values of the coefficients in the calculation of lane utility are based on the
authors' judgment and the relative importance of each variable in the lane selection. These values can be estimated using, for instance, multinomial logit or probit model. But for this estimation the conditional distribution of probability of a vehicle choosing a lane given the approach ramp, exit ramp and queue at each lane of the toll plaza is necessary. In order to collect this data, a high resolution camera placed at a high elevation for a much wider view (as compared to the video data available) is required. The values of these weights can be estimated for barrier tolls where the lane selection is assumed to be based only on the queues.

After the driver makes his/her lane choice, s/he reconsiders this decision continuously as s/he arrives at the toll plaza, i.e. calculates \( \max(U_i) \) at each time step. However, the driver is allowed to change his/her first choice only if the percent difference between the utility of the new choice and the first choice is greater than a predetermined threshold, \( \delta^w \). This threshold is assumed to be 20% in our model.

Also, as the simulation progresses, the Paramics API keeps the record of the wait time of each vehicle in the network. It is assumed that if the wait time of a vehicle is greater than a predetermined threshold \( (\delta^w) \), it is either stuck in congestion or in a toll queue. Given these assumed traffic conditions, it is also assumed that the driver will not, in reality, make drastic lane changes, by recalculating \( \max(U_i) \). This assumption is made to prevent excessive weaving upstream of the toll plaza and to model the drivers’ impatience. Therefore, in the recalculation of the driver’s utility, the vehicles’ lane range is restricted to the current lane and two neighboring lanes, one on the left and one on the right. For example, if the driver’s target lane is lane 4 at first and the conditions change before s/he reaches the toll plaza, and another toll lane seems more “attractive”, Paramics API checks if the wait time is greater than \( \delta^w \). If it is then the driver is allowed to recalculate \( \max(U_i) \) only for \( i = 3, 4, 5 \). It is to be noted that the lane range is three lanes because usually the number of lanes of the same payment type grouped together is three among the toll plazas used in this study.

The lane choice decision process during simulation of toll plaza model is shown in Figure 2.

Furthermore, the weights of each variable, namely \( \alpha^e \), \( \alpha^x \), \( \alpha^q \) are subject to change based on the wait times of vehicles. In order to model the drivers’ awareness of the prevailing traffic conditions the authors assume that the more the vehicle waits at the toll plaza, the weight for queue length \( \alpha^q \) increases, and \( \alpha^e \) and \( \alpha^x \) decreases at the same time satisfying the condition \( \alpha^e + \alpha^x + \alpha^q = 1 \). For example, if the vehicle waits for 10 seconds, then \( \alpha^q \) increases to 0.6 from 0.5, while \( \alpha^e \) decreases to 0.35 and \( \alpha^x \) decreases to 0.05. This adjustment of weights is performed after every 10 second increment of wait time at the toll plaza. These increments are based on the authors’ engineering judgment. However, more realistic values could be obtained from a multinomial probit or logit discrete choice model if detailed data were available.
CASE STUDIES AND RESULTS
In order to validate the proposed lane selection algorithm, three case studies at
three different toll plazas, namely interchanges 13, 15W and 18W of NJTPK (see Figure 1) are selected. Each case study involves a different toll plaza configuration. The first toll plaza, interchange 13, consists of two approach and two exit ramps. The second toll plaza, interchange 15W, consists of two approach ramps and one exit ramp. The third toll plaza, interchange 18W, is a barrier toll plaza located on the mainline.

Case Study 1: Toll Plaza at Interchange 13

The toll plaza at interchange 13 has approach ramps from both the northbound and southbound directions as shown in Figure 1. After exiting the toll plaza drivers can either take the ramp to reach the local roads in the town of Elizabeth (exit 1) or take the ramp towards the Goethals Bridge (exit 2). Hence in this case both weights for approach ($\alpha^a > 0$) and exit ($\alpha^e > 0$) are initially greater than zero to consider both the lane selection probability due to approach and exit in the decision process.

The OD demand was extracted for October 9, 2007, which had one of the highest demand at Interchange 13 over the year. The hourly variation of traffic exiting Interchange 13 on the selected day is shown in Figure 3.

Table 3a shows the probability of drivers' of a payment type of selecting each lane based on their approach ramp for the toll plaza at interchange 13 from the

Figure 3 Hourly Traffic Volume at Interchange 13 Exit Toll Plaza for October 9, 2007

It should be noted that only the toll plazas where drivers exit the NJTPK is considered in our analyses.
Table 3a shows the lane probabilities based on the exit direction on May 30, 2008 between 9 a.m. and 1 p.m. for toll plaza at interchange 13.

Table 3 (a) Lane Selection Probabilities Based on Approach Ramp for Interchange 13

<table>
<thead>
<tr>
<th>Lane No</th>
<th>SB</th>
<th>NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.182</td>
<td>0.072</td>
</tr>
<tr>
<td>2</td>
<td>0.231</td>
<td>0.068</td>
</tr>
<tr>
<td>3</td>
<td>0.273</td>
<td>0.109</td>
</tr>
<tr>
<td>4</td>
<td>0.293</td>
<td>0.274</td>
</tr>
<tr>
<td>5</td>
<td>0.194</td>
<td>0.145</td>
</tr>
<tr>
<td>6</td>
<td>0.153</td>
<td>0.189</td>
</tr>
<tr>
<td>7</td>
<td>0.113</td>
<td>0.217</td>
</tr>
<tr>
<td>8</td>
<td>0.275</td>
<td>0.277</td>
</tr>
<tr>
<td>9</td>
<td>0.160</td>
<td>0.340</td>
</tr>
<tr>
<td>10</td>
<td>0.051</td>
<td>0.138</td>
</tr>
<tr>
<td>11</td>
<td>0.018</td>
<td>0.043</td>
</tr>
<tr>
<td>12</td>
<td>0.058</td>
<td>0.127</td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 3 (b) Lane Selection Probabilities Based on Exit Direction for Interchange 13

<table>
<thead>
<tr>
<th>Lane No</th>
<th>Elizabeth</th>
<th>Goethals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.238</td>
<td>0.109</td>
</tr>
<tr>
<td>2</td>
<td>0.454</td>
<td>0.204</td>
</tr>
<tr>
<td>3</td>
<td>0.619</td>
<td>0.104</td>
</tr>
<tr>
<td>4</td>
<td>0.307</td>
<td>0.160</td>
</tr>
<tr>
<td>5</td>
<td>0.159</td>
<td>0.234</td>
</tr>
<tr>
<td>6</td>
<td>0.088</td>
<td>0.153</td>
</tr>
<tr>
<td>7</td>
<td>0.062</td>
<td>0.299</td>
</tr>
<tr>
<td>8</td>
<td>0.042</td>
<td>0.325</td>
</tr>
<tr>
<td>9</td>
<td>0.032</td>
<td>0.411</td>
</tr>
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<td>10</td>
<td>0.000†</td>
<td>0.000†</td>
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<tr>
<td>11</td>
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</tr>
<tr>
<td>13</td>
<td>0.000†</td>
<td>0.000†</td>
</tr>
</tbody>
</table>

†No vehicles were detected at these lanes at the time of the data collection.

To validate the model in case study 1, the lane usage proportions (averaged over seven simulation runs at 10% significance) are compared for all the lanes and the correlation is calculated between the lane usage proportions of observed, simulated, and simulations based on queue only. The simulated lane usage proportions are an average of seven simulation runs (Figure 4) and a correlation of 0.976 was obtained. Figure 4 also shows the lane usage proportions for simulation runs using lane choice solely based on queue. These simulation runs were performed to compare the lane selection process described by the proposed model and when the drivers’ decision making process is based only on the queue length at each toll booth. A correlation of
0.84 was obtained between lane usage proportions of real-world observations and simulations solely based on queue.

Figure 4 Comparison of Lane Usage for Toll Plaza at Interchange 13

Case Study 2: Toll Plaza at Interchange 15W
The toll plaza at interchange 15W has approach ramps from both the northbound and the southbound directions. After exiting the toll plaza the drivers have to take a single ramp to reach the local roads (see Figure 1). Hence in this case weight for approach ($\alpha^e>0$) is greater than zero initially whereas weight for exit ($\alpha^x=0$) is zero. Since there is no choice of exit ramp for the driver, according to the model, the decision of exit ramp will not affect the lane choice at the toll plaza.

The OD demand was extracted for April 27, 2007, which had one of the highest demands at Interchange 15W. Table 4 shows the drivers’ probability of selection of each lane based on their approach ramp for toll plaza at interchange 15W.

Table 4 Lane Selection Probabilities Based on Approach Ramp for Interchange 15W

<table>
<thead>
<tr>
<th>Lane No</th>
<th>SB</th>
<th>NB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.578</td>
<td>0.064</td>
</tr>
<tr>
<td>2</td>
<td>0.674</td>
<td>0.184</td>
</tr>
<tr>
<td>3</td>
<td>0.317</td>
<td>0.458</td>
</tr>
<tr>
<td>4</td>
<td>0.218</td>
<td>0.176</td>
</tr>
<tr>
<td>5</td>
<td>0.099</td>
<td>0.193</td>
</tr>
<tr>
<td>6</td>
<td>0.055</td>
<td>0.162</td>
</tr>
<tr>
<td>7</td>
<td>0.050</td>
<td>0.405</td>
</tr>
<tr>
<td>8</td>
<td>0.007</td>
<td>0.287</td>
</tr>
<tr>
<td>9</td>
<td>0.002</td>
<td>0.071</td>
</tr>
</tbody>
</table>
To validate the simulation model of this case study, the lane usage proportions (averaged over seven simulation runs at 10% significance) are compared for all the lanes and the correlation coefficient is calculated between the simulated and observed lane usage proportions. The simulated lane usage proportions are an average of seven simulation runs (Figure 5) and a correlation of 0.898 was obtained. Figure 5 also shows the lane usage proportions for simulation runs using lane choice solely based on queue. A correlation of 0.13 was obtained between lane usage proportions of real-world observations and simulations solely based on queue length.

![Figure 5 Comparison of Lane Usage for Toll Plaza at Interchange 15W](image)

**Case Study 3: Toll Plaza at Interchange 18W**

The toll plaza at interchange 18W does not have any approach ramps or exit ramps since it is a barrier toll (see Figure 1). Hence in this case weight for approach (α^e=0) and weight for exit (α^x=0) are both zero. Since there is no choice of exit or approach ramps for the driver, according to the model, the decision of exit ramp or approach ramp will not affect the lane choice at the toll plaza. It is only the queue length that is expected to determine the lane choice behavior at the toll plaza.

The OD demand was extracted for April 27, 2007, which had one of the highest demands at Interchange 18W.

To validate the simulation model of this toll plaza, the lane usage proportions (averaged over seven simulation runs at 10% significance) are compared for all the
lanes and the correlation coefficient is calculated between the simulated and observed lane usage proportions. The simulated lane usage proportions are an average of seven simulation runs (Figure 6) and a correlation of 0.623 between observed and simulated values was obtained.

![Figure 6 Comparison of Lane Usage for Toll Plaza at Interchange 18W](image)

**Discussion of Results**

The results of the case studies used to validate the proposed toll plaza lane choice algorithm were promising as shown in the previous sub-sections. In the case of toll plazas at interchange 13 and 15W the correlation of 0.976 and 0.898, between the simulated and observed lane usage, respectively, were obtained. A correlation of 0.84 and 0.13 respectively between lane usage proportions of observed and simulations with lane choice solely based on queue length were obtained. Only in the case of the toll plaza at interchange 18W the correlation was 0.623. The results in these case studies are found to be promising, based on the correlations and lane usage proportions. Thus the hypothesis that the drivers’ lane selection process does not only involve the length of the queue at the toll booths but also additional factors such as the geometry of the approach ramp and exit ramp, driver’s wait time (impatience) is supported by these results. These additional factors along with the queue at each toll booth have significant effects on the utility of the lane chosen by the driver given his/her approach and exit ramps. It is to be noted that the authors in a previous study (9) have compared the lane selection using default parameters in Paramics and showed that the results based on these default values are not satisfactory.

In the case of 18W, since there are no approach or exit lane probabilities, it might appear that only the queue at each toll booth influences the driver’s lane
selection. However, there are other exogenous factors that enter into the decision process. It can be seen in Figure 6 that the lane usage of lane 1 was much higher than the observed lane usage. In reality though there are no approach and exit ramps at 18W, the drivers actually select their lanes based on some unknown probability based on the lane through which they enter. The source of existence of this lane choice probability is not very clear. It is the authors’ opinion that the presence of lane 2, which is an E-ZPass lane, strongly deters the drivers from choosing the lane 1 since they would have to merge with the E-ZPass vehicles that have higher speed after exiting the toll plaza.

CONCLUSIONS AND FUTURE WORK

In this study a new utility-based heuristic lane selection algorithm at the toll plaza was developed, implemented and tested in Paramics. The algorithm is based on the idea that the driver chooses a particular lane at a toll plaza based not only on the queue at the lane but also the approach and exit ramps. Lane selection is performed by the maximization of utility of the lanes at the toll plaza calculated by using the lane choice probabilities based on approach and exit ramps, and queue at each lane. The contribution of each of these factors on the utility of each lane is dependent on the wait time of the driver and the number of times s/he has already chosen his target lane. The advantage of this modeling approach is two-fold. Firstly, use of Paramics ensures a detailed car-following and gap acceptance mechanism as an integral part of the model. Secondly, the algorithm mimics the natural decision making process of the driver, which is not available in Paramics due to the absence of a built-in toll plaza model.

The algorithm was validated using case studies at toll plaza located at three interchanges on the NJTPK, namely interchange 13, 15W and 18W. The observed and simulated lane usage proportions were compared as shown in Figure 4, Figure 5 and Figure 6. The correlation coefficients were 0.976, 0.898 and 0.623 for interchanges 13, 15W and 18W respectively. Figure 4 and Figure 5 also show the lane usage proportions of simulation runs using lane choice based solely on queue length for interchange 13 and 15W which have approach and/or exit ramps. Correlations of 0.84 and 0.13, respectively, clearly show that there are other factors influencing the drivers’ natural lane selection process aside from queue length as claimed in the standalone models discussed earlier (1-3, 5). It was found that there is some “pseudo”-lane selection probability based on entering lane of the drivers even in the absence of approach and exit toll ramps. Also, there are some exogenous factors such as presence of a different transaction type between the current and target position of the driver that influence the lane selection behavior of the driver.

As mentioned earlier, the estimation of parameters in the lane selection utility model using multinomial probit or logit models is difficult for toll plazas with multiple approach and exit ramps. This is due to the difficulty in collecting of such data collection that requires tracking of vehicles over a long space. However, for future analysis, we will estimate a utility model that is based on queue length and exit ramps using the available video data.
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REFERENCES