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Microscopic Simulation of Toll Plaza Safety and Operations

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***Abstract*—**The use of microscopic traffic simulation in evaluating the operational and safety conditions at toll plazas is demonstrated. Two toll plazas in New Jersey are selected as case studies and were developed and validated in Paramics traffic simulation software. In order to simulate drivers' lane selection behavior in Paramics, a utility-based lane selection approach is implemented in Paramics Application Programming Interface (API). For each vehicle approaching the toll plaza, a utility value is assigned to each toll lane by taking into account the factors that are likely to impact drivers' lane selection behavior, such as approach lane, exit lane and queue lengths. The results demonstrate that similar operational conditions, such as lane-by-lane toll plaza traffic volume can be attained using this approach. In addition, assessment of safety at toll plazas is conducted via a surrogate safety measure. In particular, the crash index (CI), an improved surrogate measure of time-to-collision (TTC), which reflects the severity of a crash is used in the simulation analyses. The results indicate that the spatial and temporal frequency of observed crashes can be simulated using the proposed methodology. Further analyses can be conducted to evaluate and compare various different operational decisions and safety measures using microscopic simulation models.

***Keywords*—**Microscopic simulation, toll plaza, surrogate safety, application programming interface.

I. Introduction

TOLL plazas are essential parts of turnpike systems, bridges and tunnels as they are currently the only means of collecting user fees for utilizing the roadway infrastructure. A toll plaza differs from other highway components because of its unique operational features. There are three types of toll plazas: mainline barrier toll plazas, entry or exit toll plazas at ramps, and express toll plazas without toll booths that are located either on mainlines or ramps. Toll collection technologies include cash receipts, automatic coin operated machines and electronic toll collection (ETC).

The main concerns regarding toll plazas are that they create congestion because vehicles have to slow down or stop to pay tolls, which in turn increases vehicle operating costs and adversely affect air quality, and that they are high accident prone locations.

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Toll plaza delays are mainly caused by the transaction times to pay tolls. There are many conflict points that exist upstream and downstream of a toll plaza. These conflict points not only cause delays because vehicles slow down to avoid these conflicts, but also pose as significant safety risks.

Analyzing toll plaza traffic operations are often cumbersome as a result of drivers' intricate lane selection and lane changing decisions, especially when toll plazas are located at separate locations away from the mainline - unlike mainline barrier toll plazas. There are several factors that are likely to impact drivers' lane selection at a toll plaza, among which are payment options, i.e. cash, electronic payment, exact change, queue lengths and toll plaza configuration, e.g. barrier vs. non-barrier toll plazas [1].

Because there is no closed form solution to the stochastic nature of the toll plaza operations, microscopic traffic simulation tools are often utilized to determine the effectiveness of various operational and design scenarios in terms of vehicular delays, provided that the simulation models are validated and calibrated correctly.

Although microscopic traffic simulation is favored extensively for assessing the efficiency of various components of traffic networks, there is a limited number of studies in the literature that have focused on toll plaza simulation modeling. These studies are presented in the next section. Moreover, despite the fact that traffic safety at toll plazas is a well-known problem, there are no studies that deal with the evaluation of safety measures at toll plazas. Common practice in safety evaluations are generally qualitative and based on engineering and expert judgment. Traditional methods such as statistical models and before-after comparisons have many drawbacks due to the limited time periods, sample size problems and reporting errors. The advance of traffic conflicts technique and micro-simulation method together offers a potentially innovative way for conducting safety assessment of traffic systems even before safety improvements are implemented [2].

The objective of this study is to use microscopic traffic simulation for evaluating operational and safety decisions at toll plazas. Two toll plazas in New Jersey are selected as case studies.

Paramics simulation software was used to develop simulation models of the selected toll plazas and to validate the lane utility model. The novelty of this study can be listed as follows:

1. Validated toll plaza models developed in Paramics.
2. The use Application Programming Interface (API) feature of Paramics to develop a valid toll lane selection process.

3. The use actual electronic vehicle transaction dataset for the selected toll plazas.
4. Improved safety analysis based on the latest literature on surrogate safety measures using microscopic simulation.
5. The use of Paramics API in estimating vehicle conflicts in the current and the proposed designs. Paramics API can control every vehicle during the simulation, record their speed, acceleration, and lane changing/ car following behavior. Using these microscopic traffic measures at each time step, vehicle conflicts can be estimated for the selected toll plazas.

II. Related Work

Most available microscopic simulation software packages do not have a built-in toll plaza model. Several researchers developed customized toll plaza simulation models.

Junga [3] 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. [4] 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.

Burris and Hildebrand [5] developed a discrete-event micro simulation model of the toll plaza at A. Murray MacKay Bridge at Halifax, Canada to determine the impact of ETC. The developed model could simulate various toll plaza configurations by taking into account different payment methods, vehicle types and lane usage. They generated traffic demands based on a negative exponential distribution. Effectiveness of various toll lane scenarios in terms of payment types were evaluated using a logistical routine that takes into account queue lengths, traffic volume, and proximity of the preferred payment-type lane.

Chien et al. [6] developed the simulation models of five toll plazas located at the Garden State Parkway in New Jersey using the Paramics simulation software. They estimated the impact of various payment methods to determine an optimal toll plaza configuration. In this study, the default lane changing behavior embedded in the Paramics simulation software was utilized.

Nezamuddin and Al-Deek [7] developed a toll plaza model of the Holland Toll Plaza on SR408, Orlando, Florida in Paramics to validate the delays for the year 1998 and 2004. The simulated toll plazas were mainline barrier toll plazas and, similar to the analysis in Chien et al. [6], they utilized the default lane changing behavior of the Paramics software.

Ozbay et al. [8] and Bartin et al. [9] developed a toll plaza model in Paramics that is integrated with the freeway model of New Jersey Turnpike (NJTPK). It was shown in Ozbay et al. [8] that the default Paramics lane selection at toll plazas was not sufficient. 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 ramp drivers select after crossing toll plaza.

III. Paramics Implementation of the Toll Plaza Model

Most toll plaza simulation models in the literature were built in available off-the-shelf commercial microscopic simulation software tools, and the toll plaza operations were simulated by using a number of parameters available in the default simulation engine in the software.

Unfortunately, the default lane changing behavior of simulation tools are not effective in simulating non-barrier type toll plazas, meaning they are connected to several ramps to and from different directions of the mainline, as shown in the top schematics of Fig. 1.

As an extension of Ozbay et al. [8] and Bartin et al. [9], Mudigonda et al. [1] enhanced the modeling of the decision making process of drivers at a toll plaza. This section presents 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 was formulated in Mudigonda et al. [1]. The variables that are likely to impact drivers' lane selection accurately in the simulation model were listed in Mudigonda et al. [1] as:

(i) **Approach ramp**: Drivers are assumed to favor the closest toll lanes with respect to their approach ramp. Due to the fact that drivers would avoid excessive weaving at the toll plaza which would result in a high conflict rate with other vehicles, they are expected to avoid selecting a toll lane far from their current lane. For example, in Fig. 1 drivers coming from entry ramp 1 are likely to select the toll lanes located on the right side of the toll plaza. Similarly, drivers from entry ramp 2 would probably stay on the left side of the toll plaza, where conditions permit.

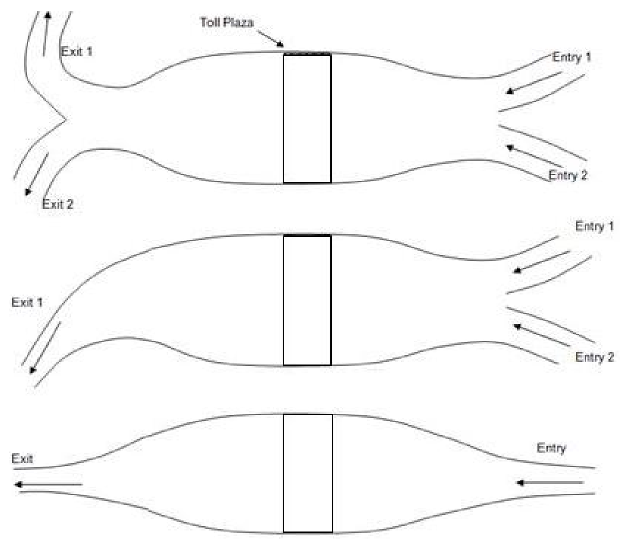

Fig. 1 Example toll plaza schematics

(ii) **Exit ramp**: Similarly, after the tolls, drivers are expected to avoid conflicting movements with other vehicles and are likely to select the toll lanes closer to their exit ramps.

(iii) **Queue Lengths**: It can be asserted that drivers are likely to choose toll lanes with shorter queues to minimize their wait times.

As mentioned earlier, the underlying lane selection behavior embedded in most microscopic traffic simulation tools, including Paramics, is not effective in simulating non-barrier toll plazas. However, the advantage of Paramics is its API feature, coded in the C++ programming language, that can be used to customize each vehicle's lane changing and lane selection decisions. Drivers' lane choice at the toll plaza is simulated in Paramics API according to the flowchart shown in Fig. 2.

Using the above listed three significant variables that are most probably influence drivers' lane choices, the utility of a given lane i can be modeled as a linear function shown below:

$$U_i = \propto^e p_i^e + \propto^x p_i^x + \propto^q p_i^q \tag{1}$$

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

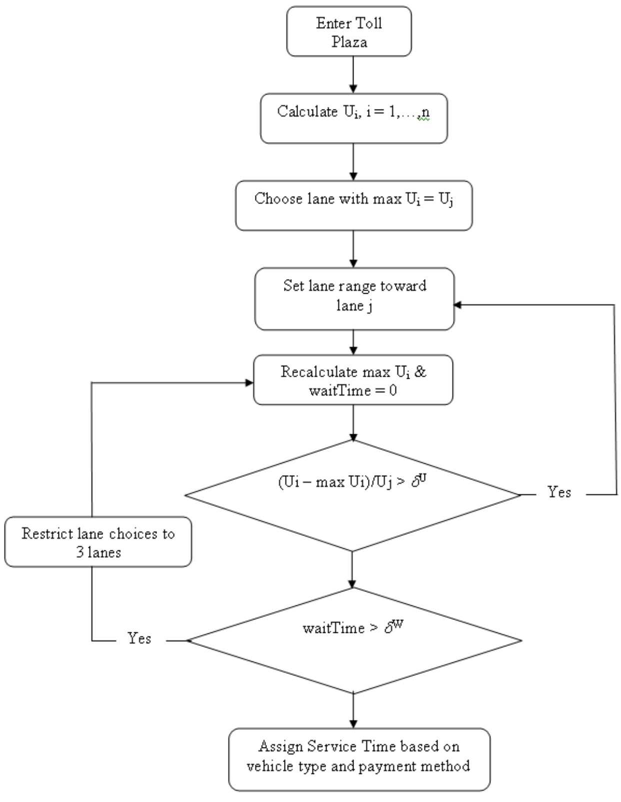

Fig. 2 Flowchart of the proposed toll plaza simulation model

Approaching a toll plaza, drivers make a decision about which lane to choose based on the lane utilities and pick the lane which maximizes their utility, $\max(U_i)$ where $i = 1 \ldots. n$ lanes. Then, they make the next lane decision with this lane as the target lane. As to the weights, the default values $\propto^e$, $\propto^x$ and $\propto^q$ were assumed as 0.4, 0.1 and 0.5, respectively. Drivers can be assumed to place more weight to the direction they are coming from than the direction they are headed to after the toll plaza [1].

It should be noted that the coefficients $\propto^e$, $\propto^x$ and $\propto^q$will vary across different toll plazas. As mentioned in Mudigonda et al. [1], their values can be estimated by known statistical techniques e.g. multinomial logit or probit using toll plaza specific data. However, collecting and processing such detailed data is not always be possible. Therefore, in this study we opt to select their values based on our familiarity with the simulated toll plazas and their assumed relative importance in drivers' lane selection decisions. In addition, the coefficients $\propto^e$, $\propto^x$ and $\propto^q$ are updated based on the recorded wait time of each driver. It is assumed that as the wait time of a driver increases, so does its weight for queue length $\propto^q$. As a result, both $\propto^e$and $\propto^x$ decrease at the same time while keeping the condition $\propto^e + \propto^x + \propto^q = 1$. Also, it is assumed that drivers continuously update their selected toll lane until arriving at the tolls, meaning they recalculate $\max(U_i)$ at each time step. In order to prevent excessive lane changing, drivers are allowed to update their lane choice only if the percentage difference between the original utility and the new one is greater than a fixed threshold, δ^u. In addition, in order to prevent drivers from making drastic lane changes at each time step it calculates the utility, each vehicle's lane range is restricted to the current lane and two neighboring lanes.

Details of the developed lane utility model can be found in Mudigonda et al. [1].

IV. Surrogate Safety Measures

Traffic safety analysis based on micro-simulation approach has gained increasing attention in recent years. Darzentas et al. [10] had initially recognized this idea. With the development of more advanced computing techniques, many powerful micro-simulators have now become available, by providing the possibility of using simulation models for different purposes. However, since micro-simulators that are currently available are developed only to represent normative driver behavior, they have many restrictions for traffic safety analysis. Evaluation of safety measures demands more complex driver behavior models with a higher level of performance variances in driving performance due to the errors caused by the driver's perception, decision-making and reaction processes. In spite of these limitations, Archer et al. [11] gave a description of the potential of micro-simulation modeling for traffic safety assessment. Many researchers recently attempted to explore the potential of simulated-based safety evaluation, which can provide valuable insights into the relative safety impacts brought about by different traffic countermeasures. The general concept used in these studies is based on the traffic conflict technique. Different conflict indicators were proposed or extended as safety measures and then simulation models were used to quantify them.

Among the proposed simulation-based safety measures, TTC is the most commonly used measure. TTC has been widely regarded by Federal Highway Administration (FHWA) to be a potential indicator to be used as surrogate safety measure [12].

TTC is formulized as:

$$TTC = \frac{D}{\Delta V} \tag{2}$$

where, *D*= relative distance (m), and *ΔV*= relative speed of two vehicles (m/s). TTC refers to the time it would take a following vehicle to collide with the leading vehicle, if neither of them changes their speeds.

The equation above simply assumes that the following vehicle just keeps its speed while ignoring the actual acceleration or deceleration until the collision has occurred. It is clear that only if the speed of the following vehicle is larger than that of the leading vehicle, a collision will happen. This assumption disregards many potential conflicts because of the discrepancies in acceleration or deceleration. Whether or not a conflict could occur is based on the trajectory parameters of the two vehicles following each other. Trajectory parameters include their relative distance, relative speed and relative acceleration. Equations (3) and (4) are used to determine if a conflict would occur based on the trajectory parameters.

$$V_F t + \frac{1}{2} a_F t^2 \geq D + V_L t + \frac{1}{2} a_L t^2 \tag{3}$$

$$\frac{1}{2} \Delta a t^2 + \Delta V t - D \geq 0 \tag{4}$$

where, V_F: Following vehicle's speed (m/s), V_L: Leading vehicle's speed (m/s), a_F: Following vehicle's acceleration (m/s^2), a_L: Leading vehicle's acceleration (m/s^2), ΔV: Relative speed (m/s), $\Delta V = V_F - V_L$, Δa: Relative Acceleration (m/s^2), $\Delta a = a_F - a_L$, D: Initial relative Distance (m), and t: Time (s).

Equations (5)-(7) present a decision criteria that calculates the minimum *TTC* for a rear-end collision for each vehicle pair.

If ($\Delta a \neq 0$)

{

$t_1 = \frac{-\Delta V - \sqrt{\Delta V^2 + 2\Delta a D}}{\Delta a}$ $t_2 = \frac{-\Delta V + \sqrt{\Delta V^2 + 2\Delta a D}}{\Delta a}$

if ($t_1 > 0$ && $t_2 > 0$)

{

if ($t_1 \geq t_2$) { $TTC = t_2$ }

else if ($t_1 < t_2$) { $TTC = t_1$ }

}

else if ($t_1 > 0$ && $t_2 \leq 0$)

$$\{ TTC = t_1 = \frac{-\Delta V - \sqrt{\Delta V^2 + 2\Delta a D}}{\Delta a} \} \tag{5}$$

else if ($t_1 \leq 0$ && $t_2 > 0$)

$$\{ TTC = t_2 = \frac{-\Delta V + \sqrt{\Delta V^2 + 2\Delta a D}}{\Delta a} \} \tag{6}$$

}

$$\text{If } (\Delta a = 0 \ \&\& \ \Delta V > 0) \ \{ TTC = \frac{D}{\Delta V} \} \tag{7}$$

Generally, if *TTC* is relatively short, a collision becomes more likely since it does not leave enough time for the following vehicle to respond. However, it is not straightforward to determine the lower limit of TTC, because drivers have varying reaction times. For instance, Van der Horst [13], and Farber [14] used a *TTC* of 4 seconds, whereas Hogema and Janssen [15] recommended a minimum of 3.5 seconds for drivers in vehicles that are not equipped with an automatic cruise control system and 2.6 seconds for drivers with equipped vehicles. Ozbay et al. [2] used 4.0 seconds as the threshold *TTC* value due to the fact that

> "a simulation model still represents none-accident environment, and the simulated drivers do not really suffer from distraction, misjudgment, and errors, which would result in many accidents under real world conditions".

However, TTC by itself does not indicate the severity of a collision since different speed differences can yield the same TTC value. To that end, Ozbay et al. [2] formulated a novel CI [2]. The proposed index builds on the TTC formulation but includes the fundamentals of kinetics to reflect the severity of a collision. The validation of the proposed *CI*, was presented in Ozbay et al. [2]. The authors used the northbound direction of the roadway between Exit 7 and Exit 7A at New Jersey Turnpike as the test network. The validation was conducted by comparing the accident frequencies observed within the selection section, and the frequency of CI obtained from the microscopic simulation model of the test network. The analysis in this paper also utilizes this new measure.

V. Case Studies

Two case studies are presented in this section. The first case study presents the validation of a toll plaza, namely interchange 13 at NJTPK, based on operational parameters. The second case study validates the Asbury Park toll plaza at Garden State Parkway (GSP) in NJ based on historical accident statistics using the surrogate safety measure described in the previous section.

A. Case Study 1 - Validation Based on Lane Volumes

Interchange 13 at NJTPK leads to the Goethals Bridge that is one of three Staten Island bridges linking New York and New Jersey. It has direct connections across the Staten Island Expressway (I-278) to the Verrazano-Narrows Bridge.

The Goethals Bridge Modernization Program sponsored by the Port Authority of New York and New Jersey (PANYNJ) proposes the replacement of the bridge due to the fact that the 80-year old bridge has become operationally insufficient for today's highway traffic demand. The Environmental Impact Statement (EIS) of the Goethals Bridge Replacement evaluates the environmental, social and economic impacts of reasonable and feasible alternative actions for the Goethals Bridge.

In order to analyze the potential impacts of the improved bridge capacity to the interchange 13, the simulation model of the toll plaza was modeled and validated. At the present, especially on Friday afternoons and weekends, the traffic backup from the bridge approaches the Interchange 13 toll plaza and creates significant congestion at the toll plaza and approach ramps.

The simulation model of the Interchange 13 toll plaza and its validation with respect to toll lane volumes is described in this section.

1) Description of Toll Plaza

There are currently 13 exit lanes at Interchange 13 toll plaza with four EZ pass and nine cash lanes. The schematics of Interchange 13 toll plaza is show in Fig. 3. As shown in the figure, traffic comes from two approach ramps, one from northbound and one from southbound direction.

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. The screen shot of the developed toll plaza simulation model is given in Fig. 4.

There are only two payment types at the NJTPK toll plazas. These are ETC lanes, i.e. EZ Pass lanes and cash lanes.

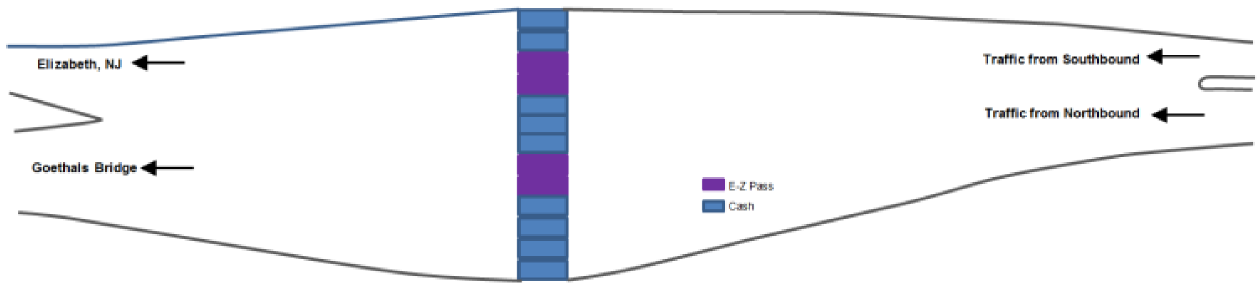

Fig. 3 Toll plaza schematics

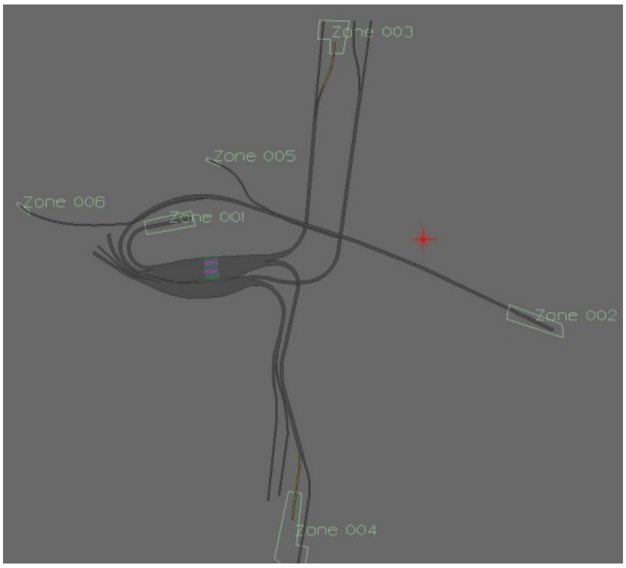

Fig. 4 Paramics simulation model of Interchange 13

2) O-D Demand

The ETC dataset was used to create origin-destination (OD) demand matrix for Interchange 13. 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 is processed for all the vehicles (both E-ZPass and Cash users). From this dataset the number of EZ Pass and Cash users was available from January 2004 to June 2008. The OD demand was extracted for October 9, 2007, which had one of the highest demands at Interchange 13.

3) Entry and Exit Lane Probabilities

As mentioned earlier, drivers' lane selection depends heavily on which direction they are approaching to toll plaza as well as which direction they are headed to after the toll plaza. Entry lane probabilities can be obtained from the ETC dataset. Since the origin interchange of individual vehicles are specified in the dataset, whether they are coming from the southbound or northbound direction are readily available in the ETC dataset.

Table I shows the drivers' probability of selection each lane based on their approach direction.

TABLE I
LANE SELECTION PROBABILITIES BASED ON ENTRY DIRECTION

Lane No	Southbound	Northbound
1	0.182	0.072
2	0.231	0.068
3	**0.273**	**0.109**
4	**0.293**	**0.274**
5	0.194	0.145
6	0.153	0.189
7	0.113	0.217
8	**0.275**	**0.277**
9	**0.160**	**0.340**
10	0.051	0.138
11	0.018	0.043
12	0.058	0.127
13	0.000	0.000

Bold values indicate E-Z Pass lanes

It should be mentioned that the sum of lane selection probabilities for cash lanes and EZ pass lanes are equal to 1.0 separately for each column in Table I. For example, if a cash vehicle is approaching the tolls from the northbound direction, its probability of selecting lane 2 is 0.068 is lower than 0.217 the probability of selecting lane 7, since lane 10 is closer to northbound entry ramp in Interchange 13 toll plaza.

Exit lane probabilities, on the other hand, are not readily available from the ETC dataset. Therefore, the authors used the video recording of Interchange 13 provided by the NJTA to collect the percentage of vehicles heading towards Elizabeth and the Goethals Bridge from each lane. The extracted exit lane probabilities are given in Table II.

TABLE II
LANE SELECTION PROBABILITIES BASED ON EXIT DIRECTION

Lane No	Elizabeth	Goethals Br.
1	0.238	0.109
2	0.454	0.204
3	0.619	0.104
4	0.307	0.160
5	0.159	0.234
6	0.088	0.153
7	0.062	0.299
8	0.042	0.325
9	0.032	0.411
10	0.000†	0.000†
11	0.000†	0.000†
12	0.000†	0.000†
13	0.000†	0.000†

†No vehicles were detected at these lanes at the time of the video recording.

4) Service Times

Video data collected from the exit toll plaza at another interchange at NJTPK 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 because of the identical driver characteristics. 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 III 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.

TABLE III
GOODNESS OF FIT RESULTS FOR EXIT TOLL SERVICE TIMES

	PC	Trucks
Sample Size	177	44
Mean (sec)	17.9	27.57
Std Dev (sec)	12.69	11.85
KS Test Statistics	0.0491	0.0894
AD Test Statistics	0.6153	0.4401
Reject Lognormal at $\alpha = 0.05$	No	No

5) Validation Results

The simulation model was run for an entire day based on the proposed lane utility model. In the lane utility model, lane entry and exit probabilities shown in

Tables I and II were utilized. The simulation model was validated based on the lane counts at the toll plaza. Fig. 5 shows the actual lane counts obtained from the ETC dataset versus the lane counts obtained from the simulation model.

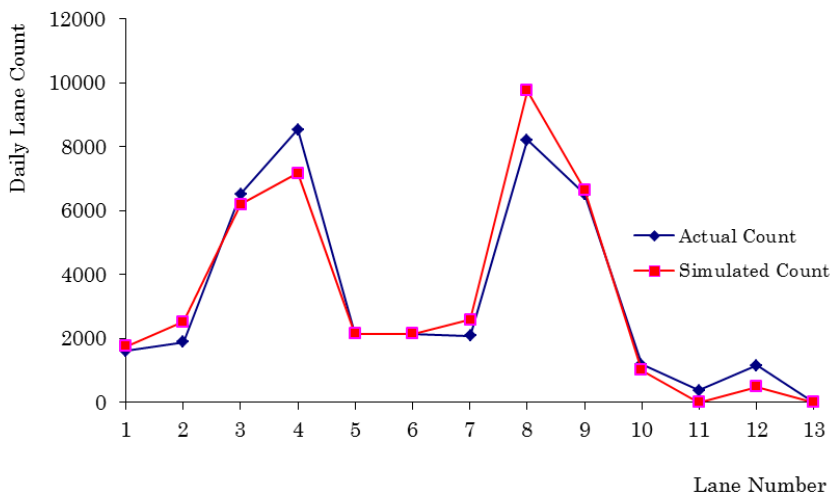

Fig. 5 Comparison of actual and simulated lane counts

The correlation between the actual counts and the simulation counts is 0.976. Although the correlation is quite satisfying, some differences in lane counts are easily observable. It can be seen in Fig. 4 that the majority of the difference between the actual and simulation counts appear on lane 4 and lane 8, which are EZ pass lanes. The main reason for the difference is due to the vehicles' lane decision process which leads to vehicles shifting from lane 4 to lane 8 due to congestion.

Ozbay et al. [8] showed that when the default Paramics model was used, the lane utilizations obtained from the simulation results are significantly differ from actual lane utilizations.

The simulation results of the toll plaza model showed that the average travel time at the toll plaza is between 6.2 and 6.8 minutes at 0.05 confidence level. It should be mentioned that the average travel time includes not only the time spent at the plaza but also the time spent on the approach off-ramps from the NB and SB directions.

As mentioned before, the insufficient capacity of the Goethals Bridge causes a queue back up that approaches the Interchange 13 toll plaza and creates significant congestion at the toll plaza. The proposed future changes to the bridge will increase the bridge capacity from 4-lanes to 6-lanes. Once the capacity of the bridge is increased in the simulation accordingly, the simulation runs did not show any queue formation before the bridge. Therefore, vehicles exiting the toll plaza did not have any problems approaching the bridge. The simulation results showed that the average travel time at the toll plaza is between 1.93 and 1.94 minutes at 0.05 confidence level. These figures show that the build alternative considerably improves the traffic flow at the toll plaza.

B. Case Study 2 - Validation Based on Safety

Asbury Park toll plaza is located at milepost 104.0 on the northbound direction of GSP. GSP is divided into two sections as local and express lanes (less interchanges) on the northbound direction immediately before Asbury Park toll plaza until all lanes merge at exit 125 in Woodbridge. There are eight local toll lanes and three express EZ-pass lanes at Asbury Park toll plaza, as shown in Fig. 6. Overhead signs warn drivers of the separation of express and local lanes, and that the express lanes are only for EZ-pass users two-miles before the toll plaza.

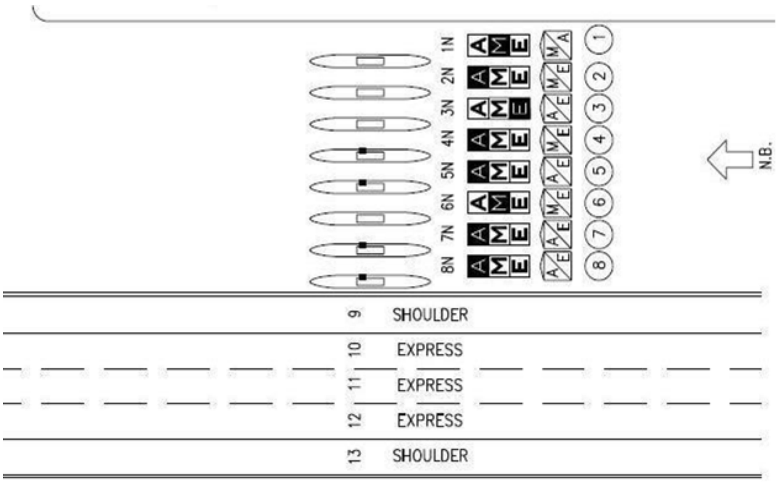

Fig. 6 Lane configuration of Asbury Park toll. Notes: (1) Dark boxes at the toll lanes indicate the primary mode of payment. (2) A: automatic coin machine, M: manual, and E: EZ-pass. (3) Primary mode of lane 8 was changed from ACM to EZ-pass in 2007 (4) The primary mode of Lane 4 was changed from ACM to EZ-pass in 2009

Excessive weaving of vehicles after Asbury Park toll plaza poses a high safety risk at this location. An approximately 580-foot section immediately after the toll plaza allows vehicles to cross from the express to local roadway, or vice versa (See Fig. 7). The accident history at this location indicates high risk of side-swipe and rear end accidents. After vehicles cross the toll plaza, lane 10, as indicated in Fig. 7, joins directly to the local roadway, leaving two lanes at the express roadway. Vehicles traveling along lane 10 need to cross one-lane to the left to continue on the express roadway. Similarly, vehicles traveling on lane 11 or lane 12 need to cross to lane 10 to continue on the local roadway. However, a problematic and accident prone movement is from the local to express roadway over the short weaving area, as shown in Fig. 7. Vehicles coming from the local toll lanes shift two-lanes over the weaving area, merging with high speed EZ-pass lanes to join express roadway.

Possible alternatives for alleviating high crash rate include extending the weaving area, using double white lines to prohibit vehicles from crossing from local to express lanes, or both. Evaluation of any safety measures using microscopic traffic simulation requires the development of a carefully validated simulation model of the current toll plaza design and operation using the real-world accident data.

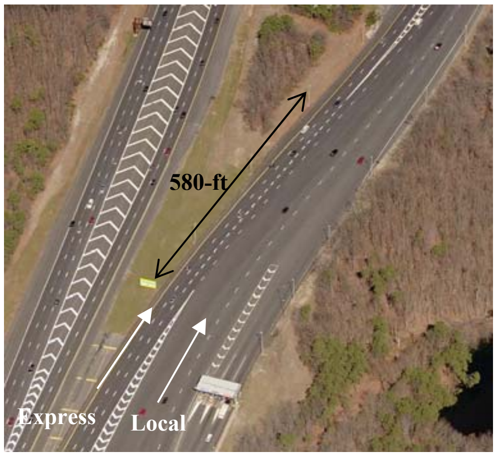

Fig. 7 Weaving section after Asbury Park toll plaza

1) O-D Demand

The OD demand matrix was created using the ETC data from August 18, 2008. This specific date was selected because the available video data (explained below) were recorded on the same date. The OD demand matrix was used to derive the simulation model, and verify if the simulation outputs were comparable with the observed data (e.g. hourly traffic volume at toll lanes and the proportion of vehicles changing lanes within the weaving area).

The available video data of the Asbury Park toll plaza was recorded on August 18, 2008 from 6 a.m. to 9 a.m. The camera view shows the traffic moving on the northbound after crossing the toll plaza, as shown in Fig. 8. Lane 2 labeled in the figure is the rightmost lane on the express toll lanes that directly joins the local roadway. The most accident prone weaving movement is the one from lane 1 to lane 3.

Fig. 8 Depiction of real traffic at the Asbury Park toll plaza

The percentages of weaving movements extracted from the video recording are shown in Table IV. The percentages show that the majority of weaving occurs from lane 3 to lane 2 and from lane 2 to lane 1. The weaving movement from lane 2 to lane 1 is unnecessary, because lane 2 directly joins the local roadway and does not merge with other lanes downstream of the toll plaza. However, it is our opinion that familiar drivers are aware of the heavy crossovers within the weaving area, and move out of lane 2 to avoid any conflicts.

The weaving movement from lane 3 to lane 2 is carried out by vehicles coming from the express toll lanes that want to take the local roadway.

TABLE IV
WEAVING PERCENTAGES BETWEEN 6 A.M. AND 8 A.M.

Weaving	**6:00- 6:15**	**6:15-6:30**	**6:30-6:45**	**6:45-7:00**	**6:00 - 7:00**
1->2->3	6.1 %	3.3	2.4	3.3	3.6 %
2->1	16.1	15.9	13.3	14.3	14.9
3->2	15.5	15.2	16.2	13.7	15.1
Weaving	**7:00- 7:15**	**7:15-7:30**	**7:30-7:45**	**7:45-8:00**	**7:00 - 8:00**
1->2->3	3.8	3.9	3.3	2.5	3.3
2->1	24.5	19.2	19.0	15.4	19.4
3->2	18.5	17.5	21.0	18.5	18.9

Although the percentage of weaving from lane 1 to lane 3 is just above 3%, the total number between 6 a.m. and 8 a.m. is 180 vehicles. As mentioned before, this weaving movement requires vehicles to cross over 2 lanes that carry hourly traffic volume of around 1,600 vehicles, and is prone to accidents.

2) Service Times

Services times used in the simulation runs of the Asbury Park toll plaza model was adopted from the data collected for the Union toll plaza on GSP. There are currently four ACM lanes, two cash lanes and two EZ-pass lanes at the Asbury Park toll plaza. Vehicles using the EZ-pass lanes do not wait to pay tolls. As to cash and ACM lanes, the service time distribution observed at the Union toll plaza are expected to apply at the Asbury Park toll plaza, because (1) service times at ACM lanes are not location specific, and (2) the same toll fee, one dollar, are being collected at both toll plazas, which would yield similar service time distributions.

Service times for cash and ACM users were collected using the video recordings of the Union Toll plaza on April 10, 2009. Service times of 81 cash and 78 ACM users were extracted. Kolmogorov-Smirnov and Anderson-Darling goodness-of-fit tests show that toll processing times follow a lognormal probability distribution for $\alpha = 0.05$ with parameters $\mu = 1.659$, $\sigma = 0.625$ for Cash users and $\mu = 1.391$, $\sigma = 0.665$ for ACM users. It should be noted that these values are in log-scale. Mean value of service times for cash and ACM users are 6.7 and 5.0 seconds, respectively. These service times were incorporated into the toll plaza model using the API capability in PARAMICS, thus obtaining a more representative toll plaza model. Cash and ACM users slow down at the toll gates to zero speed and randomly assigned a service time based on the service time distribution. Once they spend the assigned service time at the toll gate, they accelerate and exit the plaza. EZ-Pass vehicles, on the other hand, do not have a service time, thus only slow down through the toll booth and exit the plaza.

3) Accident Summary

Accident statistics at and around the Asbury Park toll plaza were extracted from the accident database, provided by the NJTA. The available accident database includes each accident that was reported by the state police from January 1, 2002 to June 28, 2007, providing detailed information about accidents such as the time, date and location (e.g. milepost, direction) of each accident, number of vehicles involved, severity type, and crash type (e.g. rear-end, sideswipe). A summary of the extracted accidents by severity and crash type is presented in Tables V and VI, respectively.

TABLE V
ACCIDENTS BY SEVERITY BETWEEN MILEPOST 102.7 AND 104.3

Section	Fatality	Injury	Property Damage
102.7-103.0	0	7	20
103-103.5	0	6	33
103.5-104.0	1	81	237
104-104.4	0	27	103
Total	1	121	393

Note: Of 551 the accidents reported between January 1, 2002 and June 28, 2007, 36 accidents did not specify severity.

Fig. 9 and 10 show the frequency of sideswipe and rear end accidents, respectively, between mileposts 102.7 and 104.4. The red line in the figures represents the Asbury Park toll plaza located on milepost 104.0. A visual examination of Fig.

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9 shows that the majority of sideswipe accidents occur at and immediately after the toll plaza (mileposts 104.2 and 104.3), indicating the current safety problem with the weaving area. As expected the rear-end accidents occur most frequently right at the toll plaza or immediately before, as shown in Fig. 9.

TABLE VI
ACCIDENTS BY CRASH TYPE BETWEEN MILEPOST 102.7 AND 104.3

Section	Rear End Accidents	Sideswipe Accidents
102.7-103.0	9	8
103-103.5	16	10
103.5-104.0	171	74
104-104.4	32	66

Notes: (1) The table does not include other crash types (e.g. overturned vehicles, crash with curb, running out of roadway), and (3) 72 of the total accidents did not have the crash type specified in the database.

The accident database does not provide information about the cause of the accidents. Therefore, it is not possible to determine how many of the accidents occurred due to the maneuvers between the barrier tolls and the express roadways. The accident report filled out by the police explains in a diagram how each accident happened, and provides the cause of the accident. The NJTA provided the authors with the police reports for the accidents occurred in 2005 between milepost 104 and 104.3. After perusing each accident report, it was found that out of 37 accidents within these mileposts 16 accidents caused by a vehicle trying to cross from the barrier tolls to the express roadway. Only 2 accidents were caused by the 2->1 maneuver shown in Fig. 8.

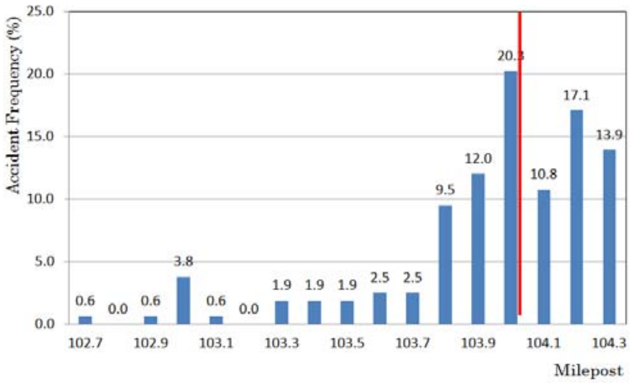

Fig. 9 Sideswipe accidents between milepost 102.7 and 104.3

There were 151 accidents in 2005 between mileposts 102.7 and 104.3. The percentage of accidents caused by the Local/Express maneuver is 10.6% (16/151). This is a noticeably high portion of all the accidents, considering the fact that on average there are only 76 vehicles per hour executing the Local/Express maneuver (3.4% of the barrier toll plaza volume).

4) Validation Results

The lane utilization of three hours in the morning peak (6 a.m. - 9 a.m.) and in the afternoon peak (3 p.m. - 6 p.m.) obtained from the simulation runs with respect to the actual lane utilization extracted from the ETC dataset. The percentage difference between the simulated and the observed total volumes at the local toll lanes is 0.51%, -0.12% and -1.31% during 6 a.m. - 7 a.m., 7 a.m. - 8 a.m. and 8 a.m. - 9 a.m., respectively. Similarly, the percentage difference between the simulated and the observed total volumes at the local toll lanes is 0.21%, 0.01% and -0.49% during 3 p.m. - 4 p.m., 4 p.m. - 5 p.m. and 5 p.m. - 6 p.m., respectively. The percentages are 0.74%, 0.64% and -1.40% at the express toll lanes during the same time periods in the morning; and 0.13%, 0.17% and -0.37% during the same time periods in the afternoon.

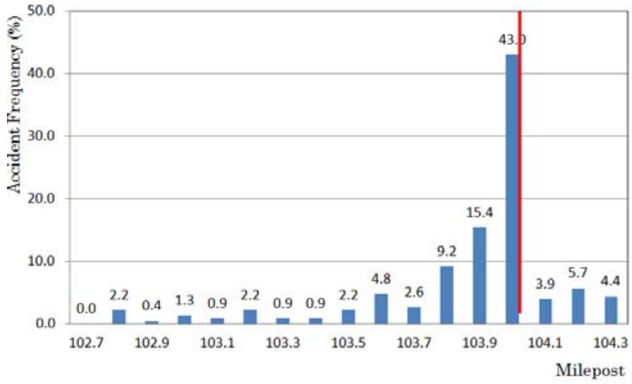

Fig. 10 Rear-end accidents between milepost 102.7 and 104.3

Generally, for a specific road section, accidents along this road section should have certain time and space characteristics. Fig. 9 and 10 demonstrate that rear-end and sideswipe accidents happen more frequently at and immediately after the Asbury Park toll plaza.

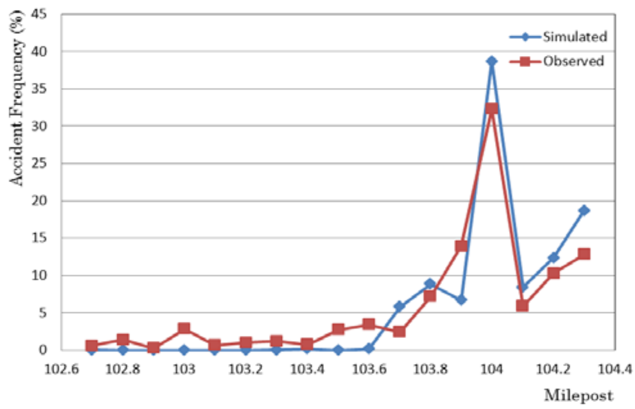

Fig. 11 Spatial frequency of accidents

Fig. 11 shows the comparison of observed and simulated accident frequencies by milepost. Note that for comparison purposes rear-end and sideswipe accidents are combined, because the surrogate safety measure used in the simulation does not differentiate among different crash types. Fig. 11 indicates that the simulation results match with the accidents occurring at the toll plaza (milepost 104.0), but overestimate the accident frequencies before the toll plaza. The correlation coefficient between the observed and simulated frequencies is 0.95.

It should be mentioned that the surrogate measures of safety obtained from microscopic traffic simulation models present better correlation with the actual accidents when the comparison is conducted in longer roadway section (see [2]). In Fig. 11, the comparison is conducted at roadway intervals of 0.1 mile. It is obvious that there would be discrepancies between the exact and simulated locations of accidents, which are also subject to errors in the database, and the location of potential accidents in the simulation model. A correlation coefficient of 0.95 based on small roadway intervals is sufficient to conclude that the surrogate safety measures obtained from the simulation model reflect the accident trend at the Asbury Park toll plaza.

Fig. 12 shows the comparison of the observed and simulated accident frequencies on a temporal scale. The correlation coefficient is calculated as 0.86.

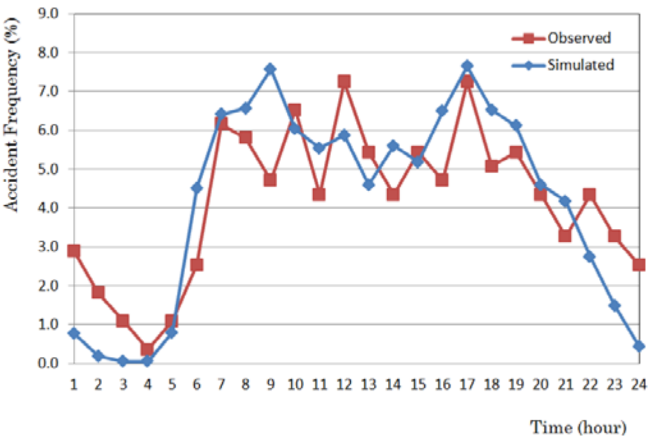

Fig. 12 Temporal frequency of accidents

Table VII shows the results of the simulation analyses for different compliance rates.

TABLE VII
ESTIMATED REDUCTION OF TRAFFIC CONFLICTS

Compliance Rates			
25%	50%	75%	100%
3.8 % -5.1%	8.4 %-9.1 %	9.5%-14.9%	16.3%-18.5%

Note: The range represents the 95% confidence interval for the results

The validated simulation model of the Asbury Park toll plaza can easily be modified in Paramics to incorporate the possible operational and geometry changes proposed to reduce the number of accidents at the weaving area. As mentioned before, a possible yet more expensive measure is to extend the weaving section. Other relatively inexpensive solutions include signage and striping to discourage or prohibit vehicles from maneuvering from local tolls to the express roadway. The expected outcome of these measures is the increase in vehicles' compliance with the restriction to the Local/ Express maneuvers. The percentage of vehicles that comply with these new restrictions is unknown. It is proposed in our simulation analyses that the change in the measure of safety performance, i.e. CI, be estimated using different compliance rates. It is possible to incorporate these restrictions in the simulation model using the Paramics API. Because every vehicle is controlled at each time step during the simulation, vehicles can be directed not to maneuver from local tolls to the express roadway.

The results show that if the compliance rate is 100%, the estimated reduction in conflicts varies between 16.3% and 18.5%. Because there are no physical obstructions such as delineators or barriers preventing the Local/ Express maneuvers, it is unlikely to achieve 100% compliance rate. Table VII suggests that if 50% compliance rate were to be achieved, the estimated reduction in traffic conflicts would be between 8.4% and 9.1%.

In the Accident Summary subsection, it was shown that the accidents due to the Local/ Express maneuvers (1->2->3 in Fig. 8) constitute 10.6% of all the accidents in the network. Therefore, one would expect that eliminating the Local/ Express maneuvers would yield 10% reduction in the accidents. The results presented in Table VII indicate that the eliminating the Local/ Express maneuvers results in higher reduction of traffic conflicts, from 16.3% to 18.5%. This is due to the fact that when the Local/ Express maneuvers are restricted, not only the probable collisions directly related to these maneuvers, but also the one indirectly affected are reduced. Put differently, when a vehicle crosses from the local tolls to the express roadway, it does not create a conflict with only one vehicle. As a result of this maneuver, the vehicle it is in conflict with reduces its speed, causing a conflict with another vehicle.

VI. Conclusions

Microscopic traffic simulation software packages are often used to evaluate various operational and geometric changes proposed for traffic networks. Their use in evaluating toll plaza operations, however, is quite limited in the literature due to the fact that the default lane changing and lane selection behavior models embedded in these off-the-shelf tools cannot replicate the complex driver dynamics observed at toll plazas. Therefore, validating and calibrating of toll plaza simulation models require additional programming for correctly representing vehicles' lane selection behavior at toll booths.

Two toll plazas in New Jersey, namely Interchange 13 toll plaza of NJTPK and Asbury toll plaza of Garden State Parkway, are selected as case studies to demonstrate the use of microscopic traffic simulation for evaluating their operational and safety performances. The selected toll plazas are modeled in Paramics traffic simulation software.

A utility-based heuristic for the drivers' lane selection is implemented in the traffic simulation model 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. Variable 1 and variable 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 variable 2 depends on the geometric design of the toll plaza (See Fig. 1).

The first toll plaza is located at Interchange 13 at New Jersey Turnpike. The toll plaza leads to the Goethals Bridge that is one of three Staten Island bridges linking New York and New Jersey. Traffic backup due to insufficient capacity at the ridge approaches the Interchange 13 toll plaza and creates significant congestion at the toll plaza and approach ramps. The simulation model was validated using hourly toll lane volumes, where a correlation coefficient of 0.976 between the observed and simulation counts was.

The second selected case study is Asbury Park toll plaza, located on the northbound direction of Garden State Parkway. After the toll plaza, the mainline divides into express and local roadways, as shown in Fig. 8, leaving only about 600 feet for vehicles to maneuver, which results in excessive weaving and a high safety risk at this section.

Safety assessment of Asbury toll plaza is conducted using surrogate safety measure concept in Paramics. A surrogate safety measure, CI, developed by Ozbay et al. [2], is an improved surrogate measure of TTC. TTC is a surrogate safety measure which is widely accepted by FHWA as the surrogate safety measure using simulation [12]. CI incorporates additional factors to reflect the “severity” of a potential crash. This new approach is not only based on the idea borrowed from the kinetics to describe the influence of speed to kinetic energy involved in the collision, but also based on the consideration of the time before the conflict occurred, through which the severity and the likelihood of a potential conflict could be interpreted even though a collision had not actually occurred.

Observed and simulated accident frequencies are compared by milepost and time of day. Simulation results showed that the correlation coefficient between the observed and simulated frequencies is 0.95 at spatial scale and 0.86 in the temporal scale.

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