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Research paper

Modelling and optimizing of electronic toll collection (ETC) at Malaysian toll plazas using microsimulation models

A. E. Jehad [1] *, A. Ismail [1], M. N. Borhan [1], S. Z. Ishak [2]

[1] Smart and Sustainable Township Research Centre, Civil Engineering Programme,
Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[2] Faculty of Civil Engineering, University Technology MARA, Shah Alam, Selangor, Malaysia
**Corresponding author E-mail: aliemad87@gmail.com*

Abstract

Toll plazas are one of the critical components of a roadway system. At the same time, they are among the most complex road structures, as drivers are exposed to a large amount of information and have a short amount of time to make a decision to avoid any collision. VISSIM and SSAM are used to investigate the effect of various Malaysian toll plazas design and traffic conditions on drivers' behaviour and level of safety. The study was made a well-calibrated and validated VISSIM simulation model and several scenarios were simulated to test their efficacy for improving toll plaza safety aspects by using SSAM afterwards. From the results it was observed that the VISSIM simulation model scenarios such as implementing booths orientation and segregating lanes for different vehicle types to improve the level of service have significant safety aspects improvement regarding conflict points and lane change accidents results while using Surrogate Safety As-sessment Model (SSAM) in order to give the need for remediation of either the roadway design or the flow-control strategy.

Keywords: *Safety; Toll Plaza; Microsimulation; VISSIM; SSAM; Traffic Management*

1. Introduction

Toll plazas are one of the most critical components of a roadway system for capital financing and ongoing infrastructure maintenance revenue. In some instances, toll plazas have additionally served as traffic maintenance and congestion control strategies. Drivers are exposed to large amounts of information within a short period of time to make decisions regarding their exit ramp, toll booth lane, and velocity. Often, in developing countries, strategies to optimize toll plaza operations are developed by the operator according to observations from the site. Strategies based only on observations can provide varied results, which can be dangerous when huge costs are involved in implementing a strategy [1].

Electronic Toll Collection (ETC) systems have been widely applied to improve the efficiency of toll plazas. The operational efficiency of auto-toll systems is usually studied by means of a simulation model and automatic vehicle identification technology [2–6]. Electronic toll collection system proposed which is the latest technology that enabling tolls to be collected from road users automatically without human interaction to eliminate time delay [7]. Current ETC system consist of four main components which are Automatic vehicle identification used to check vehicle eligibility and automatic vehicle classification designed to assort type of the car in order charge different fare of transaction process. Eventually, violation enforcement system is equipped with a high quality camera capable to record all necessary information about the violators. In today's Electronic Toll Collection system has shown to advantage in fact feasible and financially attractive in modern society to facilitate users by collecting tolls electronically in highway without delay.

2. Methodology

The micro-simulation model was created based on the Sungai Ramal (B) toll plaza, which provides an ideal base case since it connects major interstate highways and a primary route with high traffic demand.

The sheer volume of traffic during the morning and evening peaks has stretched the selected toll systems on the brink of 'failure' in terms of level of service and comfort which also would cause a dense, non-weaving maneuver area in certain number of toll booths.

2.1. Data collection

Plaza hourly traffic by class data was collected from authority for Sungai Ramal (B) toll plaza in 25th of July 2016. The number of vehicles classes enters the plaza and percentage of heavy vehicles (HVs), were extracted separately. In morning peak-hour (7-8 am), 4533 vehicles entered Sungai Ramal (B) toll plaza. About 1% of entering traffic consisted of HVs. Additionally, 62% and 69% of the total entering traffic used Touch-N-Go cards payment system. Figure 1 shows the existing lane system configuration at the subject toll plaza. Toll plaza are made up of two traditional heavy vehicles lanes in the far left, 7 lanes of the toll plaza are designated for Touch-N-Go cards payment system, and three dedicated ETC lanes.

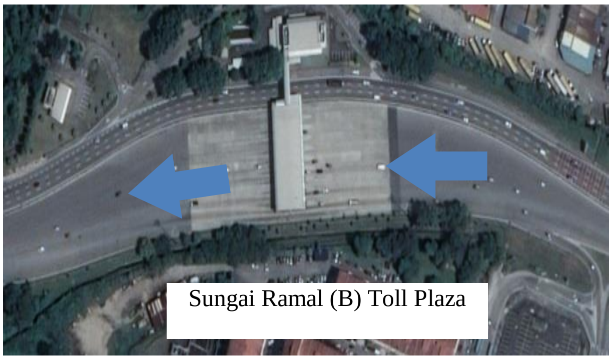

Fig. 1: Sungai Ramal (B) Toll Plaza Existing Lane System.

2.2. Model design

A micro-simulation model offers a cost-effective way of studying real-life transportation problems, either existing or anticipated, without disturbing the balance of the transportation system. Simulation allows detailed representation of the transition area, with regard to the geometry of the section, taking into account dynamic driving behavior parameters of vehicles while following or changing lanes and service time for different payment categories, adding credibility to the results [8].

Reference to figure 1, a completed toll station is consisted by the toll channel, toll plaza, toll booths, and other facilities have been modeled by VISSIM. The toll channel includes toll booths, lanes, and other parts. As shown in Figure 2, the design of merging area is based on the design of the length, number of merging lanes. Considering these factors, we first establish the indexes related safety and gap availability, and then use the method of changing lane priority to design the modification solution and reconstruction solution.

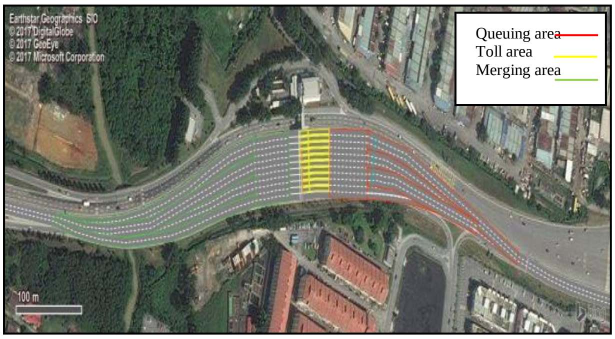

Fig. 2: Vissim Layout of Toll Plazas.

2.3. Index of safety, gap and changing lane priority

2.3.1. Index of safety

In this research, both before-and-after operational analyses have been conducted for the toll plaza to examine the levels of safety. For the operational analyses, the number of conflicts is another good indicator of the potential crash risk through the toll plaza, which has also been commonly used elsewhere to measure the safety [9–11].

VISSIM defines Conflict areas behavior as a vehicle takes into consideration all conflict areas up to the preceding vehicle, indicative of the number of Observed vehicles [12]. Average standstill distance parameter (ax): Defines the average desired distance between two cars. The tolerance lies between –1.0 m and +1.0 m which is normally distributed at around 0.0 m, with a standard deviation of 0.3 m. Additive part of safety distance parameter (bx_{add}) is the value used for the computation of the desired safety distance d. Allows to adjust the time requirement values. Multiplicative part of safety distance parameter (bx_{mult}) is the value used for the computation of the desired safety distance d. Allows to adjust the time requirement values.

The desired distance d is calculated from:

$$d = ax + bx \tag{1}$$

Where:

ax: Standstill distance

$$bx = (bx_{add} + bx_{mult} \times z)\sqrt{v} \tag{2}$$

V: vehicle speed (m/s)

Z: is a value of range (0.1), which is normally distributed around 0.5 with a standard deviation of 0.15.

2.3.1. Index of gap and changing lane priority

The general model simulates individual vehicles movements combining car-following, lane-changing and booth selection models. The general equation of a car-following model, developed in the sixties [13] is the following:

$$reaction_n(t) = sensibility_n(t-\tau_n) \times stimulus_{n-1}(t-\tau_n) \tag{3}$$

Where, the follower (n) reacts to a stimulus originated by the leader vehicle (n-1) proportionally to his sensibility, after a reaction time (τ_n).

Astarita et al. (2001) [14] proposed a car-following model based on the general equation (3). The used variables are:

$x_n(t)$, position of the follower (n) at the time (t);

$h_n(t)$, vehicle's distance (n) from the leader vehicle (n-1) at the time (t);

h_{nmax}, maximum conditioning distance from the vehicle (n-1), if $h_n(t) > h_{max}$ driver (n) is not conditioned.

$v_n(t)$, speed of vehicle (n) at time (t);

v_n^f, free speed of vehicle (n);

g_n^{min} minimum distance from vehicle (n-1) accepted by driver (n).

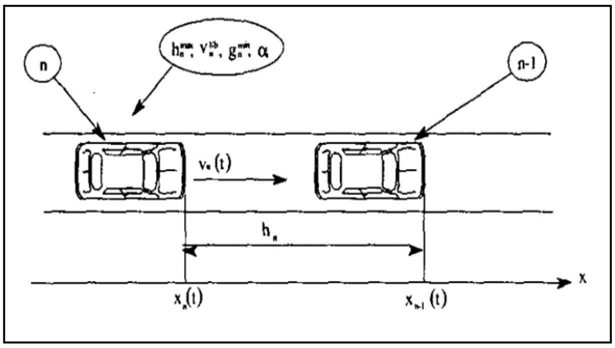

Fig. 3: Parameters of Car-Following Model According to [14].

The proposed gap acceptance index depends on advanced merging parameter which is selected accordingly to achieve the desired lane change behavior:

a) If vehicle A has to change lanes and recognizes that the neighboring vehicle in front B on the target lane has approximately the same speed or is only slightly faster (-1.0 m/s < dv < 0.1 m/s), A slows down slightly (by 0.5 m/s²) to move into the gap behind B (figure 3.a).
b) If the vehicle A with vehicle in front C detects that a neighboring vehicle in front B wants to change to the lane of A, this option can be used so that cooperative braking of A also take place when A is downstream from C (figure 3.b).
c) Vehicle A leaves the cooperation to its preceding vehicle C. In this case C may already be too close to B, so that C overtakes B, whereby A is eventually too close itself to B to brake cooperatively (figure 3.c).

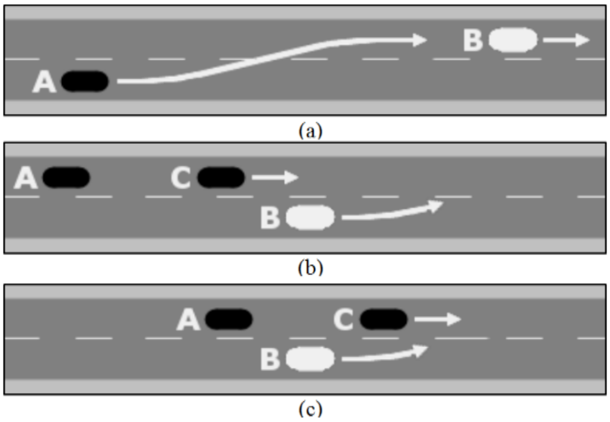

Fig. 4: Gap Acceptance Options According to Advance Merging Technique.

Let us assume vehicle B is a neighboring vehicle in front of vehicle A. A plans to let B merge, who is meanwhile driving downstream of C (in front of vehicle A), on its own lane. In this case, vehicle A forgets that B should have been permitted to merge. Thus, vehicle A can immediately permit other vehicles to change into its lane.

Regardless the previous parameters, VISSIM can models the general behavior more realistically using Cooperative lane change parameters. Which delay for changing lanes based on the specified routes for their own overtaking vehicle and the trailing vehicle is accepted by the driver while the maximum deceleration for changing lanes based on the specified routes for own vehicle overtaking and the trailing vehicle.

2.4. Proposed configuration

In real life, people often simply need to adjust the toll plaza. In order to ensure safety efficiency to achieve the optimization. Based on Nonlinear Integer Programming method, Modification model is built to enhance capacity through making adjustments to the proportion of all tollbooths; Electronic Toll Collection (ETC), TouchNGo (TNG), and Radio-frequency identification (RFID). Therefore a complete solution is proposed.

2.4.1. Variables

Lane configuration of the toll booths is the only independent variable used in this approach since traffic volume, stop time at toll booths, and reduced-speed distribution at ETC and TNG lanes are taken from the field as calibration parameters.

2.4.2. Lane design

Among 10 possible lane configurations, 4 were of interest to this study and good representatives of different types of lane configurations, and then a fifth scenario was defined as having two combination lanes (i.e., a lane that serves both ETC and TNG customers) and two ETC lanes.

Scenario 1 was the base case, having two heavy vehicle lanes in the far left of the toll plaza and three ETC lanes in the far right and the remaining seven lanes for TNG users. In Scenario 2, all of the lanes were dedicated ETC, lanes as shown in table 1. In Scenario 3, lanes 1, 3, 5, 7, and 9 were dedicated ETC lanes, and lanes 2, 4, 6, 8, and 10 were TNG lanes. In Scenario 4, lanes 5, 6, and 7 were dedicated ETC lanes, and the remaining lanes of left and right lanes were dedicated to TNG users. According to [15] who suggested a preliminary proposed design table for toll Plazas, number of ETC lanes was reduced to two lanes (7 and 8) lanes. All the first 6 lanes from the far left were dedicated to TNG users only, while 2 RFID dedicated lanes were introduced to the fifth scenario.

Table 1 represents all five simulation models scenarios, each with different lane configurations. Each simulation model had 1 simulation runs with same random seeds. The warm-up period at the start of each run was 15 minutes.

Table 1: Lane Configuration of All the Scenarios

Scenarios	Lanes									
	1	2	3	4	5	6	7	8	9	10
Scenario 1 (base case)	TNG	TNG	TNG	TNG	TNG	TNG	TNG	ETC	ETC	ETC
Scenario 2	ETC	ETC	ETC	ETC	ETC	ETC	ETC	ETC	ETC	ETC
Scenario 3	ETC	TNG	ETC	TNG	ETC	TNG	ETC	TNG	ETC	TNG
Scenario 4	TNG	TNG	TNG	TNG	ETC	ETC	ETC	TNG	TNG	TNG
Scenario 5	TNG	TNG	TNG	TNG	TNG	TNG	ETC	ETC	RFID	RFID

TNG: TouchNGo
ETC: Electronic Toll Collection
RFID: Radio-frequency identification

3. Results and evaluations

A conflict and event study was conducted in SSAM, using the trajectory output data files from VISSIM for the five different scenarios. The surrogate safety measures that were defined in SSAM are as follows:

TTC: minimum time-to-collision value observed during the conflict.

PET: minimum post-encroachment time, the time that elapses from when the first vehicle involved in the conflict passes a point until the second vehicle reaches that point.

MaxS: maximum speed of either vehicle throughout the conflict, i.e., whiles the TTC is less than the specified following distance time threshold, which is 1.5 seconds.

DeltaS: the difference in vehicle speeds at the simulation time, where the minimum TTC value for this conflict was observed.

DR: initial deceleration rate of the second vehicle.

MaxD: maximum deceleration of the second vehicle.

MaxDeltaV: maximum difference in speed between two vehicles in the conflict, i.e., the maximum difference between the speeds of the two vehicles involved in the conflict while a conflict exists based on the SSAM thresholds that define a conflict.

Scenarios with a higher TTC and PET and lower DR have a lower crash probability. Also, scenarios with a lower MaxS and lower DeltaS are expected to have a lower crash severity. A higher value of MaxDeltaV predicts a higher severity, assuming the hypothetical collision occurs between the two vehicles involved in the conflict.

Tables 2 to 5 show the results of t-tests between the base scenario and each of the four other scenarios.

The level of significance for the t-test analysis was 0.05. The results in table 2 show that Scenario 2, with all the lanes designated as ETC lanes had a lower TTC and MaxS, higher DeltaS, and MaxDeltaV as compared to the base case scenario. This reveals that Scenario 2 would have less severe conflicts than Scenario 1 (the base scenario), due to less speed variance that take place with this design.

The only significant difference observed between Scenario 3, which has ETC lanes in lanes 1, 3, 5, 7, and 9, and the base scenario is that MaxS, DeltaS and MaxDeltaV are lower in Scenario 3. This reveals that Scenario 3 would have less severe conflicts than Scenario 1 (the base scenario), due to less weaving maneuvers that take place with this design.

Table 4 shows that MaxS, DeltaS, and MaxDeltaV are significantly lower in Scenario 4, which has three ETC lanes at the centre, than in the base case scenario. This shows that the severity of collision in Scenario 4 is significantly less than that of the base case scenario. However, MaxD, which is taken as a representative of the probability of crashes, is less in the base scenario in comparison to Scenario 4. In summary, in Scenario 4, the expectation would be to have a higher number of collisions but with less severity, as compared to the base scenario.

Table 2: T-Test Results From SSAM between Scenario 1 (Base Scenario) and Scenario 2

SSAM Measures	Scenario 1		Scenario 2		t-value	t-critical	Mean Difference
	Mean	Variance	Mean	Variance			
TTC (sec.)	0.3	0.26	0.29	0.27	3.64	1.66	0.01
PET (sec.)	0.77	1.74	0.63	1.39	18.41	1.66	0.15
MaxS (m/s)	6.29	4.47	6.57	2.85	-24	1.66	-0.29
DeltaS (m/s)	5.05	7	3.09	5.3	123.08	1.66	1.96
DR (m/s^2)	-0.72	3.06	-0.94	3.2	18.55	1.66	0.22
MaxD (m/s^2)	-0.97	4.08	-1.52	5	37.9	1.66	0.55
MaxDeltaV (m/s)	2.71	2.01	1.77	1.99	100.17	1.66	0.94

Table 3: T-Test Results from SSAM between Scenario 1 (Base Scenario) and Scenario 3

SSAM Measures	Scenario 1		Scenario 3		t-value	t-critical	Mean Difference
	Mean	Variance	Mean	Variance			
TTC (sec.)	0.3	0.26	0.37	0.31	-20.7	1.66	-0.07
PET (sec.)	0.77	1.74	0.86	1.75	-9.74	1.66	-0.08
MaxS (m/s)	6.29	4.47	6.21	3.67	5.66	1.66	0.07
DeltaS (m/s)	5.05	7	2.92	4.54	143	1.66	2.12
DR (m/s^2)	-0.72	3.06	-0.99	3.41	22.37	1.66	0.26
MaxD (m/s^2)	-0.97	4.08	-1.56	5.11	41.28	1.66	0.59
MaxDeltaV (m/s)	2.71	2.01	1.66	1.67	121.7	1.66	1.05

Table 4: T-Test Results From SSAM between Scenario 1 (Base Scenario) and Scenario 4

SSAM Measures	Scenario 1		Scenario 4		t-value	t-critical	Mean Difference
	Mean	Variance	Mean	Variance			
TTC (sec.)	0.3	0.26	0.42	0.32	-44.93	1.66	-0.13
PET (sec.)	0.77	1.74	1.09	2.09	-43.96	1.66	-0.32
MaxS (m/s)	6.29	4.47	5.95	5.01	30.03	1.66	0.34
DeltaS (m/s)	5.05	7	4.19	6.63	63.63	1.66	0.86
DR (m/s2)	-0.72	3.06	-1	4.25	27.42	1.66	0.27
MaxD (m/s2)	-0.97	4.08	-1.35	5.56	33.23	1.66	0.38
MaxDeltaV (m/s)	2.71	2.01	2.26	1.94	61.94	1.66	0.45

Table 5: T-Test Results From SSAM between Scenario 1 (Base Scenario) and Scenario 5

SSAM Measures	Scenario 1		Scenario 5		t-value	t-critical	Mean Difference
	Mean	Variance	Mean	Variance			
TTC (sec.)	0.3	0.26	0.36	0.29	-25.35	1.66	-0.06
PET (sec.)	0.77	1.74	0.95	1.99	-27.44	1.66	-0.17
MaxS (m/s)	6.29	4.47	6.04	5.03	24.62	1.66	0.25
DeltaS (m/s)	5.05	7	4.88	6.74	13.39	1.66	0.16
DR (m/s2)	-0.72	3.06	-0.83	3.71	12.55	1.66	0.11
MaxD (m/s2)	-0.97	4.08	-1.09	4.75	12.03	1.66	0.12
MaxDeltaV (m/s)	2.71	2.01	2.6	1.9	16.08	1.66	0.1

Table 6: SSAM Conflicts Results for 900-Seconds Simulation

Scenarios	Scenario 1	Scenario 2		Scenario 3		Scenario 4		Scenario 5	
SSAM Measures	Mean	Mean	Significant difference	Mean	Significant difference	Mean	Significant difference	Mean	Significant difference
Crossing	15.7	8.7	Yes	8.4	Yes	11.3	Yes	10	Yes
Lane-changing	165.6	115.8	Yes	129.1	Yes	150.7	No	116.4	Yes
Total	181.3	124.5	Yes	137.5	Yes	162	Yes	126.4	Yes

As represented in Table 5, Scenario 5, which has two ETC lanes and two RFID lanes in the far right, has significantly fewer severe conflicts as compared to the base scenario, although MaxD shows the base scenario may have a lower probability of collisions than Scenario 5.

From the results of the t-test, it is observed that considering both crash probability and crash severity, the all-ETC lane scenario is the best scenario. As mentioned before, two types of conflicts that have been studied in SSAM are crossing conflicts and lane-changing conflicts. The result of the number of conflicts for 900 seconds of simulation time for each scenario is provided in Table 6. The number of conflicts represented in Table 6 is the sum of the conflicts that takes place both before reaching the plaza and after the plaza, before divergence of the road.

The number of crossing conflicts in Scenario 2 and the number of lane-changing conflicts in Scenario 5 are statistically significantly lower than those of the base scenario. Since all the lanes in Scenarios 2 and most of the lanes in scenario 5 serve ETC customers, there would be less restriction on drivers' lane choice and less incentive to switch lanes. As a result, fewer weaving maneuvers and fewer potentially conflicting situations would take place. Additionally, in

Scenario 2, the ETC speed variance is lower as compared to that of the other configurations, since all ten lanes are ETC lanes.

According to the literature, since ETC lanes cause less congestion compared to the other lane types, they show better performance and, as a result, would cause a fewer number of conflicts. This research validates the past studies and provides further evidence that a configuration consisting of only ETC lanes would be safer than a configuration consisting of a mixture of ETC and TNG. In practice, with this configuration with all ETC lanes, open road tolling gantries would be used instead of a toll plaza structure, so there would be no changes in highway operation. The second best scenario would be Scenario 5, which had less severity of collisions as compared to the other scenarios, shown in Table 3 to Table 4. This could be because, unlike Scenario 3 and the base scenario, this scenario has ETC and TNG adjusted in all lanes respectively, so the speed variance in adjacent lanes is minimal. It seems that if lanes with the same tolling system are grouped together and separated from other toll lane types, the severity of collisions would decrease on average but the probability or number of conflicts might increase. This type of design that has clustered lane types might be infeasible under some conditions, due to the considerable increase in the weaving maneuvers required for vehicles to take the proper exit after the plaza.

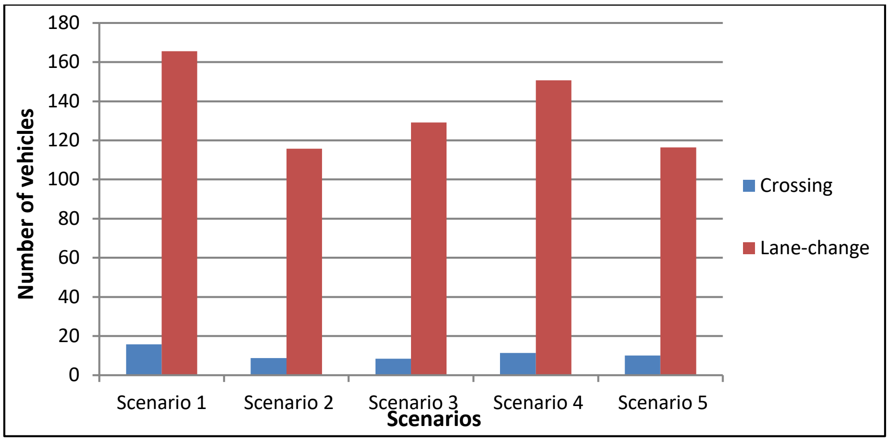

Fig. 5: Conflict Results According To Various Scenarios by Using SSAM.

In summary, an all-ETC lanes scenario performs best in terms of safety for this study location. Scenario 5, with both ETC and RFID lanes (Table 6), would be the second-most safe scenario in terms of probability of crashes; from a conflict severity standpoint. In general, it seems that fewer lane choices and fewer incentives to change lanes would increase safety at the site. For real-world implementation, a feasibility study should also be considered before deciding on lane configuration.

4. Conclusion

This study proved the feasibility of modeling traffic conditions at a toll plaza and evaluating its safety aspects using VISSIM and SSAM. Also, traffic safety was evaluated in different lane configurations at the toll plaza. All-ETC lanes, and use of both ETC, RFID, and TNG lanes, are found as the safest and second-safest configurations, respectively. The third-safest condition is the design that separates all lanes of toll plaza by ETC and TNG. The results of this study could help promote a better understanding of safety at toll plazas and the effect of toll plaza design on numbers of conflicts and events.

The data used to validate and calibrate this model was from a limited period of time taken from only one toll plaza. To validate the results of this study and extend the results to other toll plaza conditions, more data could be collected and the analysis could be re-conducted. Different conditions, such as in/out ramp distance and number of lanes, could affect the results. The road surface and weather conditions may play a role in drivers' lane choice. The video used for analysis was collected during clear, dry conditions, but drivers may drive more conservatively in more hazardous conditions.

Sensitivity analysis is another task that could be researched in the future. Thus, the effect of adding one extra lane to the road, adding one unit to the traffic volume, or changing other variables could be determined.

Conducting the same analysis with dynamic traffic assignment could be another topic of research to be investigated in the future.

Lack of data on driver behavior is a point that needs comprehensive study. The effect of different variables such as queue length, vehicle compositions in a queue, and origin-destination of a vehicle, could affect drivers' lane choice.

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