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INVESTIGATION OF SAFETY AT TOLL PLAZAS THROUGH MICROSIMULATION AND DRIVING SIMULATION APPROACHES

Foroogh Sadat Hajiseyedjavadi

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Thesis Presented

by

FOROOGH SADAT HAJISEYEDJAVADI

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FOROOGH SADAT HAJISEYEDJAVADI

Approved as to style and content by:

Michael A. Knodler Jr., Chair

Eleni Christofa, Member

Siby Samuel, Member

Richard N. Palmer, Department Head
Department of Civil and Environmental Engineering

DEDICATION

To my parents who showed me the meaning of love.

Who have always been there for me whenever I needed them and have been patient with my absence during the graduate school years.

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I would like to express my sincere gratitude to my advisor Professor Michael Knodler for all his great help and support through the course of this research. I would also like to thank the committee members for their comments and guides that helped this research improve. And last but not least, I would like to thank my parents who have always been a great support and a role model to me and without their support I could not complete this task.

ABSTRACT

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FOROOGH SADAT HAJISEYEDJAVADI

B.S.C.E., SHARIF UNIVERSITY OF TECHNOLOGY

M.S.C.E., UNIVERSITY OF MASSACHUSETTS, AMHERST

Directed by: Dr. Michael A. Knodler Jr.

Toll plazas are one of the critical components of a roadway system for capital financing, infrastructure maintenance revenue, or traffic maintenance and congestion control strategies. 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. Since the advent of electronic toll collection (ETC) technology, the complexity of toll plazas has greatly increased.

The objective of this study is to investigate the effect of toll plaza design and traffic conditions on drivers' behavior and level of safety. This study contains two approaches: (1) a microsimulation study using VISSIM and the Surrogate Safety Assessment Model (SSAM); and (2) a driving simulation study.

The microsimulation model was calibrated and validated using traffic data from recorded video at the West Springfield toll plaza, Massachusetts, connecting Interstate 90 to Interstate 91 and State Route 5. Distribution of traffic volumes, stop delays at cash lanes, and reduced speed distribution at electronic toll collection (ETC) lanes were used as

calibration variables, and the number of conflicts was used as a validation parameter. Results identified that the safest lane configuration was the one consisting of only ETC lanes, and the second-safest configurations were the ones that grouped ETC lanes and separated them from cash lanes.

In the second part of the study, a simulation model of the same toll plaza was created to be used in a fixed-base driving simulator with a 150 degree field of view. The objective of this part of the study was to investigate drivers' behavior when they are exposed to different lane configurations and traffic conditions at toll plazas. Independent variables of this study were lane configuration (i.e., which lanes were signed as "E-ZPass" and "Cash"), origin-destination of the subject vehicle (i.e., right or left origin ramp, right or left destination ramp), traffic queue (i.e., having a queue or not), traffic composition (i.e., having a leading heavy vehicle or not), and customer type (i.e., cash or E-ZPass). The result of this simulation study was expected to give a better understanding of drivers' behavior at toll plazas and might lead to safer toll plaza designs.

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CHAPTER 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. Toll plazas are among the most complex road structures. 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. Since electronic toll collection (ETC) technology has been introduced, the complexity of toll plazas has increased greatly. According to Mohamed et al. (*1*), drivers' decision-making process as they approach a toll plaza has become more complex due to the advent of ETC technology. Greater mental workload is placed on drivers and more attention is needed. This might have a direct correlation with crash risk and near-miss rate (*1*). One mitigation effort that could alleviate this effect would be optimization of lane configuration at the plaza. The term "lane configuration" means placing lanes with different toll collection technologies in a specific order at a toll plaza (*1*).

Since the advent of ETC lanes, many studies have been focused on efficiency and performance of electronic toll collection systems; however, less research has been done on their safety impacts. Apparently, each state transportation agency has its own approach on lane configuration and toll plaza design, once there are both cash and ETC lanes available at the toll plaza. In some states, such as New Jersey, ETC lanes are placed in the middle lanes to reduce the number of lane changes and potential conflicts. Some other agencies put ETC lanes in the farthest right and left lanes of the roadway to avoid low-speed cash customers' crossing ETC lanes to reach their desired lane or exit ramp.

Florida, Texas, and Colorado have all-ETC-lane toll booths in some cities. Having all lanes at a toll plaza enhanced by ETC technology would reduce the number of choices available to drivers and decrease their lane-changing incentives. As a result, a number of potential conflicts and events are supposed to be reduced under this condition. However, to be able to serve cash customers with an all-ETC lane configuration, camera toll-enforcement technology is used to take a picture of the license plate of non-ETC customer vehicles and then sends the bill for the toll to the vehicle owner's address. This study investigates some of the different lane configuration scenarios in order to determine the safest lane configuration for an off-ramp toll plaza with close merging and diverging ramps.

Underlying Objective

The objective of this study is to investigate the effect of toll plaza design and traffic conditions on drivers' behavior and traffic safety at toll plazas.

The base case of this study was the West Springfield toll plaza, located at Exit 4 of the Massachusetts Turnpike. The location provided an ideal base case, given that it was located at the intersection of two major interstates and a primary state route (Interstate 90, Interstate 91, and State Route 5) and the on-ramps and off-ramps were too close to each other, allowing only a short amount of time for drivers to select their lane and perform the required maneuvers to switch to their target lane.

Existing lane configuration at the study site was made up of two traditional cash lanes in the far right and far left lanes of the plaza, and two dedicated ETC lanes in the middle.

CHAPTER 2: BACKGROUND

Toll plazas rank among the most complex driving environments, in terms of number of conflicts and events. There are few roadway elements that might compete with toll plazas in terms of complexity. This is due to the large amount of stimuli presented to drivers in a short amount of time. Numerous signs and pavement markings give required information to drivers to make an appropriate lane choice, but at the same time, they result in high mental workload. Adding ETC lanes to traditional toll plazas has improved the efficiency of toll collection but increased the drivers' involvement and has impacted roadway safety. To date, there are few studies investigating safety issues at toll plazas. This chapter reviews previous work that has been done on toll plaza performance and safety analysis.

Although ETC technology causes an increase in throughput capacity of the plaza and reduction in congestion and amount of emissions, it might increase the probability and severity of collisions due to the speed variance between cash lanes and ETC lanes (*2*).

An analysis conducted using New York Thruway crash data from 1992 to 1998 by the New York State Thruway Authority showed that the number of crashes would increase with an increase in the prevalence of ETC lanes. However, crash rate, which is the number of crashes per throughput traffic volume, decreased or remained unchanged. According to the same study, common crash types within toll plazas with a combination of ETC and cash lanes are as follows:

- Rear-end crash
- Sideswipe crash

- Fixed-object collision
- Back-into crash
- Pedestrian-related crash

Rear-end crashes have the highest frequency. They are more frequent during peak hours and in the lanes that have queues. The most common reasons for sideswipe crashes and fixed-object collisions are merging movements and high-speed driving, respectively. Usually, pedestrian-related crashes have the lowest frequency at toll plazas (*2*).

McKinnon (*3*) used a computer-based static evaluation to conclude that drivers' lane choice is derived by minimizing travel time, and even a short queue (e.g. 2 to 3 vehicles) at toll plaza would be an incentive for drivers to change lanes. He also found that drivers' lane decision at toll plazas is based on the relative transaction time at ETC and cash lanes. For combo lanes, which serve both cash and ETC customers, motorists instinctively weigh the risk of waiting behind a cash customer versus the risk of waiting behind slower-moving heavy vehicles in an ETC lane. Combo lanes might increase drivers' inattention while at the same time reducing vehicle throughput and increasing delays (*3*).

According to Mohamed et al. (*1*), toll lane type, vehicle deceleration rates, final velocity, number of toll lanes, and volume of crossing traffic between lanes would affect the location of conflict points at a toll plaza. The authors also stated that the number of conflicts would decrease by increasing the number of ETC lanes at a plaza, since ETC lanes result in a more organized traffic flow through the toll plaza (*1*).

Mohamed et al. also acknowledged that finding an optimum lane configuration for a toll plaza is one of the most difficult tasks in toll plaza design. Each configuration should provide services to all payment types and not be confusing for the drivers (*1*).

According to Mohamed et al., having queues at the plaza, especially during peak hours, leads to more rear-end conflicts. One of the factors that increases rear-end collisions during congestion is the motorists' loss of forward attention to the decelerating front vehicle while they are under the lane-decision process (*1*). By increasing toll booth throughput capacity, ETC lanes can help reduce the number of rear-end conflicts. However, there were two major problems with ETC lanes. The first problem was unfamiliarity among motorists who often stop at the plaza in an attempt to understand the payment methods. The other issue was the speed variation between cash lanes and ETC lanes that increased the probability of conflicts. All things considered, the ETC system decreased the level of safety at toll plazas (*1*).

According to Sze et al. (*4*), although throughput capacity of toll booths increases by adding ETC lanes, lane-changing movements between ETC and cash lanes increase the probability of conflicts. To account for this effect, the authors introduced a "weaving ratio" parameter, which is the number of lane-changing movements across ETC lanes compared to the total possible lane-changing movements. They found that with an increase in traffic volume, crash risk would increase for inbound traffic and decrease for outbound traffic. In total, the rate of increase in the number of traffic crashes would be less than the rate of increase in traffic volume. Thus, crash risk would decrease as the traffic volume increases. This might be due to an average speed reduction during congested conditions. Sze et al. also stated that crash likelihood downstream of the plaza is not sensitive to traffic volume, because the number of interactions downstream of the plaza, is small (*4*).

Drivers' lane change behavior is a contributing factor in toll plaza conflicts and events. In fact, it is an important parameter in microsimulation studies of toll plazas. As Mudigonda et al. (*5*) mentioned in their study, lane decision-making process for a driver depends on complex intervehicle conditions. The exit lane destination and queue lengths at each lane affect drivers' decisions. Mudigonda et al. also stated that the utility of each lane for each driver depends on the travel time associated with that lane and the total number of lane decisions a driver has already made before choosing that lane. Macroscopic simulation software could not capture drivers' lane-changing behavior. Microscopic models, such as SimTraffic, Paramics, and VISSIM, employ driver behavior models, but they do not have a built-in toll plaza toll pack (*5*).

Russo (*6*) utilized a toll plaza queuing model, SHAKER, to represent traffic characteristics observed in the field. The author collected demand, throughput, queue lengths, vehicle types, lane choice, processing time, payment type, whether the vehicle arrived during a queue or not, arrival time, departure time, and interarrival time between vehicles. The author selected throughput and capacity of a toll plaza per hour as its measure of effectiveness (MOE). If the MOE from the simulation model was different from field data, key parameters were re-examined and calibration parameters were changed. After multiple trials and errors, calibration was completed (*6*).

Wong et al. (*7*) reported that lane-searching process was the main cause of crashes. They used number of lane-changing maneuvers and number of conflicts, situations in which a vehicle needs to brake or steer suddenly to avoid a collision, as surrogate measures of crash risk (*7*).

The Smith and Wilbur Smith Associates study (*8*) stated that to increase the level of safety, the speed difference between ETC and cash lanes needs to be reduced and lanes with the same payment method should be clustered (*8*).

Some studies have used the Surrogate Safety Assessment Model (SSAM) for safety analyses at intersections or roundabouts, and the results of SSAM showed an acceptable fit to the field data for those studies. However, there are not many safety analyses done using this software to investigate safety at toll plazas. SSAM analyzes vehicle trajectory data files that are generated by microsimulation software. SSAM can support trajectory data files of four simulation software packages, including PTV (VISSIM), Transportation Simulation Systems (Aimsun), Quadstone (Paramics), and Rioux Engineering (TEXAS). It has two thresholds to define vehicle-to-vehicle conflicts. One is time-to-collision (TTC), with a default value of 1.5 seconds, and the other one is post-encroachment time (PET). The values for the thresholds can be changed by the user to fit the real condition. The results would be displayed in a table representing number of conflicts categorized in tree types (including rear-end, crossing, and lane-changing conflicts). The results could also be presented in conflicts and events map. T-test comparison could also be done on two sets of trajectory files in SSAM (9).

CHAPTER 3: MICROSIMULATION

3.1. INTRODUCTION

This chapter presents the safety analysis through microsimulation models. A model of a 50-foot sketch of an off-ramp toll plaza was built in VISSIM. In order to do safety analysis, the Surrogate Safety Assessment Model (SSAM) provided by the Federal Highway Administration was used as supplementary software, which took the vehicle trajectories from VISSIM and conducted a safety analysis. The data used for the calibration of the model were captured from a pair of videos recorded in 2012.

Depending on the arrangement of the lane types (i.e., cash or E-ZPass), the trend of weaving maneuver may change, and so do the number and type of conflicts and events. The goal of this part of the study was to compare the level of safety across five representatives of different lane configurations and find the design with the minimum number of conflicts and less severe conflicts.

In this approach, drivers' behavior was not a variable, and the default values from the software package were used across all the different lane configurations. Different lane configurations were all tested under the same conditions. This study proves the applicability of microsimulations on safety analysis at toll plazas and provides a better understanding of the effect of toll plaza design on traffic safety.

The methodology, specifications of the models, and results are presented in the following sections.

3.2. METHODOLOGY

The microsimulation model was created based on the West Springfield toll plaza, which provides an ideal base case since it connects major interstate highways and a primary route with high traffic demand (Interstate 90, Interstate 91, and State Route 5). Also, the distance between the merging ramps upstream of the plaza and the diverging ramps downstream of the plaza is just about 500 feet, which would cause a dense, weaving maneuver area and would give less longitudinal space for the drivers to switch lanes (see Figure 1).

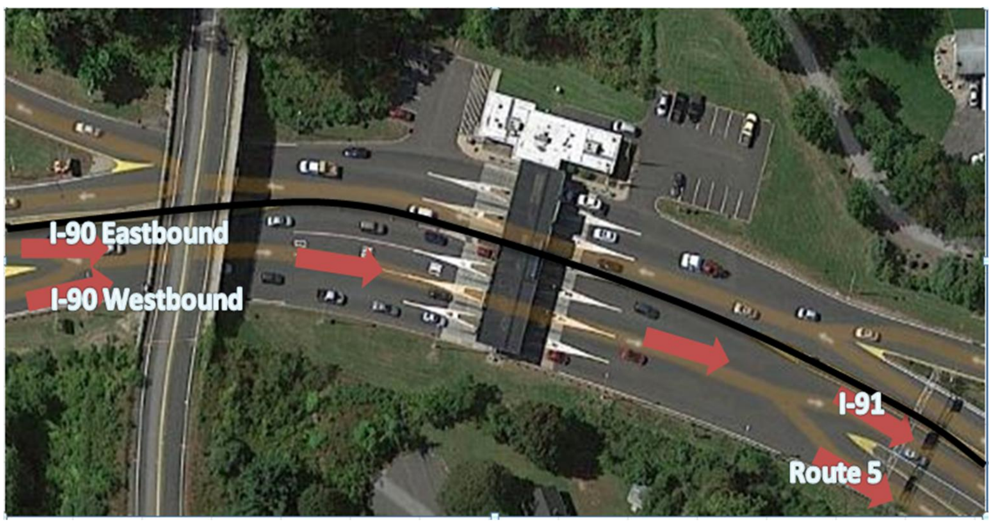


Figure 1. West Springfield toll plaza

The existing lane configuration at the subject toll plaza, as shown in Figure 2, is made up of two traditional cash lanes in the far right and far left lanes of the plaza, and two dedicated ETC lanes in the middle.

Figure 2. West Springfield toll plaza lane configuration

Conflicts and events that were captured and defined from the video collected in the field were as follows:

1. Immediate lane-changing maneuvers
2. Hesitation to make lane decisions
3. Driving slowly in E-ZPass lanes
4. Stopping before the plaza and changing lanes
5. Driving in reverse gear (backing up)
6. Secondary conflicts (e.g., braking because of an intruding vehicle entering from another lane, which could lead to a rear-end collision or lane-changing collision).

The VISSIM model was calibrated using traffic volume distribution, traffic composition of heavy vehicles and passenger cars, stop delay distribution at cash lanes, and speed reduction at ETC lanes from recorded video. The model was then validated by comparing the number of conflicts that occurred in the simulation versus field video data. After calibration and validation of the model, five scenarios consisting of different lane configurations of ETC and cash lanes were created and compared to the base case.

Since VISSIM does not have any safety analysis tool packs, the vehicle trajectories taken from VISSIM were imported into the Surrogate Safety Assessment Model (SSAM), a safety assessment software provided by the Federal Highway Administration (FHWA), for safety analysis. Although conflicts defined in SSAM are limited to rear-end conflicts, lane-changing conflicts, and crossing conflicts, the software was able to fairly represent the traffic safety conditions and the conflicts observed at the plaza.

3.3. DATA COLLECTION

Vehicle-by-vehicle origin-destination data was collected from recorded videos from two traffic cameras at the West Springfield off-ramp toll plaza, Exit 4 of the Massachusetts Turnpike, in December 2012. The two cameras were mounted on top of a bridge upstream of the plaza. One of the cameras faced toward the plaza and the diverging lanes after the plaza, and the other one faced away from the plaza toward the merging lanes entering the plaza, as shown in Figure 3.

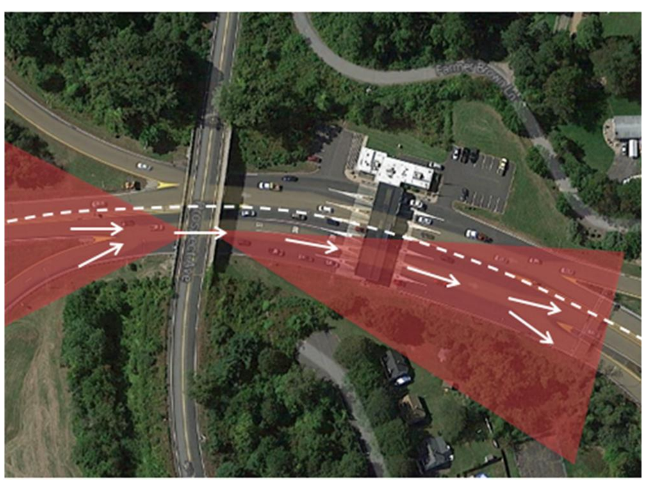


Figure 3. Camera placement and range of vision

Values collected from the video and used as independent variables to build the model are described as follows.

Traffic volume and vehicle composition

The number of vehicles entering the plaza and percentage of heavy vehicles (HVs) coming from each of the two entry lanes were extracted separately. In one hour, 840 vehicles entered the plaza from I-90 Westbound and 748 from I-90 Eastbound. About 6% of I-90 Westbound entering traffic and 16% of I-90 Eastbound entering traffic consisted of HVs. Additionally, 62% and 69% of the total entering traffic from each lane used E-ZPass lanes, respectively.

Origin-destination matrix

The two videos were recorded simultaneously from the two cameras placed back to back. Vehicles originating from each entrance lane on the first camera were tracked to the other camera. Their lane choice and then their exit lane were documented. An origination-destination matrix was created from that video.

Dwell time

Dwell time was recorded for vehicles using cash lanes. The average dwell time was 3.78 seconds for passenger cars and 21.0 seconds for heavy vehicles.

Speed

The reduced speed limit for ETC lanes is 15 mph (24 kph). The average speed of passenger vehicles and HVs using these lanes was 18.6 mph (30 kph) and 15.5 mph (25 kph), respectively. The speeds were collected from the field video data. The length of some pavement markings was extracted from the field's map, then the timing of the vehicles traveling along that segment was recorded. The speed was calculated using those data.

3.4. SCENARIO LAYOUT

3.4.1. Variables

Lane configuration is the only independent variable used in this approach. Traffic volume, stop time at cash lanes, and reduced-speed distribution at E-ZPass lanes are taken from the field as calibration parameters.

3.4.2. Experimental Design

Among 16 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 cash and E-ZPass customers) and two E-ZPass lanes.

Scenario 1 was the base case, having two cash lanes in the far left and far right of the toll plaza and two E-ZPass lanes in the middle, similar to the study field lane configuration. In Scenario 2, all of the lanes were dedicated ETC, lanes as shown in Figure 4. In Scenario 3, lanes 1 and 3 were dedicated ETC lanes, and lanes 2 and 4 were cash lanes. In Scenario 4, lanes 1 and 2 were dedicated ETC lanes, and lanes 3 and 4 were cash lanes. Finally, in Scenario 5, lanes 1 and 4 were combined ETC and cash lanes, while lanes 2 and 3 were dedicated ETC lanes. The scenarios represented the effect of grouped payment methods of ETC and cash lanes and the interaction zones between them. Scenario 2 was used to analyze the border of that clustered payment method.

Scenarios	Lane 1	Lane 2	Lane 3	Lane 4
Scenario 1 Base Case	CASH ONLY	E-ZPass ONLY NO CASH	E-ZPass ONLY NO CASH	CASH ONLY
Scenario 2	E-ZPass ONLY NO CASH	E-ZPass ONLY NO CASH	E-ZPass ONLY NO CASH	E-ZPass ONLY NO CASH
Scenario 3	E-ZPass ONLY NO CASH	CASH ONLY	E-ZPass ONLY NO CASH	CASH ONLY
Scenario 4	E-ZPass ONLY NO CASH	E-ZPass ONLY NO CASH	CASH ONLY	CASH ONLY
Scenario 5	CASH OR E-ZPass	E-ZPass ONLY NO CASH	E-ZPass ONLY NO CASH	CASH OR E-ZPass

Figure 4. Lane configuration of all the scenarios built in VISSIM

3.5. MODELING

The model of the plaza was made using a group of four parallel links as four toll booth lanes. Stop signs with a stochastic normal distribution were placed in the middle of the cash lanes to have vehicles stop for a certain amount of time. The average dwell time was set to 3.78 seconds for passenger cars and 21.0 seconds for trucks.

A reduced speed limit zone feature was used in ETC lanes to replicate the 15 mph reduced speed limit zone near the toll booth.

Static routing was used based on the traffic distribution taken from field data. This resulted in the distribution of traffic in the model being strictly determined to match the real-world conditions observed.

A total of five simulation models were created, each with different lane configurations, as shown in Figure 4. Each simulation model had seven simulation runs with different random seeds, each of 10 minutes run time. The warm-up period at the start of each run was 30 seconds.

Each simulation run generated a trajectory file containing trajectories of all the vehicles appearing in the simulation. All trajectory files of the seven different runs of each scenario were imported into SSAM as a set. Conflict and event analysis was conducted on each run separately. Runs with the maximum and minimum number of conflicts were excluded from the analyses, so that a total of five runs were reported as the result of the model.

The SSAM average number of rear-end, lane-changing, and crossing conflicts from the base case scenario (i.e., the scenario with a lane configuration similar to the design in the actual field) was compared to the conflicts observed from video files to validate the model. The average number of rear-end conflicts before reaching the toll plaza was 8.6, and the corresponding number from the video was 9 conflicts. The number of lane-changing conflicts was 4.4 in the model, and it was 5 conflicts in the field. No crossing conflict was observed in the model or in the actual field. Since there was about a 92.3% match between the total number of conflicts in the simulation and in the field, the model was accepted and considered as a valid representative of traffic safety conditions in the field. As the result, the rest of the scenarios were modeled.

3.6. RESULTS AND CONCLUSIONS

A conflict and event study was conducted in SSAM, using the trajectory output data files from VISSIM for five different scenarios with ten minutes of simulation time. 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., while 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 1 to 4 show the results of t-tests between the base scenario and each of the four other scenarios.

Table 1. T-test results from SSAM between base scenario and Scenario 2

	Scenario 2 E-E-E-E		Base Scenario C-E-E-C						
SSAM Measures	Mean	Variance	Mean	Variance	t value	t critical	Signifi-cant	Mean Diff.	Better Performed Scenario
TTC (Sec)	0.917	0.298	0.524	0.429	2.517	1.66	YES	0.393	2
PET (Sec)	1.36	1.257	1.057	2.348	1.139	1.66	NO	0.303	N/A
MaxS (m/s)	6.185	8.903	6.92	5.18	-1.665	1.66	YES	-0.735	2
DeltaS (m/s)	2.983	2.448	4.524	7.393	-3.753	1.66	YES	-1.541	2
DR (m/s^2)	-0.981	4.475	-0.244	3.719	-2.074	1.66	YES	-0.737	1
MaxD (m/s^2)	-2.994	10.666	-0.702	5.9	-4.836	1.66	YES	-2.293	1
MaxDeltaV (m/s)	1.808	1.162	2.589	2.718	-2.961	1.66	YES	-0.78	2

Note: N/A= not applicable

Letter "E" stands for electronic lane and letter "C" stands for cash lane

The level of significance for the t-test analysis was 0.05. The results show that Scenario 2, with all the lanes designated as E-ZPass lanes, had a higher TTC and lower MaxS, 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 and less weaving maneuvers that take place with this design.

Table 2. T-test results from SSAM between base scenario and Scenario 3

	Scenario 3 E-C-E-C		Base Scenario C-E-E-C						
SSAM Measures	Mean	Variance	Mean.	Variance	t value	t critical	Signifi-cant	Mean Diff.	Better Performed Scenario
TTC (Sec)	0.688	0.519	0.524	0.429	1.13	1.66	NO	0.164	N/A
PET (Sec)	1.33	2.583	1.057	2.348	1.171	1.66	NO	0.273	N/A
MaxS (m/s)	6.285	4.95	6.92	5.18	-2.03	1.66	YES	-0.635	3
DeltaS (m/s)	4.073	5.175	4.524	7.393	-1.302	1.66	NO	-0.451	N/A
DR (m/s^2)	-0.232	5.022	-0.244	3.719	0.043	1.66	NO	0.013	N/A
MaxD (m/s^2)	-0.669	7.649	-0.702	5.9	0.094	1.66	NO	0.033	N/A
MaxDeltaV (m/s)	2.324	1.919	2.589	2.718	-1.154	1.66	NO	-0.265	N/A

Note: N/A= not applicable

The only significant difference observed between Scenario 3, which has ETC lanes in lanes 1 and 3, and the base scenario is that MaxS is lower in Scenario 3. The values of all other measures did not have any significant differences between these two designs. This implies that there exists no difference in the probability of collisions between these two cases.

Table 3 shows that MaxS, DeltaS, and (MaxDeltaV) are significantly lower in Scenario 4, which has two ETC lanes to the far left, 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 3. T-test results from SSAM between base scenario and Scenario 4

	Scenario 4 E-E-C-C		Base Scenario C-E-E-C						
SSAM Measures	Mean	Variance	Mean.	Variance	t value	t critical	Signifi-cant	Mean Diff.	Better Performed Scenario
TTC (Sec)	0.48	0.39	0.524	0.429	-0.337	1.66	NO	-0.044	N/A
PET (Sec)	0.917	1.778	1.057	2.348	-0.816	1.66	NO	-0.14	N/A
MaxS (m/s)	5.549	7.195	6.92	5.18	-3.841	1.66	YES	-1.372	4
DeltaS (m/s)	3.3	4.279	4.524	7.393	-3.318	1.66	YES	-1.212	4
DR (m/s^2)	-0.403	2.738	-0.244	3.719	-0.807	1.66	NO	-0.159	N/A
MaxD (m/s^2)	-1.298	6.906	-0.702	5.9	-2.313	1.66	YES	-0.596	1
MaxDelta V (m/s)	1.83	1.219	2.589	2.718	-3.532	1.66	YES	-0.759	4

Note: N/A= not applicable

As represented in Table 4, Scenario 5, which has two ETC lanes in the middle and two combination lanes on the sides, 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.

Table 4. T-test results from SSAM between base scenario and Scenario 5

	Scenario 5 Comb-E-E-Comb		Base Scenario C-E-E-C						
SSAM Measures	Mean	Variance	Mean.	Variance.	t value	t critical	Signifi-cant	Mean Diff.	Better Performed Scenario
TTC (Sec)	0.725	0.455	0.524	0.429	1.259	1.66	NO	0.201	N/A
PET (Sec)	1.372	2.219	1.057	2.348	1.132	1.66	NO	0.315	N/A
MaxS (m/s)	6.12	8.678	6.92	5.18	-1.843	1.66	YES	-0.8	5
DeltaS (m/s)	3.673	3.815	4.524	7.393	-1.969	1.66	YES	-0.851	5
DR (m/s^2)	-0.519	3.02	-0.244	3.719	-0.828	1.66	NO	-0.275	N/A
MaxD (m/s^2)	-1.447	6.552	-0.702	5.9	-1.741	1.66	YES	-0.745	1
MaxDeltaV (m/s)	2.35	1.799	2.589	2.718	-0.842	1.66	NO	-0.239	N/A

Note: N/A= not applicable

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, three types of conflicts that have been studied in SSAM are crossing conflicts, rear-end conflicts, and lane-changing conflicts. The result of the number of conflicts for 600 seconds of simulation time for each scenario is provided in Table 5. The number of conflicts represented in Table 5 is the sum of the conflicts that takes place both before reaching the plaza and after the plaza, before divergence of the road.

Table 5. SSAM conflicts results for 600-second simulation

	Base Scenario	Scenario 2		Scenario 3		Scenario 4		Scenario 5	
SSAM Measures	Mean	Mean	Significant difference	Mean	Significant difference	Mean	Significant difference	Mean	Significant difference
Crossing	0	0.4	NO	0.2	NO	1.2	NO	0	NO
Rear-end	9.4	2.4	YES	7.2	NO	10	NO	5	NO
Lane-changing	5.6	4.2	NO	4.6	NO	13.4	NO	2.2	YES
Total	15	7	YES	12	NO	24.6	NO	7.2	NO

The number of rear-end 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 5 serve E-ZPass 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 E-ZPass speed variance is lower as compared to that of the other configurations, since all four lanes are E-ZPass lanes.

According to the literature, since E-ZPass 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 E-ZPass lanes would be safer than a configuration consisting of a mixture of E-ZPass and cash. In practice, with this configuration with all E-ZPass 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 4, which had less severity of collisions as compared to the other scenarios, shown in Table 2 to Table 4. This could be because, unlike Scenario

3 and the base scenario, this scenario has only one ETC lane and cash lane adjacent to each other and no combination lane, 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.

In summary, an all-ETC lanes scenario performs best in terms of safety for this study location. Scenario 5, with both E-ZPass and combination lanes (see Table 5), would be the second-most safe scenario in terms of probability of crashes; from a conflict severity standpoint, this scenario is in third place after Scenario 4.

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.

3.7. DISCUSSION

This study proved the feasibility of modeling traffic conditions at a toll plaza and evaluating its safety using VISSIM and SSAM. Also, traffic safety was evaluated in different lane configurations at the toll plaza. All-ETC lanes, and use of both combination lanes and ETC lanes, are found as the safest and second-safest configurations, respectively. The third-safest condition is the design that separates different toll lane types (i.e., cash and E-ZPass lanes) from each other. 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, removing the split after the toll plaza, 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. Microsimulation analysis is unable to see those details. Hence, a simulation study in a virtual reality world would better illustrate those points. The next chapter of this thesis covers that question.

CHAPTER 4: DRIVING SIMULATION

4.1. INTRODUCTION

This chapter presents human behavior analysis at toll plazas through driving simulation. The same toll plaza from the first part of the study was modeled in Real Time Technology (RTI) SimCreator software. The virtual world created for the simulator was a 600 meters by 200 meters (1968.5 feet by 656.168 feet) sketch of the West Springfield toll plaza. Five variables, including toll plaza lane configuration (i.e., which lanes were signed as E-ZPass and Cash), traffic queue (i.e., having a queue or not), traffic composition (i.e., having a leading heavy vehicle or not), origin-destination of the subject driver (i.e., right or left origin ramp, right or left destination ramp), and customer type (i.e., cash or E-ZPass driver), were defined, in order to find their effect on drivers' lane choice. The result of this simulation study is expected to give a better understanding of drivers' behavior at toll plazas and could lead to safer toll plaza designs. Also, the result could be used to modify and enhance drivers' behavior parameters in microsimulation software like VISSIM.

4.2. PARTICIPANTS

Twenty licensed drivers, ten females and ten males between the ages of 18 and 60, participated in this experiment. Subjects were recruited through the Human Performance Lab (HPL) general recruiting email list and through general flyers of the HPL driving simulation studies that were posted in the University of Massachusetts, Amherst (UMass Amherst) campus area.

Subjects needed to have a valid U.S. driver's license and no special physical or health conditions that might eliminate or affect their driving abilities. They were required not to have experienced motion sickness, either in their own car as a passenger or driver, or in other modes of transport.

Participants were compensated $20 following the completion of all the tasks in the experiment. Withdrawal of the experiment in the middle of the session was compensated proportionally.

4.3. INSTITUTIONAL REVIEW BOARD APPROVAL

This research was approved by the University of Massachusetts, Amherst Institutional Review Board. The protocol title is "Safer-Sim: Safety & Lane Configuration at Toll Plazas Protocol," and the protocol number is 2015-2563.

4.4. METHODOLOGY

Understanding drivers' lane choice behavior requires either a close scrutiny of their behavior in the field or the creation of a simulation environment similar to that of the field and looking at drivers' behavior in a controlled environment.

Real field study is more realistic but makes it hard to find the effect of each single variable independent of environmental conditions, since it is hard to keep all other variables constant in different experiments. Because of that, the toll plaza study site was created in the full-scale driving simulator to study subjects' behavior in a controlled environment.

This study looked at five factors affecting drivers' lane choice, including toll plaza lane configuration, origin and destination of the subject vehicle, traffic condition (i.e., having queue or not), traffic composition (i.e., having a lead heavy vehicle or not), and customer type (i.e., cash customer or ETC customer).

4.4.1. Driving Simulator and Equipment

A virtual reality of a four-lane toll plaza environment was created in the Arbella Human Performance Laboratory (HPL) at UMass Amherst in order to test drivers' behavior in a simulated toll plaza environment. The simulation system was a full-scale driving simulator supported by RTI SimCreator technology.

The RTI fixed-base, full cab (Saturn cab) driving simulator consists of four processing channels, namely the host, right, center, and left channels. Right, center, and left channels processed the image feed that was projected through right, center, and left projectors, respectively, over three screens that provided a horizontal view of 150 degrees and vertical view of 30 degrees of the forward driving scene. The visuals projected on the screens were refreshed by the frequency of 60 Hz and the display resolution of the image was 1024 by 768 dpi on each screen. The simulated sound tracks played via a surround sound system replicated both, the engine sound as well as the sound of the environment and ambient traffic. The sedan could be operated like a normal car (see Figure 5).

Figure 5. Driving simulator at Human Performance Laboratory, UMass Amherst

The simulation environment was created through the Internet Scene Assembler (ISA), which has a library of roadway modules. Roadway structures that are not in the ISA library can be built in AutoCAD Civil 3D and/or SketchUp and Blender. Then the model is imported into ISA or added to the ISA library. The published world that is created in ISA can be run using FullSim model in SimCreator technology from the host channel.

Since there was no toll plaza module in the ISA library, and considering that the geometry of the toll plaza needed to correspond to the field environment, the toll booths and the specific roadway geometry of the study site were built and added to the ISA library. In order to have a compatible output from all of the three graphical software packages, specific versions of each of the software were used, including AutoCAD Civil 3D 2013, SketchUp Pro 2014, and Blender 2.49b.

An aerial image of the study site was imported into AutoCAD Civil 3D to copy the geometry of the road. Three frames of a 200 meter by 200 meter (656.168 foot by

656.168 foot) sketch of the roadway were created in AutoCAD Civil 3D. The plaza structure and the raised medians were created in SketchUp. Both Civil 3D and SketchUp drawings were then imported into Blender to be textured and exported with the right format for ISA. Blender has the feature to export .wrl file formats of the objects, which could be read by ISA after some changes to the files. Each closed polygon recognized as an object with a single texture, was exported separately with .wrl format. The .wrl files keep the physical shape, texture, direction, and relative positions of the objects, so as they are imported in ISA, each object sits in its correct place and orientation relative to the other objects.

Once the objects were imported into ISA, the whole scene was published to run in SimCreator. During the experiment, an ASL mobile eye tracker was used to monitor and record eye movements of subject drivers. The mobile eye tracker had two cameras, one facing toward the scene that recorded with the frequency of 30 frames per second and an infrared optic facing toward the subject's eye that also recorded with the frequency of 30 frames per second. The interleaved videos recorded by the eye tracker included a crosshair that showed where the driver was looking at on the virtual roadway during the experiment. The eye tracker has an accuracy of approximately 0.5 degrees of visual angle.

4.5. SCENARIO LAYOUT

4.5.1. Variables

As described previously, five independent variables were defined, including lane configuration, origin-destination, queue (at the closest lane with the same payment type), traffic composition, and customer type. The description of the variables is given in Table 6. Considering all the possible combinations of those five variables, having a four-lane toll plaza would lead to 512 possible scenarios. To restrict the number of testing scenarios, the lane configuration variables were narrowed down to the ones represented in Table 7**Error! Reference source not found.**. As a result of that, the number of possible scenarios was reduced from 512 to 96 scenarios. Among those, 20 scenarios were chosen for further analysis in this study. The final scenarios are also summarized in Table 6, and described in more detail in the following sections of this thesis report.

Table 6. Description of factors

Factor	Description	Specifications
Lane Configuration	Combination of E-ZPass and cash lanes	Cash–E-ZPass–E-ZPass–Cash
		E-ZPass–Cash–E-ZPass–Cash
		E-ZPass–E-ZPass–Cash–Cash
Origin/Destination	On/off ramps	Right-to-right
		Right-to-left
		Left-to-right
		Left-to-left
Traffic Queues	Having queue or not	With queue
		Without queue
Traffic Composition	Having lead heavy vehicles or not	With lead heavy vehicle
		Without lead heavy vehicle
Customer Type	E-ZPass or cash customer	E-ZPass customer
		Cash customer

Table 7. Lane configurations

Configuration 1	ETC–ETC–Cash–Cash
Configuration 2	ETC–Cash–ETC–Cash
Configuration 3	Cash–ETC–ETC–Cash

4.5.2. Experimental Design

Out of the 20 scenarios, 12 of them were E-ZPass scenarios and 8 were cash scenarios. The 12 E-ZPass scenarios were divided evenly among three lane configurations; each configuration was tested with different O-D and/or traffic compositions. The eight cash scenarios were evenly divided between two lane configurations; each configuration was tested with two different O-D and traffic queue conditions. Table 8 summarizes the testing scenarios.

Table 8. Testing scenarios

Customer Type	Lane Configuration	Scenario Level*	Scenarios
Cash	Configuration 3	Left to left with queue	Scenario 1
		Left to left without queue	Scenario 2
		Right to right with queue	Scenario 3
		Right to right without queue	Scenario 4
	Configuration 2	Left to left with queue	Scenario 5
		Left to left without queue	Scenario 6
		Right to right with queue	Scenario 7
		Right to right without queue	Scenario 8
ETC	Configuration 3	Right to left with lead truck	Scenario 9
		Right to left without lead truck	Scenario 10
		Left to right with lead truck	Scenario 11
		Left to right without lead truck	Scenario 12
	Configuration 2	Right to left with lead truck	Scenario 13
		Right to left without lead truck	Scenario 14
		Left to right with lead truck	Scenario 15
		Left to right without lead truck	Scenario 16
	Configuration 1	Right to left with lead truck	Scenario 17
		Right to left without lead truck	Scenario 18
		Left to right with lead truck	Scenario 19
		Left to right without lead truck	Scenario 20

*If a factor is not listed, it is in the null state. So, for example, in Scenario 9, nothing is listed at the scenario level for Traffic Composition or Traffic Queue. This implies that the lead vehicle is a passenger car and that there is no queue.

Cash customer scenarios were designed to investigate the effect of a queue with different lane configurations on drivers' lane change behavior. With these scenarios, the closest lane to the subjects' path, considering their origin and destination, would be blocked by a queue of five vehicles, and the driver needed to decide between staying behind the queue and avoiding a lane change or choosing the farther lane to avoid the queue. Each of the queued scenarios had a similar base case scenario for comparison, in which all the variables were the same, except that there was no queue in drivers' travel lane (see Figure 6).

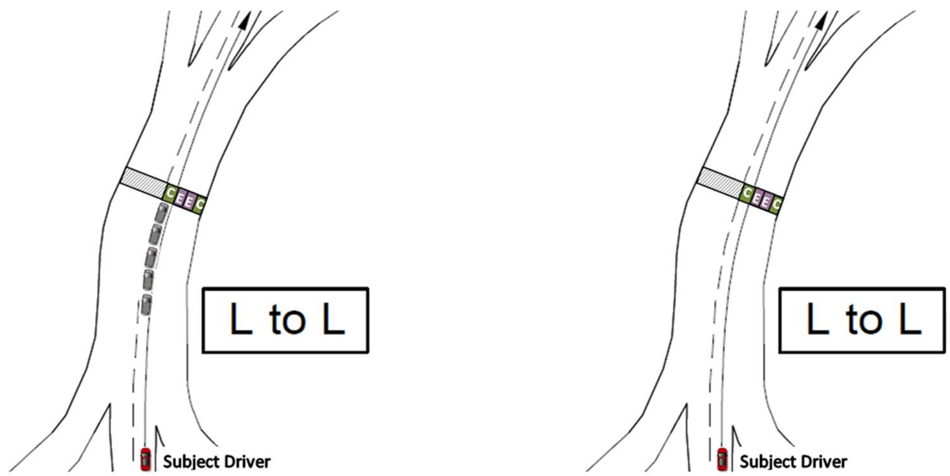


Figure 6. Sketch of two cash scenarios: Scenario 1 (left) and Scenario 2 (right)

E-ZPass customer scenarios are designed to study the effect of having a slow moving lead heavy vehicle in front of the drivers' travel lane with different origin-destinations and three different lane configurations. Each lane configuration and origin-destination scenario is tested both, with and without the slow moving lead heavy vehicle to investigate if drivers' lane choice would change due to having a truck ahead in the travel lane or not (see Figure 7).

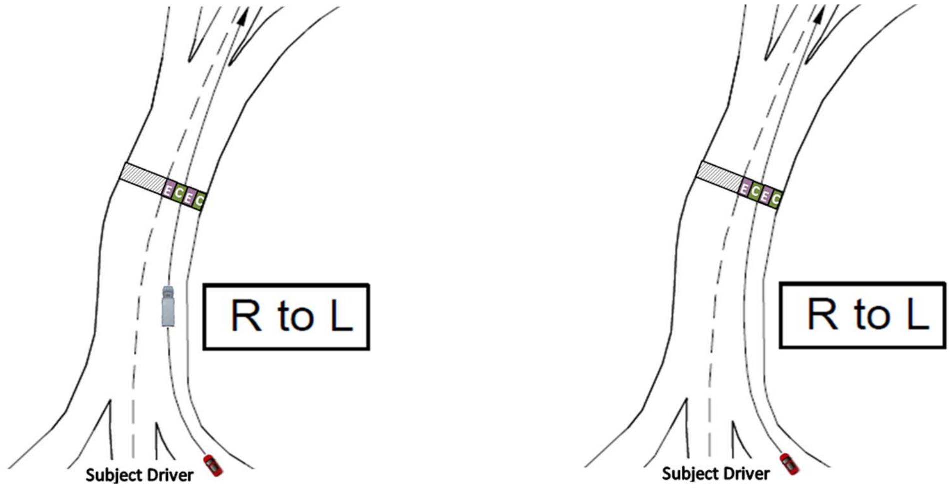


Figure 7. Sketch of two E-ZPass scenarios: Scenario 13 (left) and Scenario 14 (right)

This study used 20 subjects in total, and each subject participated in all 20 scenarios. Half of the subjects started with the E-ZPass scenario set and completed all the scenarios in that set before switching to cash scenarios, and half of them started with the cash scenario set and complete it before switching to the other one. This arrangement was set to counterbalance the learning effect due to the order of presentation. The experiment was designed in such a way that each two sequenced scenarios would have different lane configurations and differ in scenario level, either in terms of O-D or in terms of having/not having queue (having/not-having trucks in the E-ZPass cases). The above algorithm was coded in MATLAB in order to generate described pseudo-random scenario configurations.

4.6. PROCEDURE

Each participant took part in one session experiment at the Arbella Human Performance Laboratory (ELab I Building, Room 110), located at the College of Engineering at UMass Amherst. The session was approximately 40 to 50 minutes. Once a participant arrived at the lab, he or she was asked to read and sign a consent form that explained the experiment and asked about his or her willingness to participate in the study. Then, participants were given one questionnaire on their demographic information and one on their physical conditions, and asked if they had motion sickness history. A very similar simulator sickness questionnaire was given to them after they finished the experiment. Upon the completion of the forms, each participant was moved to the vehicle, the eye tracker was set on the participant, and complementary instructions were given. A sample practice drive was shown to enable the participant to become familiar with the environment and the vehicle. Participants were asked to drive at 35 miles per hour on ramps, stop at cash lanes, and reduce their speed to 15 miles per hour at E-ZPass lanes.

4.7. RESULTS AND CONCLUSIONS

Data used in this study were collected from an ISA head-mounted eye tracker and subject drivers' lane choice behavior that was observed by the experimenter. Among the total of 20 subjects, 1 person dropped out of the study after completing the cash set of scenarios, due to simulation sickness symptoms. Drivers' lane choice was captured, as well as the number of glances at the toll signs and the duration of travel in the final target lane, as a measure of timeliness/lateness of drivers' lane decision making.

Drivers had two lane choices in each scenario. The scored lane choice behavior was defined as a binary variable, in the sense that if the driver picked the closest possible lane to his or her driving path upstream of the plaza, the "path distance" variable was scored as 0, and if he or she chose the farthest lane, the variable was scored as 1. The objective was to find a trend in drivers' lane decision making.

4.7.1. Summary of Results

Two types of statistical tests were done on the drivers' lane choice, conditional logit tests to find the effect of different variables and also sets of pairwise t-tests to compare each pairs of scenarios separately. Three sets of conditional logit tests and 12 sets of Pairwise Wilcoxon tests were conducted on data.

Before moving to the statistical tests, some comparisons on drivers' performance in different scenarios are provided in Figure 8 to Figure 12.

According to the results, drivers are more prone to choose the right lane than the left lane (Figure 8 to Figure 12). In Scenario 2, with lane configuration 3 and origin and destination both on the left ramp, 90% of drivers chose the closest left lane and still 10% of drivers chose the farthest right lane, which cost them three lane crossings before the plaza and three lane crossings after the plaza to get back to the left lane to take the left ramp. However, in Scenario 4, by keeping all the conditions the same as those of Scenario 2 except changing origin and destination to be on the right, all of the drivers chose the closest lane on the right end, without any exception. Comparing Scenarios 6 and 8 in Figure 9 also shows that with lane configuration 2 and origin-destination on left ramp, still 5% of drivers chose the right end lane, with the cost of two lane crossings. However, with the same condition but having origin-destination on the right, all the drivers chose the right end lane without exception. Comparing Figure 8 and Figure 9 shows that once the left end cash lane is shifted to the right, fewer drivers would cross lanes aiming for the right lane.

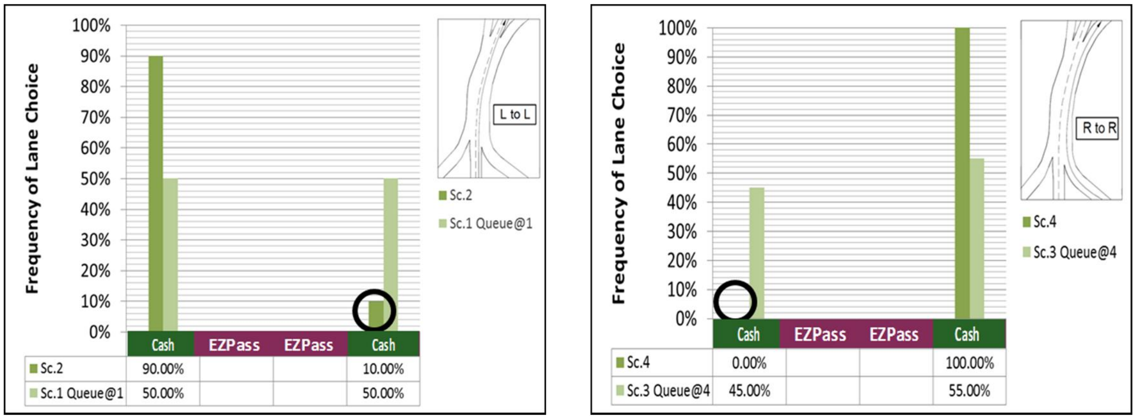


Figure 8. Frequency of lane choice in Scenarios 1 to 4

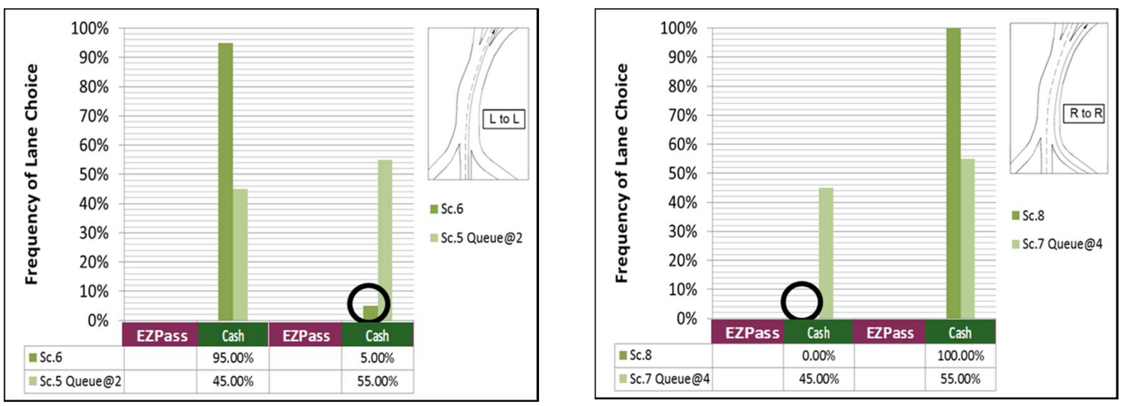


Figure 9. Frequency of lane choice in Scenarios 5 to 8

Comparing E-ZPass Scenarios 14 to 16 and Scenarios 18 to 20 shows that, in the same conditions and regardless of lane configuration, drivers have more incentive to pick the right lane than the left (Figure 10 and Figure 11).

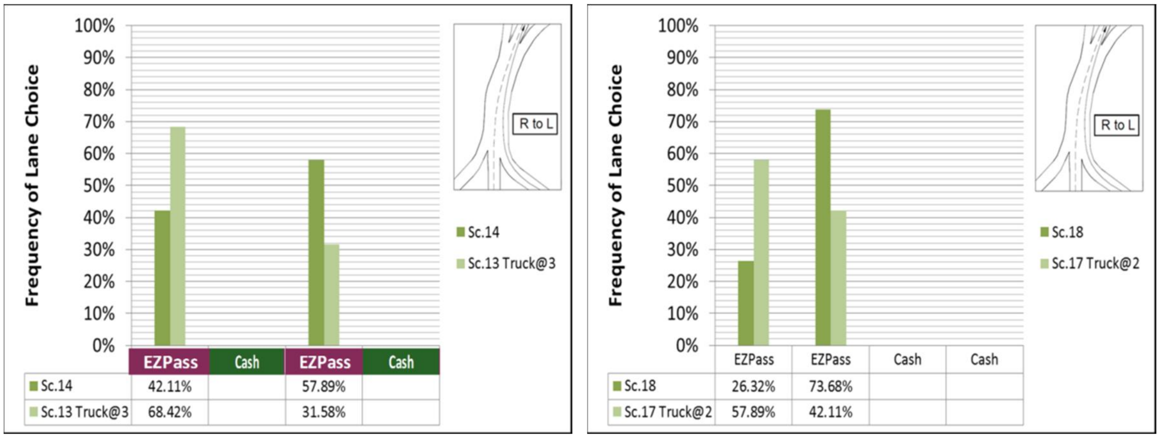


Figure 10. Frequency of lane choice in Scenarios 13, 14, 17, and 18

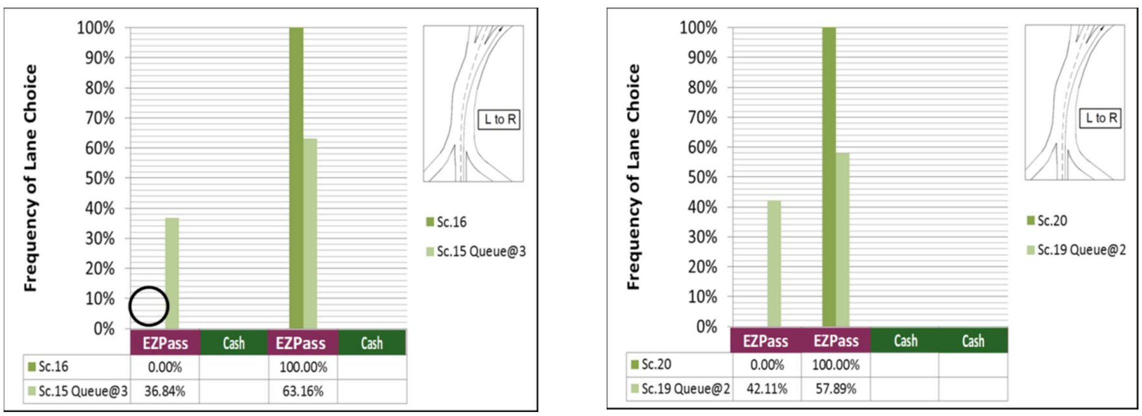
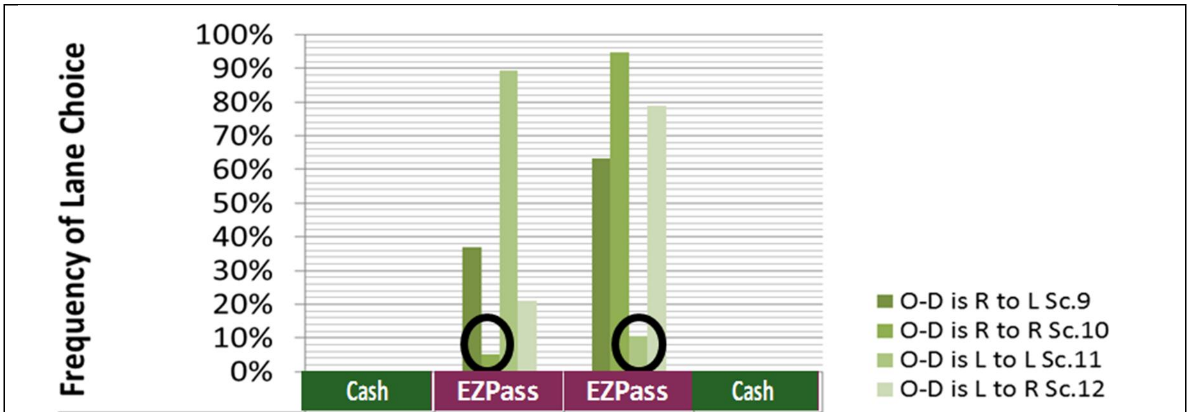


Figure 11. Frequency of lane choice in Scenarios 15, 16, 19, and 20

Comparing Scenarios 9 to 12, with equal origin and destination conditions, more drivers pick the right lane than the left (see Figure 12). In Scenario 11, with origin and destination both on the left, 10% of the drivers still switch to the right. However, with similar conditions having origin-destinations on the right, only 5% of drivers switch to the left lane. This could support the idea that drivers are more willing to switch to the right lane (Figure 12).



	Cash	EZPass	EZPass	Cash
O-D is R to L Sc.9		36.84%	63.16%	
O-D is R to R Sc.10		5.26%	94.74%	
O-D is L to L Sc.11		89.47%	10.53%	
O-D is L to R Sc.12		21.05%	78.95%	

Figure 12. Frequency of lane choice in Scenarios 9 to 12

4.7.2. Conditional Logit Test

To determine the significant difference in drivers' lane choice across different scenarios, three sets of conditional logit tests were conducted comparing cash scenarios, E-ZPass scenarios of lane configuration types 1 and 2, and E-ZPass scenarios across all lane configurations, excluding truck scenarios. The confidence interval was 5%. The dependent variable in all three sets was the binary variable of choosing the longest or shortest path upstream of the plaza. The variable is called path distance, and it would be 1 if the subject chose longest path upstream of the plaza, and 0 otherwise. The independent variables changed in each set.

Cash Scenarios (Scenarios 1 to 8)

The independent variables were origin-destination, queue, and lane configuration. Origin-destination in cash scenarios were either from left to left or from right to right. Left to left was set to 1 and right to right was set to 0. Queue variable was 1 if there was a queue of five vehicles in the closest lane to the subject's lane, and it was 0 if there was no queue. Cash scenarios were tested over two lane configurations (i.e., configuration 2 and configuration 3). The configuration variable was 1 if it was lane configuration 2, and 0 otherwise.

Based upon the result of the test, with 5% confidence interval, only queue had a statistically significant effect on drivers' lane choice (see Table 9).

Table 9. Cash scenarios conditional logit table

Path Distance	Coefficient	Standard Error	z	P>|z|	[95% Confidence Interval]	
Origin-Destination	0.79295	0.5841	1.36	0.175	-0.35181	1.93771
Queue	4.09191	0.79000	5.18	0.000	2.54352	5.64029
Configuration	0.15632	0.55993	0.28	0.780	-0.94112	1.25375

E-ZPass Configurations 1 and 2 (Scenarios 13 to 20)

The independent variables were origin-destination, having leading truck, and lane configuration. Origin-destination in E-ZPass scenarios with configurations 1 and 2 was either from left to right or from right to left. Left to right was set to 1, and right to left was set to 0. Truck variable was 1 if there was a slow lead heavy vehicle in the scenario, and 0 otherwise. The configuration variable was 1 if it was lane configuration 2, and 0 otherwise.

The results of the test, with 5% confidence interval, show that only origin-destination has a statistically significant effect on drivers' lane choice (see Table 10). It appeared that if origin was on the left ramp and destination was on the right exit, then drivers were more likely to switch to the right lane upstream of the plaza. However, if origin was on the right ramp and destination was on the left ramp, drivers stayed within the closest lane before the plaza and would switch to the left downstream of the plaza. It appears that drivers are more comfortable driving closer to the right side of the roadway.

The design of the truck variable in the experiments was not necessarily to block the shortest path to the driver, but considering the fact that drivers were more prone to pick the right lane as shown in the previous results and also in the E-ZPass scenarios without truck, trucks were located in the right lane regardless of origin-destination of the subject driver.

In other words, since a slow leading truck is not necessarily located in the closest lane to the subject, it might not necessarily be a potential incentive to pick a longer path, and its effect could not be captured by this test. However, its effect was analyzed through a Pairwise Wilcoxon test later in this report.

Table 10. E-ZPass scenarios with configuration 1 and 2 conditional logit table

Path Distance	Coefficient	Standard Error	z	P>|z|	[95% Confidence Interval]	
Origin-Destination	1.81533	0.43751	4.15	0.000	0.95782	2.6728
Truck	-0.32592	0.40534	-0.80	0.421	-1.12036	0.46853
Configuration	0.48739	0.40676	1.2	0.231	-0.30985	1.2846

E-ZPass Scenarios without Trucks (Scenarios 9, 12, 14, 16, 18, and 20)

The independent variables were origin-destination and lane configuration. Scenarios 9, 12, 14, 16, 18, and 20 were base E-ZPass scenarios without any slow lead heavy vehicle. The only variables between these sets of scenarios were lane configurations (i.e., configurations 1, 2, and 3) and origin-destination. Origin-destination in these scenarios was either from left to right or from right to left. Left to right was set to 1, and right to left was set to 0. The configuration 2 variable was 1 if it was lane configuration 2, and 0 otherwise. The configuration 3 variable was 1 if it was lane configuration 3, and 0 otherwise.

The result of the test, with 5% confidence interval, showed that only origin-destination had a statistically significant effect on drivers' lane choice (see Table 11). The result was very similar to the result of the previous test (E-ZPass scenarios with truck). It appeared that if drivers entered from the left ramp and wanted to exit to the right after the plaza (i.e., origin-destination was 1), they were more likely to switch to the right lane upstream of the plaza or, in other words, pick the longest path. But when they entered from the right ramp and wanted to exit to the left ramp after the plaza, they stayed with the closest lane to their current lane and switched to the left downstream of the plaza. Lane configuration in this case did not have any effect on drivers' lane decision.

Table 11. E-ZPass scenarios without truck conditional logit table

Path Distance	Coefficient	Standard Error	z	P>|z|	[95% Confidence Interval]	
Origin-Destination	3.68277	0.77852	4.73	0.000	2.15689	5.2086
Configuration 2	0.64843	0.66856	0.97	0.332	-0.66193	1.9588
Configuration 3	-0.39460	0.63248	-0.62	0.533	-1.6342	0.84504

4.7.3. Pairwise Wilcoxon Test

A pairwise comparison was conducted on scenarios to find out if there was any significant difference between each two pairs of scenarios. Since all of the variables were categorical, the Pairwise Wilcoxon test was used. The results are summarized in Table

12. It is shown that the Pairwise Wilcoxon test results comply with the conditional logit test results. The only difference is with the effect of leading truck on E-ZPass scenarios which was expected to be so. As explained in the previous section, the effect of truck could not have been tested through conditional logit test. However according to the Wilcoxon test, having truck has a statistically significant effect on drivers' lane choice.

Table 12. Pairwise Wilcoxon test results

H0	z	P>|z|	Note	Comply with Cond. Logit
Sc.1 = Sc.2	2.828	0.0047	Queue has a statistically significant effect on lane choice	Yes
Sc.3 = Sc.4	3.000	0.0027	Queue has a statistically significant effect on lane choice	Yes
Sc.5 = Sc.6	2.887	0.0039	Queue has a statistically significant effect on lane choice	Yes
Sc.7 = Sc.8	3.162	0.0016	Queue has a statistically significant effect on lane choice	Yes
Sc.13 = Sc.14	2.236	0.0253	Truck has a statistically significant effect on lane choice	No
Sc.15 = Sc.16	-2.646	0.0082	Truck has a statistically significant effect on lane choice	No
Sc.17 = Sc.18	2.121	0.0339	Truck has a statistically significant effect on lane choice	No
Sc.19 = Sc.20	-2.828	0.0047	Truck has a statistically significant effect on lane choice	No
Sc.2 = Sc.11	0.000	1.000	Customer type does not have a statistically Significant effect on lane choice	--
Sc.4 = Sc.10	-1.000	0.3173	Customer type does not have a statistically significant effect on lane choice	--
Sc.14 = Sc.16	-3.317	0.0009	Origin-dest. has a statistically significant effect on lane choice	Yes
Sc.18 = Sc.20	-3.742	0.0002	Origin-dest. has a statistically significant effect on lane choice	Yes

Eye Tracker Data Analysis

Eye-tracking videos were coded manually to find the number of glances drivers make at toll lane signs to investigate if there was any trend with drivers' lane decision making and their glance pattern at the signs, and if the trend changed across cash and E-ZPass drivers.

From the total of 20 subjects, 1 subject dropped the study after the cash set of scenarios due to simulation sickness symptoms. Some of the eye tracking videos were partially or completely impaired. In total 17 subject videos of the cash set of scenarios and 15 subject videos of the E-ZPass set of scenarios were used for the analysis.

In all the scenarios, drivers had only two lane options to pick that matched their payment method (i.e., two cash lanes and two E-ZPass lanes). Subject drivers who chose to stay behind the queue of five vehicles during the cash-scenarios-with-queue experienced a longer drive because of the time they spent in the queue. The chance of having a higher number of glances at each lane can potentially increase because of the increase of the exposer time. To take care of that effect, the scorers eliminated the random glances that were not part of the drivers' lane decision--making process and did not count them in the number of glances.

Figure 13 shows the average number of glances drivers made as a cash customer with two conditions, and as an E-ZPass customer.

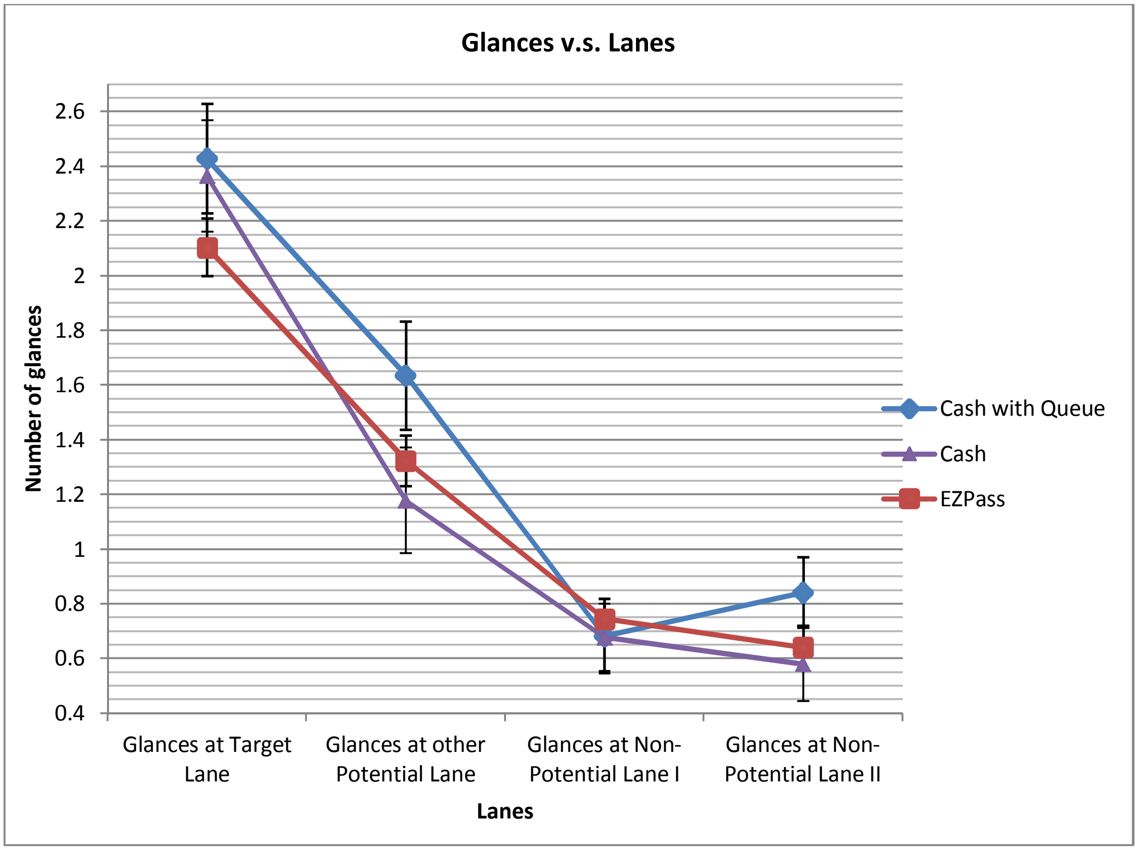


Figure 13. Number of glances at lanes

In the figure, "target lane" is the driver's final lane choice at the toll plaza, and "other potential lane" is the lane that has the same payment method and could have been chosen by the driver. "Non-potential lane I" and "Non-potential lane II" are the two lanes with different payment methods than that of the drivers' type.

The average number of glances that a cash driver took at his or her target lane (M=2.37, SE=.2) was statistically similar to that of E-ZPass drivers (M=2.10, SE=.11) and to queue conditions (M=2.43, SE=.20). Also, the number of glances taken at "other potential lane" was statistically similar for cash (M=1.18, SE=.19) and E-ZPass (M=1.32, SE=.09) drivers. However, the presence of queue increased this percentage significantly (M=1.63, SE=20). The number of glances taken at either of the non-potential lanes was less than 1 for all cash (M=0.68, SE=.12 and M=0.58, SE=.14), E-ZPass (M=.75, SE=.07 and M=.64, SE=0.08), and queue scenarios (M=.68, SE=.14 and M=.84, SE=.13).

The comparison of the results of glances for queued cash scenarios and the rest of the scenarios showed significant difference. The Wilcoxon rank-sum (or Mann–Whitney–Wilcoxon (MWW)) test showed that once the driver is facing a queue in front of his or her path at the toll booth, the frequency of glances at the other potential lane (the cash lane which had less utility to be picked by the driver) is significantly higher. Driver scanning the other lane more frequently can be an indicator that deciding between two options cause more workload as the utilities of the two options (farther lane without queue and the closer lane with queue) get closer with the presence of queue compared to previous condition (no queue at either lanes).

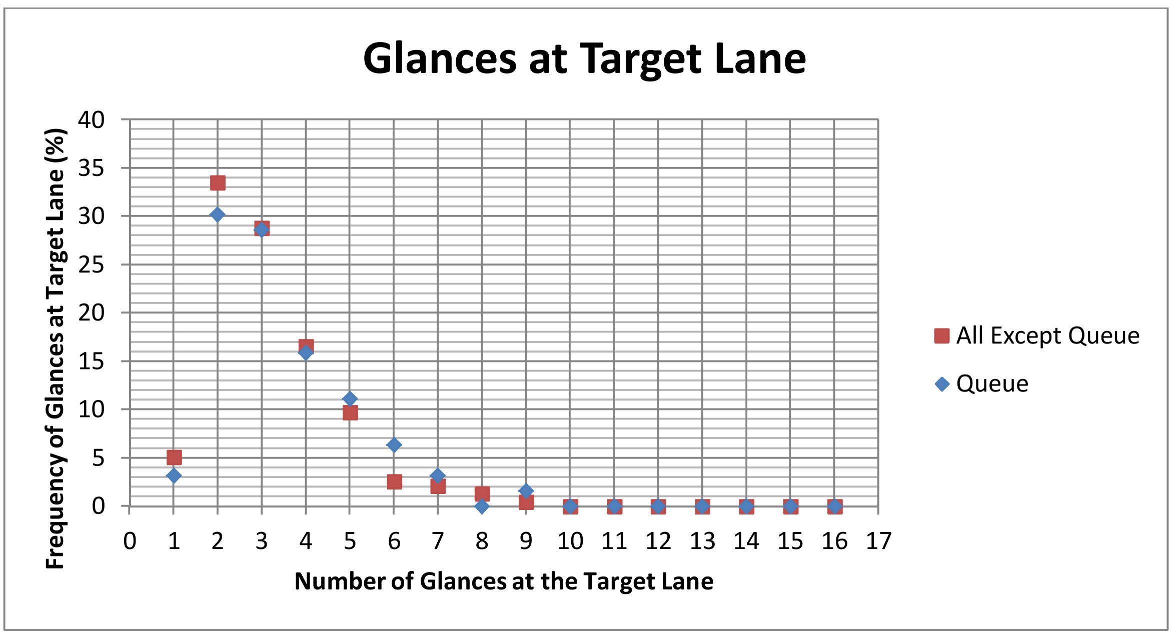


Figure 14. Glance frequency at target lane

Also, the graph of the frequency of glances at target lane in Figure 14 shows a similar distribution for queued scenarios and the rest of the scenarios. It is shown that in the presence of queue, the distribution of drivers' glances at target lane gets thicker right tail (i.e. mostly higher frequency for more than 4 number of glances is observed with queue scenarios).

CHAPTER 5: CONCLUSION

This study proved the feasibility of modeling traffic conditions at a toll plaza and evaluating its safety using VISSIM and SSAM. Also, traffic safety was evaluated in different lane configurations at the toll plaza.

In general, it seems that fewer lane choices and fewer incentives to change lanes would increase safety at the site.

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.

Based on the microsimulation study, All-ETC lanes design and use of both combo lanes as well as ETC lanes, are found as the safest and second-safest configurations, respectively. The third-safest condition is the design that separates different toll lane types (i.e., cash and E-ZPass lanes) from each other.

Based on the driving simulation data it seems that the right lanes have potentially higher utility for the drivers and in the similar conditions (between lanes), drivers are more prone to choose the lane that is closer to the right edge of the road. This is regardless of payment types the driver is going to pick (i.e. cash or EZPass).

The glance distribution shows that drivers glance more frequently at the other lane (the lane with less utility) when the queue exists. This indicates driver is going through higher workload to decide between the two options as the utilities of the two options (farther lane without queue and the closer lane with queue) gets closer with the presence of queue compared to previous condition (no queue at either lanes).

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