Safety and Lane Configuration at Toll Plazas

SAFETY RESEARCH USING SIMULATION

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Abstract

Toll plazas are one of the critical components of a roadway system for capital financing, infrastructure maintenance revenue, and traffic maintenance and congestion control strategies. At the same time, they are amongst the most complex road structures because drivers are exposed to a large amount of information and have a short amount of time in which 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 through VISSIM and 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 in Massachusetts, which connects Interstate 90 to Interstate 91 and Route 5. Distribution of traffic volumes, stop delays at cash lanes, and reduced speed distribution at ETC lanes were used as calibration variables, and number of conflicts was used as the validation parameter. Results identified that the safest lane configuration was the one consisting of only ETC lanes and that 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 the SimCreator driving simulator. The objective of this part of the study was to investigate drivers' behavior when they were 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 EZPass 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 EZPass). The result of this simulation study was expected to give a better understanding of drivers' behavior at toll plazas, which might lead to safer toll plaza designs.

1 Safety and Lane Configuration at Toll Plazas

1.1 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 amongst the most complex road structures. Drivers are exposed to large amount of information and have a short period of time within which to make decisions regarding their exit ramp, toll booth lane, and velocity. Since the introduction of electronic toll collection (ETC) technology, 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 by 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 is optimization of lane configuration at the plaza. The term *lane configuration* refers to 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 the efficiency and performance of electronic toll collection systems; however, less research has been done on their safety impacts. Apparently, each agency has its own approach to lane configuration and toll plaza design once there are both cash and ETC lanes available at the toll booth. 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 the drivers and decrease their lane-changing incentives. As a result, the number of potential conflicts and events are expected to be reduced in this condition. To be able to serve cash customers in an all-ETC lane configuration, camera toll-enforcement technology is used to take a picture of the non-ETC customer's license plate, and the bill for the toll is sent to the vehicle owner's address.

The current study investigates some different lane-configuration scenarios in order to determine the safest lane configuration for an off-ramp toll plaza with close merging and diverging ramps.

1.1.1 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 is the West Springfield toll plaza located at Exit 4 of the Massachusetts Turnpike. This location provides an ideal base case because it is located at the intersection of two major interstates and a primary state route (Interstate 90, Interstate 91, and State Route 5). In addition, the on-ramps and off-ramps are too close to each other, which provides a short amount of time for drivers to decide on their lane and to perform the required maneuvers to switch to their target lane.

The existing lane configuration at the study site 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.

1.2 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 so they can 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 has also increased drivers' involvement and impacted roadway safety. To date, there are few studies investigating safety issues at toll plazas. This chapter presents previous work that has been done on toll plaza performance and safety analysis.

Although ETC technology causes an increase in the throughput capacity of the plaza and a 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 increased 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 rear-end, sideswipe, fixed-object, back-into, and pedestrian-related crashes. Rear-end crashes have the highest frequency and are most frequent during peak hours and in the lanes that have a queue. The most common reasons for sideswipe crashes and fixed-object crashes 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 based on minimizing travel time and that even a small queue at a 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 affect the location of conflict points at a toll plaza. They also stated that the number of conflicts decreases with an increase in the number of ETC lanes at a plaza since it results in more organized traffic flow through the toll plaza [1].

They 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 drivers [1].

According to them, 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 motorists’ loss of forward attention to the decelerating front vehicle while they are in 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 speed variation between cash lanes and ETC lanes, which increased the probability of conflicts. All things considered, the ETC system decreased the level of safety at toll plazas [1].

According to Wong et al. [4], although the throughput capacity of toll booths increases with the addition ETC lanes, the lane-changing movements between ETC and cash lanes increases the probability of conflicts. To account for this effect, they 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 the increase in traffic volume. Thus, crash risk would decrease as traffic volume increases. This might be due to the 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 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, the lane-decision-making process for a driver depends on complex inter-vehicle 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 drivers have 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. He 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 inter-arrival time between vehicles. He selected throughput and capacity of a toll plaza per hour as the 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, situation in which a vehicle needs to brake or steer suddenly to avoid a collision, as surrogate measures of crash risk [7].

As it is stated by Smith [8], to increase level of safety, speed difference between ETC and cash lanes needs to be reduced and lanes with the same payment method should be clustered.

Some studies have used the Surrogate Safety Assessment Model (SSAM) for safety analyses at intersections or roundabouts, and the results have shown an acceptable fit to the field data for those studies. However, not many safety analyses have been done using this software to investigate safety at toll plazas. The SSAM analyzes the vehicle trajectory data file that is generated by microsimulation software programs. The SSAM can support the trajectory data files of four simulation software programs: PTV (VISSIM), TSS (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 the number of conflicts categorized into three types: rear-end, crossing, and lane-changing conflicts. They could also be presented in a conflicts and events map, and a T-test comparison could also be done on two sets of trajectory files in the SSAM (9).

1.3 Micro-Simulation

1.3.1 Introduction

This chapter presents the safety analysis through microsimulation models. A model of a 500 foot stretch of an off-ramp toll plaza was built in VISSIM. In order to do safety analysis, the SSAM provided by the Federal Highway Administration (FHWA) was used as supplementary software; it 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 EZPass), the trend of weaving maneuver may change and so may the number and types 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 events, as well as the least severe conflicts.

In this approach, driver behavior was not a variable, and the default values from the software package were used across all different lane configurations. The different lane configurations were all tested under the same conditions. As result of this study, the applicability of microsimulations for safety analysis at toll plazas has been proven, and a better understanding of the effect of toll plaza design on traffic safety has been gained.

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

1.3.2 Methodology

The microsimulation model was based on the West Springfield toll plaza (see Figure 1.1). It is an ideal base case because it connects major interstate highways and a primary route (Interstate 90, Interstate 91, and State Route 5) and has sufficient traffic passing through it. Also, the distance between 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.

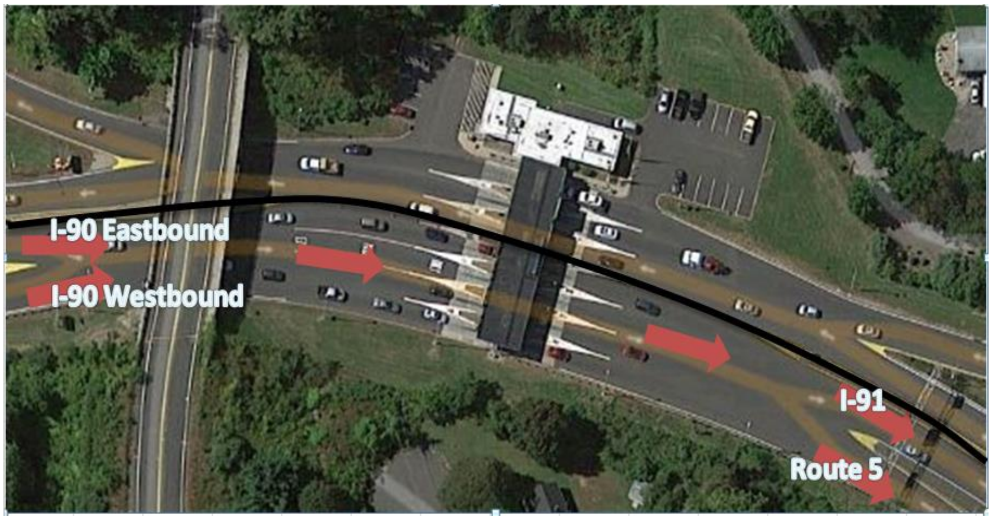


Figure 1.1 - West Springfield toll plaza

The existing lane configuration at the subject toll plaza, as shown in Figure 1.2, 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 1.2 - West Springfield toll plaza lane configuration

Conflicts and events that were captured and defined from 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), and

6. secondary conflicts (e.g., braking because of an intruding vehicle entering from another lane, which could lead to a rear-end or lane-changing collision).

The VISSIM model was calibrated using traffic volume distribution, traffic composition of heavy vehicles and passenger cars, stop delay distribution in cash lanes, and speed reduction in ETC lanes. The model was then validated by comparing the number of conflicts that occurred in the simulation versus in the 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 a safety analysis tool pack, the vehicle trajectories taken from VISSIM were imported into SSAM, a safety assessment software provided by the FHWA, for safety analysis. Although conflicts defined in SSAM are limited to rear-end, lane-changing, and crossing conflicts, the software was able to fairly represent the traffic safety conditions and the conflicts observed at the plaza.

1.3.3 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 at 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 was facing towards the plaza and the diverging lanes after the plaza, and the other one was facing away from the plaza toward the merging lanes entering the plaza, as shown in Figure 1.3.

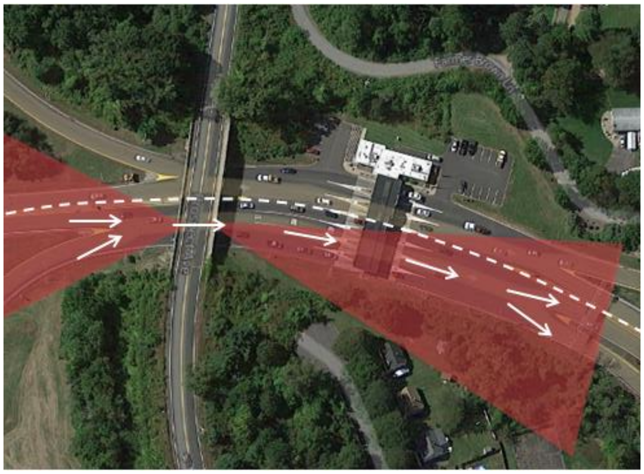


Figure 1.3 - Camera placement and range of vision

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

1.3.3.1 Traffic volume and vehicle composition

The number of vehicles entering the plaza and the percent of heavy vehicles (HVs) coming from each of 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 EZPass lanes, respectively.

1.3.3.2 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 O-D matrix was created from that video.

1.3.3.3 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.

1.3.3.4 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 lengths of some pavement markings were extracted from the field's map, then the timing of the vehicles travelling along those lines was recorded. The speed was calculated using those data.

1.3.4 Scenario Layout

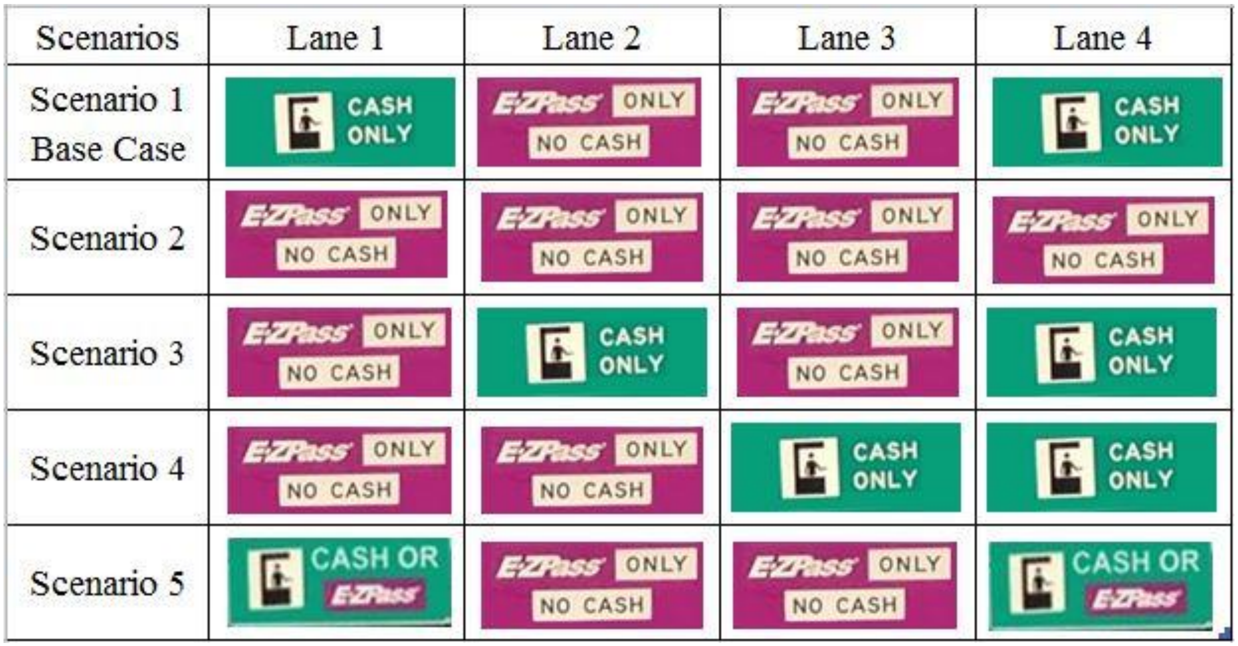
1.3.4.1 Variables

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

1.3.4.2 Experimental Design

Among 16 possible lane configurations, four were of interest for this study and a good representation of different types of lane configurations, and then a fifth was defined as having two combo lanes (i.e., a lane that serves both cash and EZPass customers) and two EZPass lanes.

Scenario 1 was the base case, which had two cash lanes in the far left and far right lanes of the toll plaza and two EZPass 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 1.4. 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 the 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 1.4 - Lane configuration of all the scenarios built in VISSIM

1.3.5 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.

Five simulation models were created, each with a different lane configuration as shown in Figure 1.4. Each simulation model had seven simulation runs with different random seeds, each with a 10-minute run time. The warm-up period at the start of each run was 30 seconds.

Each simulation run generated a trajectory file containing the vehicle trajectories of all the vehicles that appeared in the simulation. All of the 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 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 5 in the field. No crossing conflict was observed in the model or in the actual field. Since there was about a 92.3 percent 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 a result, the rest of the scenarios were modeled.

1.3.6 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 10 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. This is the time that takes place 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. In other words, it is 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. Table 3.1 to Table 3.4 show the results of t-tests between the Base Scenario and each of the four other scenarios.

Table 1.1 - 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	Significant	Mean Difference	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

The level of significance for the t-test analysis was 0.05. The results show that Scenario 2, with all the lanes being EZPass lanes, had higher TTC and lower MaxS, DeltaS, and MaxDeltaV compared to the Base Scenario. This reveals that Scenario 2 would have less severe conflicts than Scenario 1, due to less speed variance and fewer weaving maneuvers.

Table 1.2 - 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	Significant	Mean Difference	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

Delta S (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 value of all other measures did not have any significant differences among these two designs. This implies that no difference in the probability of collisions exists between these two cases.

Table 1.3 - 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	Significant	Mean Difference	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
Delta S (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
MaxDeltaV (m/s)	1.83	1.219	2.589	2.718	-3.532	1.66	YES	-0.759	4

Note: N/A= not applicable

Table 3.3 shows that MaxS, DeltaS, and maximum speed difference (MaxDeltaV) are significantly lower in Scenario 4, which has two ETC lanes in the far left lanes, than in the Base Scenario. This shows that the severity of collision in Scenario 4 is significantly less than in the Base Scenario. However, MaxD, which is taken as a representative of the probability of crashes, is less in the Base Scenario than in Scenario 4. In summary, in Scenario 4 we expect to have a higher number of collisions but with less severity, compared to the Base Scenario.

Table 1.4 - 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	Significant	Mean Difference	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
Delta S (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

As represented in Table 4, Scenario 5, which has two ETC lanes in the middle and two combo lanes on the sides, has significantly less severe conflicts than the Base Scenario. However, MaxD shows that the Base Scenario may have a lower probability of collisions than Scenario 5.

From the results of the t-test, it is found that considering both crash probability and crash severity, the All ETC Lane Scenario is the best scenario. As mentioned before, the 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 3.5. The number of conflicts represented in the table below is the sum of the conflicts that took place both before reaching the plaza and after the plaza, before divergence of the road.

Table 1.5 - SSAM conflicts results for 600 seconds of 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 in the Base Scenario. Since all the lanes in Scenarios 2 and 5 serve EZPass customers, there would be less restriction on drivers' lane choice and less incentive to switch lanes. As the result, fewer weaving maneuvers and fewer potentially conflicting situations would take place. Additionally, in Scenario 2, the speed variance is lower than in the other configurations since all the four lanes are EZPass lanes.

According to the literature, since EZPass lanes cause less congestion compared to the other lane types, they show better performance and as a result cause fewer conflicts [2]. This research validates the past studies and provides further evidence that a configuration consisting of only EZPass lanes would be safer than a configuration consisting of a mixture. However, in practice with this configuration of all EZPass 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 was Scenario 4, which had less-severe collisions than the other scenarios (Table 1.2 through Table 1.4). 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 combo lane, so the speed variance in adjacent lanes are 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 in average but the probability or number of conflicts might increase. This type of design that has clustered lane types might be infeasible in some conditions due to the considerable increase in the weaving maneuvers required for the vehicles to take the proper exit after the plaza.

In summary, an all-ETC-lane scenario performs best in terms of safety for this study location. Scenario 5, with a combination of EZPass and combo lanes, would be the second-safest scenario in terms of probability of crashes (Table 1.5); from a conflict-severity standpoint it is in third place and is placed after Scenario 4.

In general, it seems that fewer lane choices and fewer incentives to change lanes would increase safety at the site. However, for real-world implementation, a feasibility study should also be considered before deciding on lane configuration.

1.3.7 Discussion

This study proved the feasibility of modeling traffic conditions at a toll plaza and evaluating its safety using VISSIM and SSAM. In addition, traffic safety has been evaluated in different lane configurations at the toll plaza. All-ETC lanes and a combination of combo lanes and ETC lanes were found to be the safest and second-safest configurations, respectively. The third-safest condition is the design that separates different toll lane types (i.e., Cash and EZPass lanes) from each other. The results of this study could provide a better understanding of safety at toll plazas and the effect of toll plaza design on number 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 them 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 done in future work. The effects 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 to be investigated in the future.

Lack of data on driver behavior is a point that needs comprehensive studies. 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. Micro-simulation analysis is unable to see those details. Hence, a simulation study in a virtual-reality world would clarify those points. The next chapter of this study addresses that question.

1.4 Driving Simulation

1.4.1 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 meter by 200 meter (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 EZPass 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 EZPass driver), were defined 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, which might lead to safer toll plaza designs. Also, the result might be used to modify and enhance drivers' behavior parameters in microsimulation software like VISSIM.

1.4.2 Participants

Twenty licensed drivers, 10 females and 10 males, between the ages of 18 and 60 years participated in this experiment. Subjects were recruited through the general recruiting email list of Arbella Human Performance Laboratory (HPL) in the College of Engineering at the University of Massachusetts in Amherst and/or through general flyers about the HPL driving simulation studies that were posted in the UMass Amherst Campus area.

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

Participants were compensated $20 by completing all the tasks in the experiment. Withdrawal from the experiment in the middle of the session was compensated proportionally.

1.4.3 Internal Review Board Approval

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

1.4.4 Methodology

Understanding drivers' lane choice behavior requires close scrutiny of their behavior in the field or the creation of a simulation environment similar to the field in which to examine their behavior in a controlled environment.

A field study is more realistic, but it is difficult to find the effect of each variable independent of environmental conditions because 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 looks at five factors affecting drivers' lane choice: toll plaza lane configuration, origin and destination of the subject vehicle, traffic condition (i.e., having a queue or not), traffic composition (i.e., having a lead heavy vehicle or not), and customer type (i.e., cash customer or ETC customer).

A virtual-reality representation of a four-lane toll plaza environment was created in the Arbella HPL in order to test drivers' behavior in a simulated toll plaza environment.

The simulation system is a full-scale driving simulator supported by Real Time Inc. (RTI) SimCreator technology (see Figure 1.5).

The RTI simulation system consists of four processing channels, the host, right, center, and left channels. The right, center, and left channels process the image feed that is projected through the right, center, and left projectors over three screens that provide a horizontal view of 150 degrees and a vertical view of 30 degrees of the forward driving scene in front of a Saturn sedan. The visuals projected on the screens are refreshed at a frequency of 60 Hz and a resolution of 1024 X 768 dpi on each screen. The simulated soundtracks replicate the engine sound as well as the sound of the environment and ambient traffic. The sedan can be operated like a normal car.

Figure 1.5 - Driving simulator at Human Performance Laboratory, UMass Amherst

The simulation environment is generally created through the Internet Scene Assembler (ISA), which has a library of roadway modules. Roadway structures that are not in the ISA library are built in AutoCAD Civil 3D and/or SketchUp and Blender. Then the model is imported into ISA or added to the ISA library. A published world that is created in ISA can be run using the 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 compatible output from all three graphical software programs, a specific version of each of the software programs was used: 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 feet by 656.168 feet) 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 in the correct format for ISA. Blender has the feature to export .wrl file format of the objects, which could be read by ISA after some changes to the file. Each closed polygon recognized as an object with a single texture had to be exported separately in .wrl format. The .wrl files keep the physical shape, texture, direction and relative positions of the objects as they are imported in ISA, so that each object sits in the correct place and orientation relative to the other objects. Once the objects were imported into ISA, the whole scene could be published to run in SimCreator. During the experiment, an ASL mobile eye tracker was used to monitor and record the eye movements of subject drivers. The mobile eye tracker has two cameras, one facing toward the scene, which records with a frequency of 30 frames per second, and an infrared optic facing toward subject's eye, which also records with a frequency of 30 frames per second. The videos recorded by the eye tracker showed where the driver was looking during the experiment.

1.4.5 Scenario Layout

1.4.5.1 Variables

As described previously, five independent variables have been defined: lane configuration, origin-destination, queue, traffic composition, and customer type. The description of the variables is given in Table 1.7. Considering all the possible combinations of those five variables in a four-lane toll plaza would lead to 512 possible scenarios. In order to restrict the number of testing scenarios, the lane configuration variable was narrowed down to the ones represented in Table 1.6. As a result, the number of possible scenarios has been reduced from 512 to 96 scenarios. Among those, twenty scenarios have been chosen for further analysis in this study. The description of the scenarios is given in the following section of this report and in Table 1.7.

Table 1.6 - Lane configurations

Configuration1	ETC-ETC-Cash-Cash
Configuration2	ETC-Cash-ETC-Cash
Configuration3	Cash-ETC-ETC-Cash

Table 1.7 - Description of factors

Factor	Description	Specifications
Lane Configuration	Combination of EZPass and Cash Lanes	Cash-EZPass-EZPass-Cash
		EZPass-Cash-EZPass-Cash
		EZPass-EZPass-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	EZPass or Cash Customer	EZPass Customer
		Cash Customer

1.4.5.2 Experimental Design

Out of the 20 scenarios, 12 were EZPass scenarios and 8 were cash scenarios. The 12 EZPass scenarios were divided evenly between three lane configurations; each configuration was tested with different origins/destinations and/or traffic compositions. The eight cash scenarios were evenly divided between two lane configurations; each configuration was tested with two different origin/destination and traffic queue conditions. Table 1.8 explains the scenarios in a tabular format.

Table 1.8 - Testing Scenarios

Customer Type	Lane Configuration	Scenario Level[1]	Scenarios
Cash	Configuration 3	Left to Left with queue	Scenario1
		Left to Left without queue	Scenario2
		Right to Right with queue	Scenario3
		Right to Right without queue	Scenario4
	Configuration 2	Left to Left with queue	Scenario5
		Left to Left without queue	Scenario6
		Right to Right with queue	Scenario7
		Right to Right without queue	Scenario8

ETC	Configuration 3	Right to Left with lead truck	Scenario9
		Right to Left without lead truck	Scenario10
		Left to Right with lead truck	Scenario11
		Left to Right without lead truck	Scenario12
	Configuration 2	Right to Left with lead truck	Scenario13
		Right to Left without lead truck	Scenario14
		Left to Right with lead truck	Scenario15
		Left to Right without lead truck	Scenario16
	Configuration 1	Right to Left with lead truck	Scenario17
		Right to Left without lead truck	Scenario18
		Left to Right with lead truck	Scenario19
		Left to Right without lead truck	Scenario20

[1]It is assumed that 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, was 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 further lane to avoid the queue. Each of the queued scenarios had a similar base scenario, for comparison, in which all the variables were the same except that there was no queue in drivers' travel lane (Figure 1.6

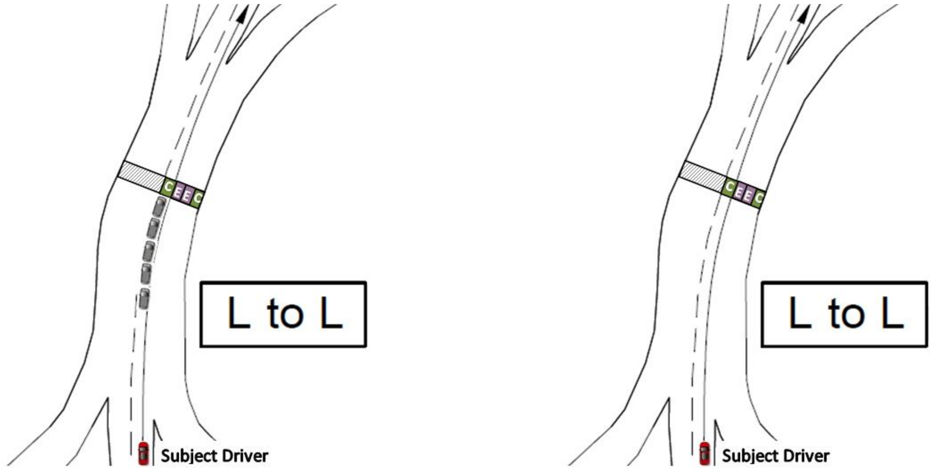


Figure 1.6 - Sketch of two cash scenarios; Scenario 1 on the left and Scenario 2 on the right

EZPass customer scenarios were 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 was tested both with and without the slow-moving lead heavy vehicle to investigate whether or not the drivers' lane choice would change due to having a truck ahead in the travel lane (Figure 1.7).

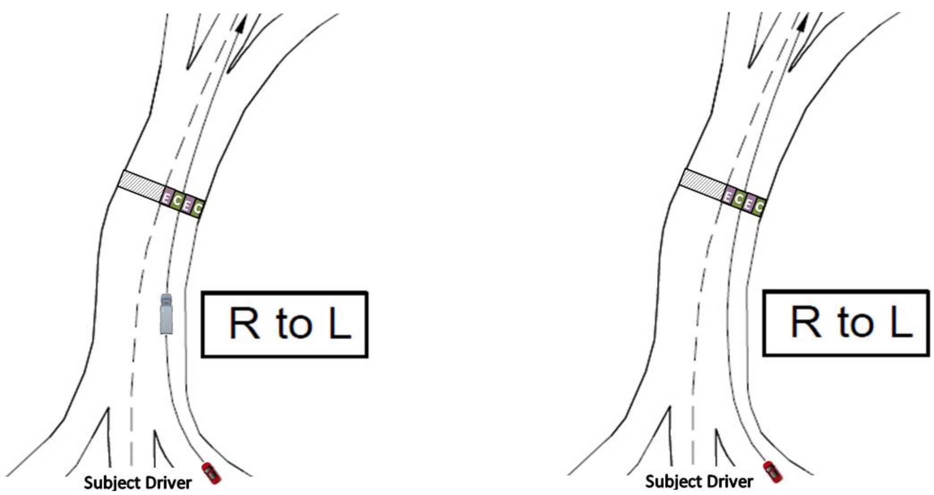


Figure 1.7 - Sketch of two EZPass scenarios; Scenario 13 on the left and Scenario 14 on the right

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

1.4.6 Procedure

Each participant took part in a one-session experiment at the HPL. The session was approximately 40 to 50 minutes. Once a participant arrived at the lab, he/she was asked to read and sign a consent form that explained the experiment and asked about their willingness to participate in the study. Then the participants were given one questionnaire about their demographic information and another about their physical conditions and motion sickness history. A similar simulator sickness questionnaire was given after they finished the experiment. Upon completion of the forms, the participant was moved to the vehicle, fitted with the eye tracker, and given instructions. A sample practice drive helped the subject get 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 in the EZPass lane.

1.5 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 20 subjects, 1 person dropped the study after completing the cash set of scenarios due to simulation sickness symptoms. Drivers' lane choices were 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 is defined as a binary variable in the sense that if the driver picked the closest possible lane to his driving path upstream of the plaza, the "path distance" variable was scored as 0 and if he chose the farthest lane the variable was scored as 1. The idea is to find a trend in drivers' lane decision making.

Two types of statistical tests were done on the drivers' lane choice. 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 below in Figure 1.8 through Figure 1.12.

According to the results, drivers were more prone to choose the right lane than the left lane (Figure 1.8 through Figure 1.12). 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 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 take the left ramp. Interestingly, in Scenario 3, by keeping all the conditions the same as Scenario 2 but changing the origin and destination to be on the right, all of the drivers chose the closest lane on the right without any exception. Comparing Scenarios 6 and 8 in Figure 1.9 also shows that with Lane Configuration 2 and the origin and destination on the left ramp, 5% of drivers still chose the right lane at the cost of two lane crossings. However, with the same condition but having the origin and destination on the right, all the drivers chose the right lane without any exceptions. Comparing Figure 1.8 and Figure 1.9 shows that once the left cash lane is shifted to the right, fewer drivers cross lanes aiming for the right lane.

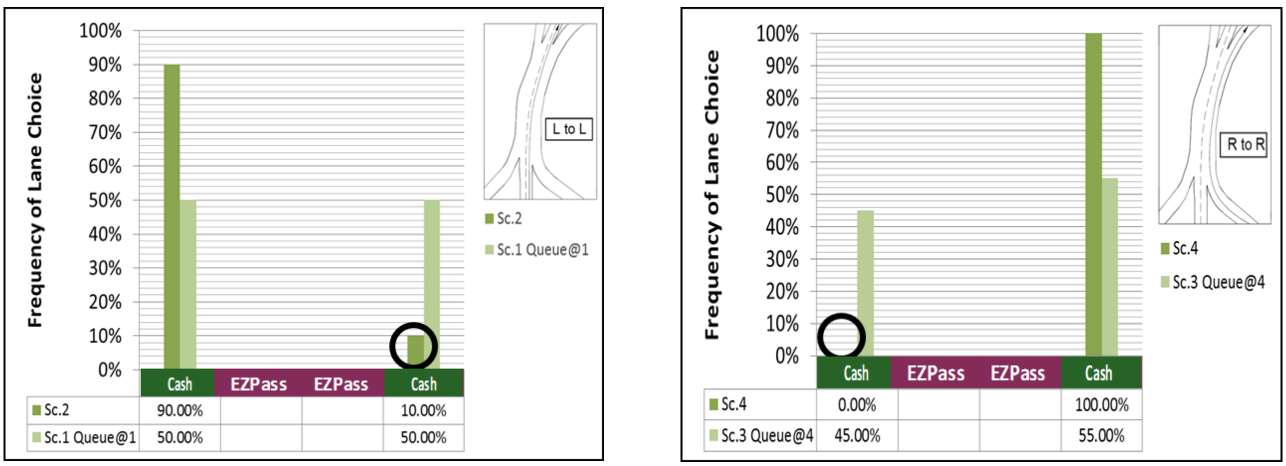


Figure 1.8 - Frequency of lane choice in Scenarios 1 to 4

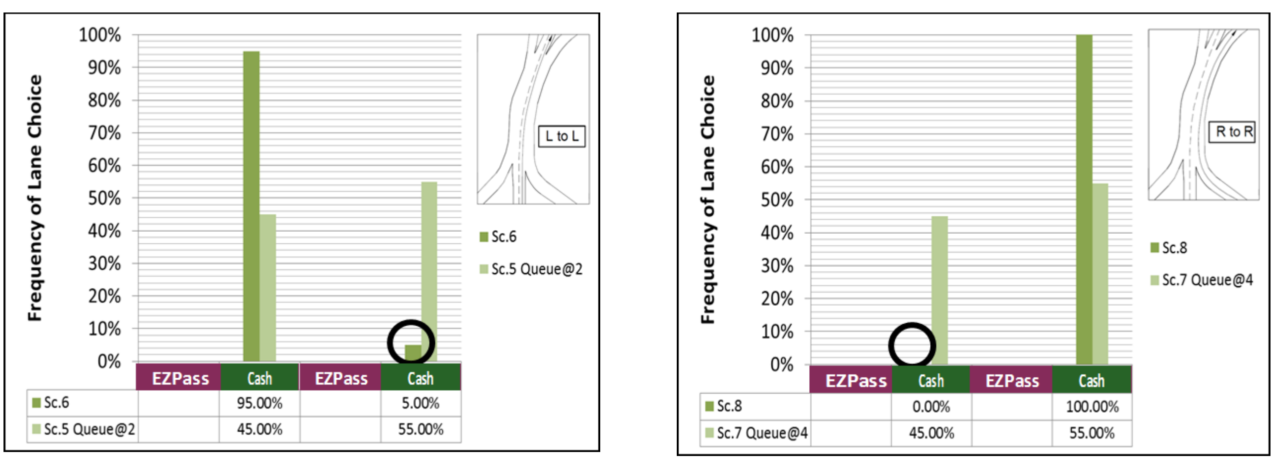


Figure 1.9 - Frequency of lane choice in Scenarios 5 to 8

Comparing EZPass Scenarios 14 to 16 and Scenarios 18 to 20 shows that, under the same conditions and regardless of lane configuration, drivers have more incentive to pick the right lane than the left (**Figure 1.10** and Figure 1.11).

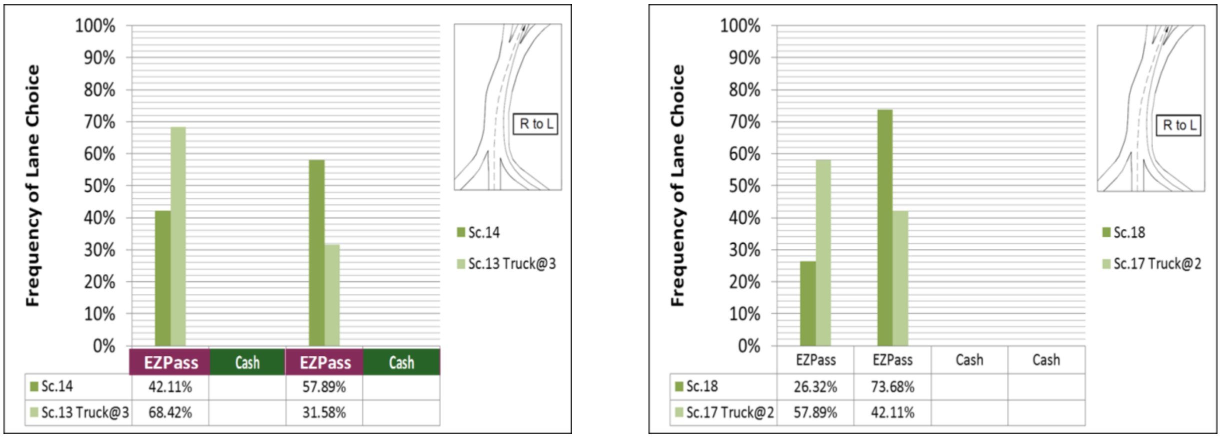


Figure 1.10 - **Frequency of lane choice in Scenarios 13, 14, 17, and 18**

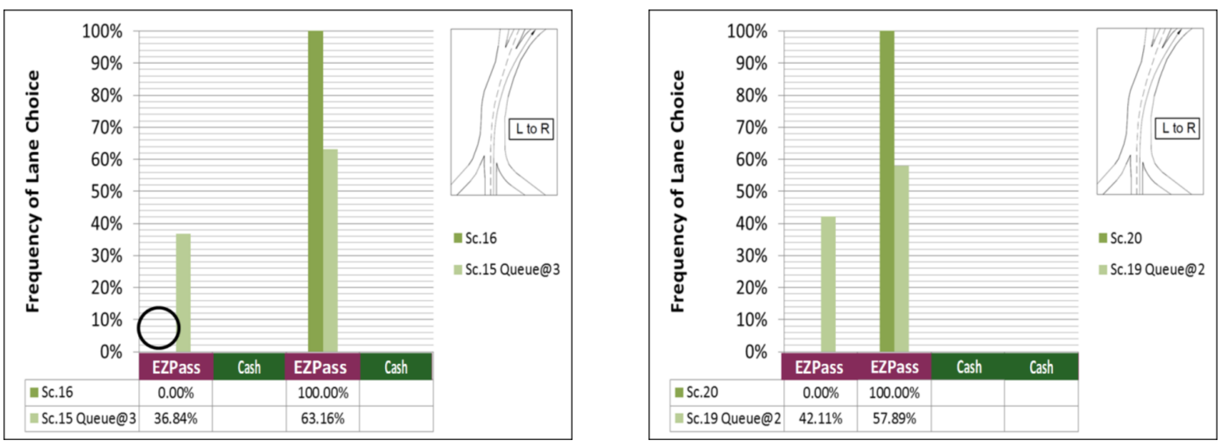
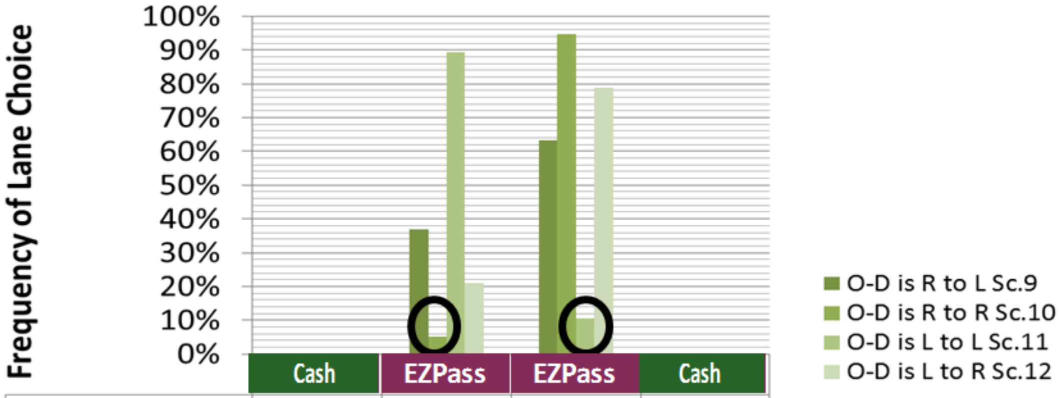


Figure 1.11 - Frequency of lane choice in Scenarios 15, 16, 19, and 20

Comparing Scenario 9 to 12 with equal origin and destination conditions, more drivers picked the right lane than the left (Figure 1.12). In Scenario 11 with the origin and destination both on the left, 10% of drivers still switched to the right. However, with similar conditions and having the origin and destination on the right, only 5% of drivers switched to the left lane. This could support the idea that drivers are more willing to switch to the right lane (Figure 1.12).



	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 1.12 - Frequency of lane choice in Scenarios 9 to 12

1.5.1 Conditional Logit Test

To determine the significant differences in drivers' lane choices across different scenarios, three sets of conditional logit tests were conducted to compare cash scenarios, EZPass scenarios of lane configuration type 1 and 2, and EZPass scenarios across all lane configurations excluding truck scenarios. The confidence interval is 5%. The dependent variable in all three sets is 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 the longest path upstream of the plaza and 0 otherwise. The independent variables change in each set.

1.5.1.1 Cash Scenarios (Scenarios 1 to 8)

The independent variables are origin-destination, queue, and lane configuration. Origin and destination in the 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 5 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). Configuration variable was 1 if it was Lane Configuration 2, and 0 otherwise.

The results show, with a 5% confidence interval, that only queue had a statistically significant effect on drivers' lane choice (Table 1.9).

Table 1.9 - 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

1.5.1.2 EZPass Configurations 1 and 2 (Scenarios 13 to 20)

The independent variables were origin-destination, having a leading truck, and lane configuration. Origin-destination in the EZPass 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 leading heavy vehicle in the scenario, and 0 otherwise. Configuration variable was 1 if it was Lane Configuration 2, and 0 otherwise.

The results show, with a 5% confidence interval, that only origin-destination had a statistically significant effect on drivers' lane choice (Table 1.10). It appeared that if the origin was on the left ramp and the destination was on the right exit, then drivers were more likely to switch to the right lane upstream of the plaza. However, if the origin was on the right ramp and the destination was on the left ramp, drivers might stay in the closest lane before the plaza and then switch to the left downstream of the plaza. It seems 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. However, considering the fact that drivers are more prone to pick the right lane as shown in previous results and also in the EZPass scenarios without a truck, trucks were located in the right lane regardless of the origin-destination of the subject driver.

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

Table 1.10 - EZPass 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

1.5.1.3 EZPass 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 EZPass scenarios without any slow leading heavy vehicle. The only variables between these scenarios were lane configurations (i.e., Configuration 1, Configuration 2, and Configuration 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 results show, with a 5% confidence interval, that only origin-destination had a statistically significant effect on drivers' lane choice (Table 1.11). The result is very similar to the result of the previous test (i.e., EZPass 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 is 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 were likely to stay in the lane closest to the current lane and switch to the left downstream of the plaza. Lane configuration in this case did not have any effect on drivers' lane decision.

Table 1.11 - EZPass 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

1.5.2 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 are categorical, Pairwise Wilcoxon test has been used. The results are summarized in Table 1.12. The Pairwise Wilcoxon test results comply with the conditional logit test result. The only difference is with the effect of a leading truck on EZPass scenarios, which was expected. As explained in the previous section, the effect of the truck could not have been tested through a conditional logit test. However, according to the Wilcoxon test, the existence of a truck had a statistically significant effect on drivers' lane choice.

Table 1.12 - 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-destination has a statistically significant effect on lane choice	Yes

Sc.18 = Sc.20	-3.742	0.0002	Origin-destination has a statistically significant effect on lane choice	Yes

1.5.3 Eye-Tracker Data Analysis

Eye-tracking videos were coded manually to find the number of glances drivers made at toll lane signs to investigate if there is any trend with drivers' lane decision making and their glance pattern at the signs and if the trend changes across cash and EZPass drivers.

Of the 20 subjects, 1 subject dropped the study after the cash set of scenarios due to simulation sickness symptoms. Of the remaining 19 subject videos, 3 were completely impaired, and 1 was partially impaired due to technical issues with the eye tracker. In total, 17 subject videos of the cash set of scenarios and 15 subject videos of the EZPass 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 EZPass lanes). Subject drivers that 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 exposure 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 1.13 shows the average number of glances drivers made as a cash customer, with two conditions, and as an EZPass customer.

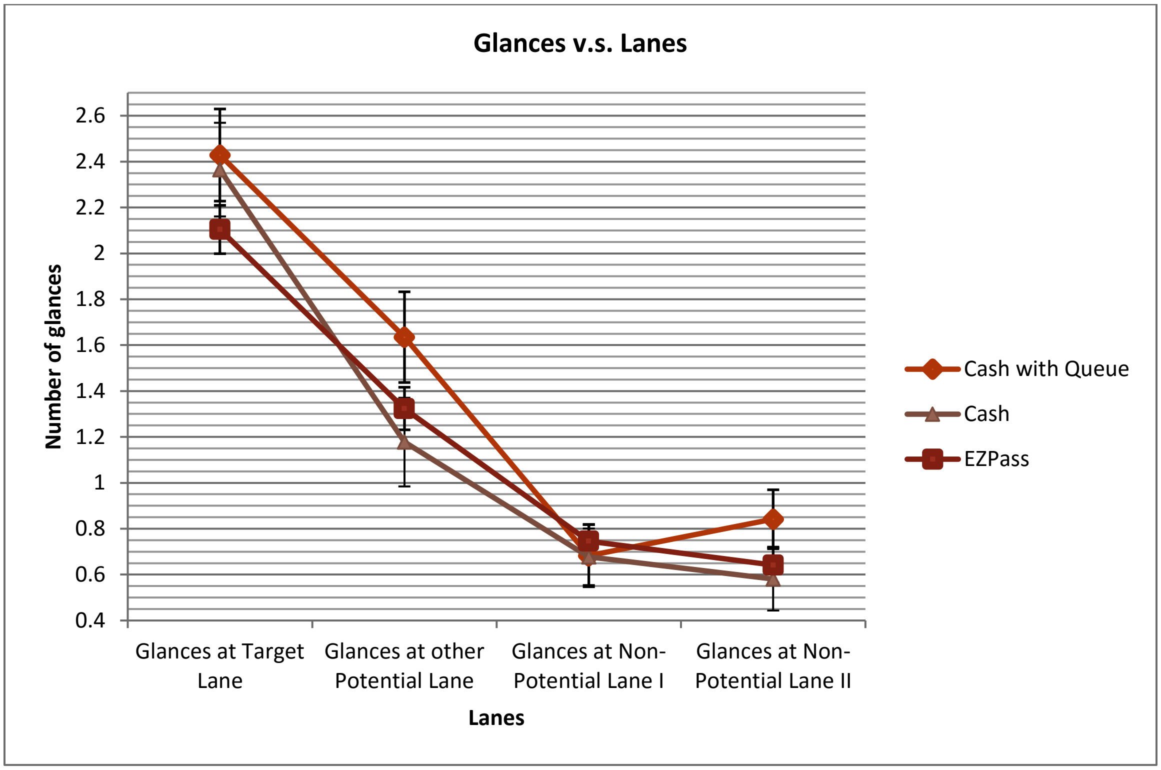


Figure 1.13 - Number of glances at lanes

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 the drivers' type.

The average number of glances that a cash driver took at his target lane (M=2.37, SE=.2) is statistically similar to that of EZPass 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" is statistically similar for cash (M=1.18, SE=.19) and EZPass (M=1.32, SE=.09) drivers. However, the presence of a queue increases this percentage significantly (M=1.63, SE=20). The number of glances taken at either of the non-potential lanes is less than 1 for all cash (M=0.68, SE=.12 and M=0.58, SE=.14), EZPass (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 a significant difference. The Wilcoxon rank-sum (or Mann–Whitney–Wilcoxon (MWW)) test showed that, once the driver was facing a queue in front of his path at the toll booth, the frequency of glances at each of the four lanes (target lane, potential lane, non-potential lane I, and non-potential lane II) changed significantly.

Also, the graph of the frequency of glances at the target lane in Figure 1.14 shows a similar distribution for the queued scenarios and the rest of the scenarios.

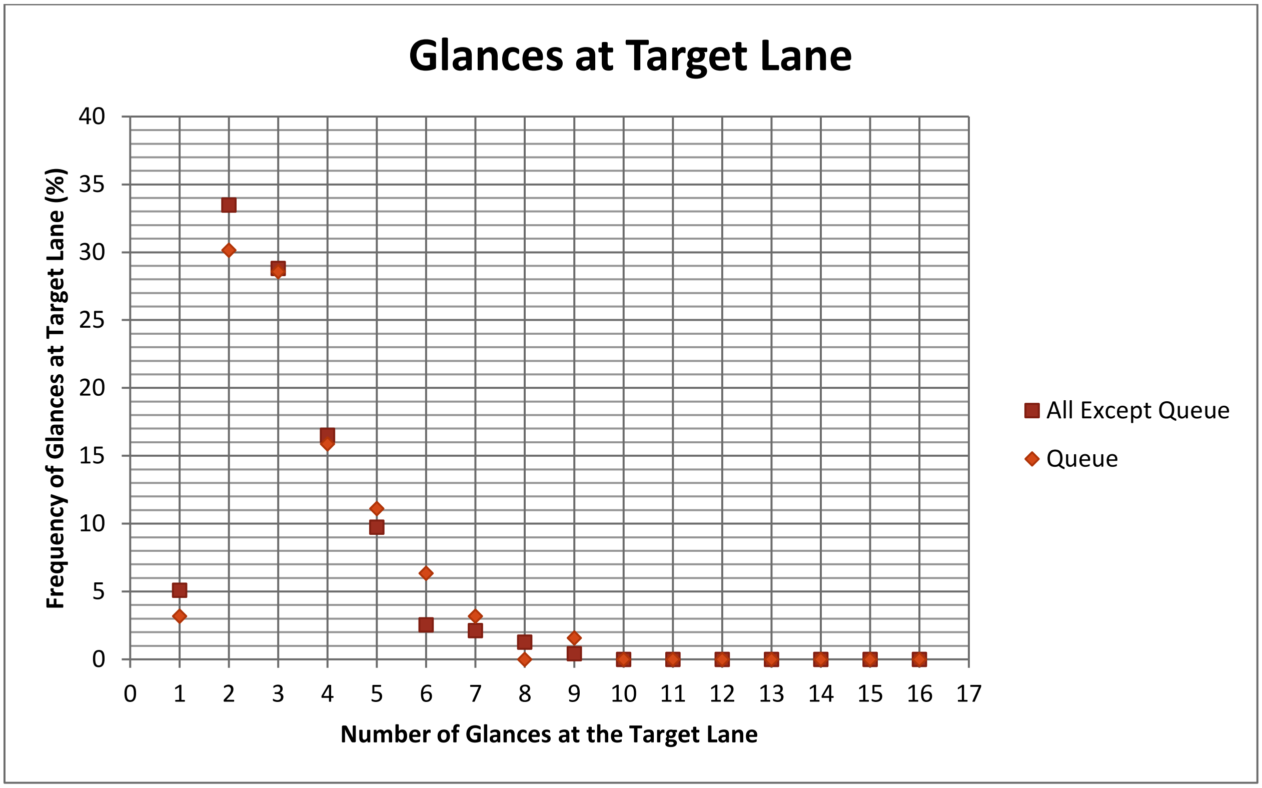


Figure 1.14 - Glance frequency at target lane

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