Final Report

SIMULATION AND EVALUATION OF THE ORLANDO-ORANGE COUNTY EXPRESSWAY AUTHORITY (OOCEA) ELECTRONIC TOLL COLLECTION PLAZAS USING TPSIM©

By

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Prepared for
The Florida Department of Transportation Research Center

April 2000

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Simulation And Evaluation Of The Orlando-Orange County Expressway Authority (OOCEA) Electronic Toll Collection Plazas Using TPSIM©	April, 2000
	6. Performing Organization Code
7. Author (s) Haitham Al-Deek, and Ayman Mohamed	8. Performing Organization Report No.
9. Performing Organization Name and Address Dept. of Civil & Environmental Engineering University of Central Florida 4000 Central Florida Boulevard Orlando, FL 32816-2450	10. Work Unit No. (TRAIS) 11. Contract or Grant No. BC-096
12. Sponsoring Agency Name and Address Florida Department of Transportation Research Center 605 Suwannee Street Tallahassee, FL 32399-0450	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with Florida Department of Transportation

16. Abstract

A discrete-event stochastic microscopic simulation model developed by the Transportation Systems Institute (TSI) at the University of Central Florida known as TPSIM© was validated in this study. Real-life data collected at the busiest toll plaza in the Orlando-Orange County Expressway Authority (OOCEA) system was used to validate the developed model. Statistical tests indicated that there is no significant difference at the 95% confidence level between Measures of Effectiveness obtained from the model and those collected in the real world.

TPSIM© was used to quantify operational benefits gained by installing E-PASS. Sensitivity analysis of market penetration of the E-PASS system indicates that an increase in E-PASS subscription rate improves the efficiency of the toll plaza operation. For all plaza configurations simulated with the manual lanes operating over capacity, the total plaza delay can be reduced in half and average queuing delay per vehicle can be reduced by more than 90 seconds if only 10% of the users can switch from manual to ETC lanes. Sensitivity of peak hour delay to the plaza traffic demand increases more rapidly with higher traffic volumes. An increase of 20%-30% of the plaza throughput can be achieved by switching only 10% of the manual users to ETC users during the morning peak hour when the manual lanes operate over their capacities. Analysis of peak hour delay showed also that adding more dedicated ETC lanes immaturely, i.e., without an increase in the level of ETC subscription, can cause an increase in the plaza queuing delay and decrease in the total plaza throughput.

17. Key Words	18. Distribution Statement
Toll Plaza, Traffic Simulation, ETC, E-PASS, AVI, TPSIM, OOCEA	No restriction - this report is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security classif. (of this report)	20. Security Class. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	133	

Form DOT F 1700.7 (8_72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

This report was prepared as part of Project *Contract No.: BC096, "Simulation And Evaluation Of The Orlando-Orange County Expressway Authority (OOCEA) Electronic Toll Collection Plazas Using TPSIM©"*. The research was conducted by the Transportation Systems Institute (TSI) of the University of Central Florida.

The authors would like to acknowledge the financial support of the Center of Advanced Transportation Systems and Simulation (CATSS) and the Florida Department of Transportation (FDOT).

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DISCLAIMER

The opinions, findings and conclusions in this publication are those of the authors and not necessarily those of the Florida Department of Transportation of the US Department of Transportation. This report does not constitute a standard specification, or regulation. This report is prepared in cooperation with the State of Florida Department of Transportation.

EXECUTIVE SUMMARY

Traffic simulation models are used to enhance planning, design, operation, and management of transportation facilities. A discrete-event stochastic object-oriented microscopic simulation model developed by the Transportation Systems Institute (TSI) at the University of Central Florida known as TPSIM© was validated in this study. Real-life data collected at the busiest toll plaza in the Orlando-Orange County Expressway Authority (OOCEA) system was used to validate the developed model. Statistical tests indicated that there is no significant difference at the 95% confidence level between Measures of Effectiveness obtained from the model and those collected in the real world.

After testing TPSIM© credibility to simulate traffic operation at toll plazas, TPSIM© was used to quantify operational benefits gained by installing E-PASS. Sensitivity analysis of market penetration of the Electronic Toll Collection (ETC) system indicates that an increase in ETC subscription rate improves the efficiency of the toll plaza operation. The benefits of ETC depend on the specific plaza configuration. The findings of this study showed that, for all plaza configurations simulated with the manual lanes operating over capacity, the total plaza delay can be reduced in *half* and average queuing delay per vehicle can be reduced by more than *90 seconds* if only 10% of the users can switch from manual to ETC lanes.

Sensitivity analysis of market penetration of the Electronic Toll Collection (ETC) system indicates that an increase in ETC subscription rate improves the efficiency of the toll plaza operation. The benefits of ETC depend on the specific plaza configuration. The findings of this study showed that, for all plaza configurations simulated with the manual lanes operating over capacity, the total plaza delay can be reduced in half and average queuing delay per vehicle can be reduced by more than 90 seconds if only 10% of the users can switch from manual to ETC lanes. An increase of 20%-30% in the plaza throughput can be achieved by switching only 10% of the manual users to ETC users

during the morning peak hour when the manual lanes operate over their capacities. Analysis of peak hour delay showed also that adding more dedicated ETC lanes immaturely, i.e., without an increase in the level of ETC subscription, could cause an increase in the plaza queuing delay and decrease in the total plaza throughput.

Since ETC vehicles do not experience any delays when the dedicated ETC lanes operate under capacity, total plaza delay does not have any impact on the decision of converting one of the manual lanes to a dedicated ETC lane. Sensitivity analysis of the ETC market penetration showed that when ETC usage during the rush hour is high (> 60%), delays reach a considerably reduced level for all plaza configurations, and an additional dedicated ETC lane does not have an impact on the plaza operational performance. Capacity of the dedicated lanes may be the most important factor that influences the decision of introducing a new dedicated ETC lane.

Sensitivity analysis of plaza delay indicated that plaza delay is insensitive to the locations of the dedicated ETC lanes. ETC vehicle's accessibility to the dedicated ETC lanes from the approach lanes is the main factor that influences the locations of the dedicated ETC lanes within the toll plaza. For a plaza configuration with one dedicated ETC lane, there is no significant difference in plaza delay between locating the dedicated ETC lane in the middle of the plaza or to the far left of the plaza. However, for a plaza configuration with two dedicated ETC lanes, simulation resulted in a significant decrease in the peak hour delay of 30% when these lanes were located in the middle of the plaza rather to the far left of the plaza. For a plaza configuration with three dedicated ETC lanes, a slight decrease (5%) in the simulated peak hour delay resulted in when these lanes were located to the far left of the plaza rather than the middle of the plaza. Animation was used to interpret these results.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

OVERVIEW OF TPSIM© MODEL

No general standards exist for toll plaza design, and the only standards are those developed by individual toll operators, based on their experience through improvements or expansions of their facilities; *(NCHRP 240), 1997 [1]*. Data collection is costly, time consuming, and may not be feasible at all times. Therefore, toll plaza simulation is an alternative tool to evaluate different operation and management improvements. A close look at the output and performance of a simulation model can be very useful in future planning of toll plazas. Computer simulation integrated with animation of traffic movements can be also used to show potential customers advantages to using ETC systems on both existing and proposed toll plazas. There is always a need to assess the toll plaza performance and the impacts of the new ETC systems under various scenarios of toll plaza configurations and traffic characteristics.

In attempt to simulate toll plaza operation, the Transportation System Institute at the University of Central Florida, Orlando, Florida, has developed a Toll Plaza Simulation model called TPSIM©. TPSIM© is a stochastic object-oriented discrete-event microscopic simulation model. TPSIM© was coded using Microsoft Visual Basic 6.0 to provide a user-friendly interface under Windows98/NT environment on PC.

1.1 MODEL DESIGN

TPSIM© can model toll plazas with up to 5 approach lanes and up to 10 toll lanes in each direction. In this model, approach lanes are located far enough upstream of the toll plaza where uninterrupted free flow conditions occur during plaza operation. Downstream of the approach lane zone is a transition zone with more lanes for traffic to maneuver while approaching the desired tollbooths. Finally, the toll lane zone is at the end of the transition zone, where vehicles have to pay toll. TPSIM© has the capability of simulating passenger cars as well as trucks with five different payment options (manual, automatic, ETC, manual/ETC, and automatic/ETC). Traffic volumes are inputted per 5, 10, 15, 30, and 60 minutes for each simulated hour. Within TPSIM©, a total of ten different distributions can be used by the user to represent various input parameters such as arrival distribution, service time distribution, and approach speed distribution.

1.2 MODEL CONCEPT AND STRUCTURE

TPSIM© package consists of three main modules, as illustrated in Figure 1.1. These modules are Data-Entry Interface, Simulation Logic and Algorithms, and Output Data Representation. TPSIM© utilizes database files to store the updated values of the system performance every time scan interval during each simulation run.

1.2.1 Data Entry Interface

An important attribute of TPSIM© is to provide the analyst with a system where data is categorized and displayed visually, so that it can be easily understood. Figure 1.2 illustrates a sample of TPSIM© data entry interface.

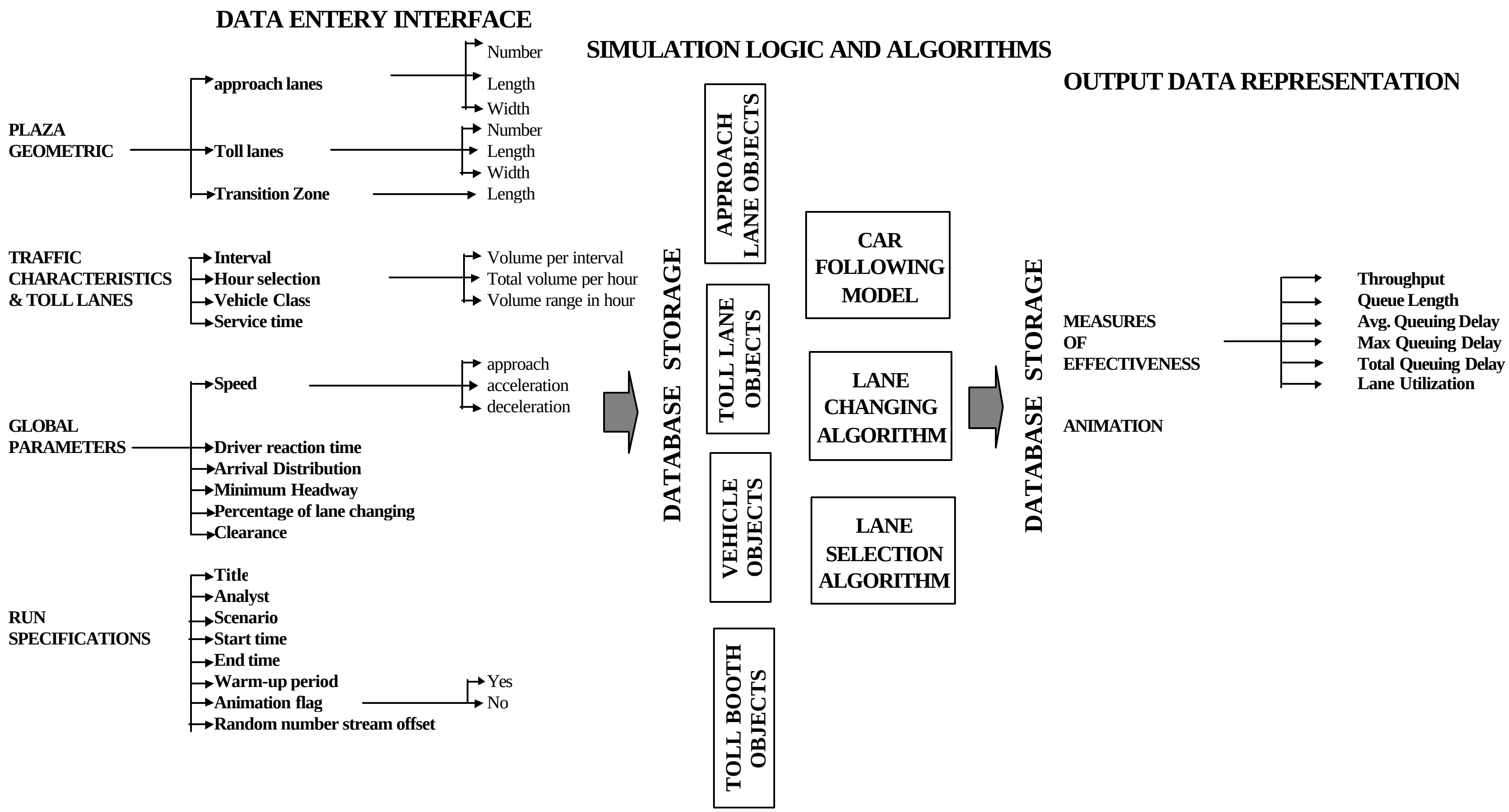


Figure 1.1: TPSIM© Structure

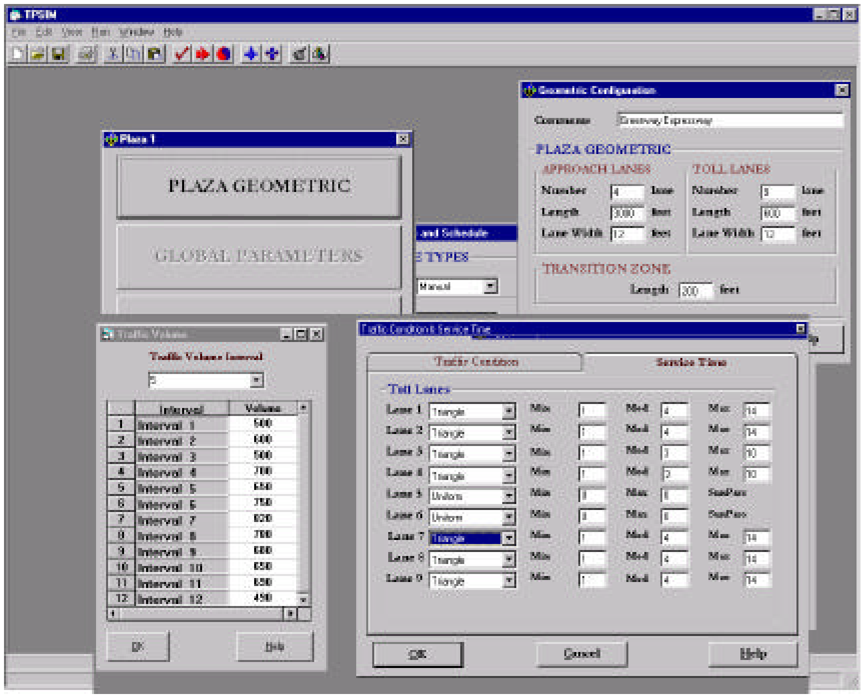


Figure 1.2: Sample of TPSIM© Data Entry Interface

1.2.2 Model logic and Algorithms

TPSIM© divides the toll plaza into three zones. These are the approach zone, the transition zone, and the toll zone. Each one of these zones has its own configuration and characteristics. Vehicles are generated in each approach lane according to their arrival times. The time between arrivals (inter-arrival times) in each approach lane is a random variable that follows a distribution specified by the user input at the entry point. This distribution can be estimated using a shifted negative exponential distribution with a minimum headway; *Al-Deek et-al, 1997[2]*. After generating the inter-arrival time distribution, each vehicle is randomly assigned an arrival time.

Before simulation starts, vehicle attributes are assigned values. These random values are stored in a database file. For example, the vehicle's desired speed is assigned a certain value obtained from the desired speed distribution that is specified by the user at the beginning of the simulation. Similarly, the vehicle's payment type, class, maximum acceleration rate, maximum deceleration rate, and driver reaction time are assigned values based on random distributions. Some constraints are considered in assigning these values. For example, the vehicle's class attribute determines the vehicle's payment type, vehicle's length, maximum acceleration and deceleration rate, and desired speed attributes.

After assigning to each vehicle its attribute values, simulation starts and the vehicle starts to move through its assigned approach lane. During the vehicle movement in the approach zone, it applies the Car-Following and the Lane-Changing Algorithms to update its travel speed, latitude, longitude, and approach lane during each time scan interval. Then, the current positions and speeds are stored in the database file every time scan interval. During each time scan interval, the vehicle checks if it reaches the end of the approach zone or not. If the vehicle is at the end of the approach zone, then it starts to apply the Toll-Lane Selection Algorithm to select the desired toll lane.

As the vehicle maintains its desired toll lane, it joins the queue (if any) and keeps moving in the queue until it reaches the tollbooth. Then, a certain service time value is assigned to this vehicle according to a distribution associated with the toll booth service time attribute. As the vehicle joins the queue, the Lane-Changing and the Toll-Lane Selection Algorithms are no longer applicable to the vehicle's operation. When the vehicle is served at the tollbooth, it starts to accelerate using its desired acceleration attribute and departs the plaza. Statistics required for measuring the efficiency of the plaza are collected and updated every time scan interval.

The following sections describe the Car-Following, the Lane-Changing, and the Toll-Lane Selection Algorithms used in TPSIM©.

1.2.2.1 __Car-Following Model__

One of the most important models for simulating the behavior of drivers is the Car-Following Model. This model is based on the fact that, the driver must adjust himself/herself to other vehicles in the traffic stream. When a driver closely approaches another leader vehicle from behind and can not pass, the driver must slow down to prevent collision with the leader vehicle. The basic concept of car-following theory is the hypothesis that when the spacing between two vehicles is critical, the driver of the following vehicle adjusts his speed so that at the end of a time scan interval the new position of his vehicle is no closer than desired. The basic elements of the *modified* Car-Following Algorithm used in TPSIM© can be summarized as follows:

- If there is no leader vehicle or the vehicle is the first unit in the system, the acceleration rate is assigned a zero value and the vehicle travels using its desired speed value.
- If the following vehicle is moving but has not reached its desired speed, then a typical value of the acceleration rate is assigned depending on the vehicle's type and its current speed.
- If the following vehicle is approaching the tollbooth, and the vehicle is equipped with ETC system, then it uses its desired deceleration rate to maintain the required safe speed at the tollbooth which is specified by the user at the beginning of the simulation

run. The required distance to maintain this speed from its current speed is calculated using the desired deceleration rate. If the vehicle is not an ETC vehicle, it must stop at the tollbooth and the required stopping distance is calculated using the vehicle's desired deceleration rate. The vehicle checks during every time scan interval to see if it has reached this required distance or not, if the answer is yes, it starts to apply its desired deceleration rate.

- If the following vehicle is stopped and has to start from a standing still position (stopping occurs only in queuing conditions), then a random value of start-up delay for this vehicle is assigned before the vehicle starts to move. The vehicle is not allowed to move as long as the non-collision constraint is not satisfied.
- If both the leader and the follower vehicles are moving or stopping, then the car following rules are initiated to guarantee the non-collision constraints.

Once the proper acceleration or deceleration rate that a vehicle should maintain in a given time scan interval is calculated from the Car-Following Algorithm, it is used to compute and update the travel speed and the location of the vehicle at the end of that time scan interval.

1.2.2.2 Lane-Changing Model

Lane changing and lane merging at high volumes are essential for satisfactory performance of microscopic simulation models. It is also essential that, the lane changing components be fully integrated with the Car-Following Algorithm components.

Lane changing attempts are initiated for a percentage of following vehicles that could be affected by the low speed of the leader vehicles. The Lane-Changing Algorithm maybe activated in the approach zone and throughout the transition zone until the vehicle reaches its desired toll lane. At the end of the approach zone, the vehicle must first select its desired toll lane per the procedures of the Toll-Lane Selection Algorithm, as will be explained later in this paper. Then the vehicle starts merging from its current approach lane, through the transition zone, to the desired toll lane.

Given the spacing and relative speed between the two vehicles in the vehicle's adjacent lane, the Lane-Changing Algorithm tests whether or not the gap between these two vehicles is sufficient based on safety constraints. The Car-Following Algorithm is called to determine the required acceleration/deceleration rate that the merging vehicle has to maintain at the given spacing and relative speed conditions. If the calculated acceleration/deceleration rate is greater than the maximum deceleration rate for the specific vehicle's type at its current speed then the lead distance is considered safe for lane changing. This check is performed one more time to determine whether the merging vehicle would cause the follower vehicle in the adjacent lane to decelerate at a rate higher than its maximum acceptable deceleration rate. It is only if both merging conditions (with the leader and the follower vehicles in the adjacent lane) are satisfied that the lane change maneuver is initiated in the current time scan interval. If the vehicle is traveling in the most right lane, the lane changing procedures are conducted for the adjacent left lane. On the other hand, if the vehicle is traveling in the most left lane, these procedures are conducted for the adjacent right lane. Finally, if the vehicle is traveling in any of the middle lanes, the lane changing procedures are performed for the adjacent left lane first, and if it is not successful, then merging in the adjacent right lane is attempted.

1.2.2.3 Toll-Lane Selection Algorithm

Gulewicz and Danko, 1995 [3] utilized a General Purpose Simulation System (GPSS) to evaluate the optimal lane staffing requirements necessary to satisfy toll plaza off-peak demand. Using a toll plaza consisting of 16 toll lanes with the same payment type, a random sample of vehicles entering the plaza was observed. This study indicated that most drivers exit the plaza from the same side they enter the toll plaza area and once they have selected which half of the plaza to enter, they select the lane with the shortest queue on that side. Also, some drivers were observed entering the lane with the shortest queue, a small percentage of drivers appeared to randomly choose a toll lane.

Based on findings of this real life study, a unique Toll-Lane Selection Algorithm was developed within TPSIM©. This Toll-Lane Selection Algorithm has a two-step process. The first step starts as the vehicle travels in the approach zone. The vehicle starts to scan the plaza configurations and tests which of the toll lanes matches its desired payment type. It selects the toll lane with the minimum queue length. This lane becomes the vehicle's initial desired toll lane. As this vehicle travels in the approach lane, it tries to achieve the approach lane that leads to its initial desired toll lane. Then, as soon as the vehicle reaches the beginning of the transition zone, it applies the Toll-Lane Selection Algorithm *again* to select the final desired toll lane. At this stage, it tests if there is any queue in its initial desired toll lane. If there is no queue in this lane, the vehicle checks if it needs to change its current traveled lane to the desired toll lane. Then, the Lane-Changing Algorithm is called and the vehicle keeps changing its traveled lane until it reaches its desired toll lane where it is served at the tollbooth.

If there is a queue in the initial desired toll lane, the tollbooth-grouping concept developed in this paper is applied. According to this concept vehicles traveling in each approach lane are assigned to a specific group composed of two or three tollbooths. The exact number of tollbooths within each group depends on the plaza configuration. The vehicle checks the availability of opened tollbooths within its tollbooth-group that accept its toll payment method. If all tollbooths within this group are not available (e.g., closed or accept only automatic payment using coins), the vehicle examines the tollbooth group assigned to the immediately adjacent approach lane (either the left or the right approach lane). If there are more than one opened tollbooth that satisfy the vehicle's payment method, the vehicle selects the tollbooth with the shortest queue length. In case of equal queue lengths among two or more tollbooths, the vehicle selects one of these tollbooths randomly. Finally, when the vehicle located in the transition zone selects the desired tollbooth, a check is performed to see if lane changing is required by the vehicle to achieve the toll lane associated with its desired tollbooth.

1.2.3 Model Output

This includes detailed and summarized statistical data which aggregate the system's MOEs, graphical representations of the statistical data in a user-friendly format, animation of traffic movements to visualize and detect special conditions during simulation. Figure 1.3 illustrates TPSIM©'s output data representation.

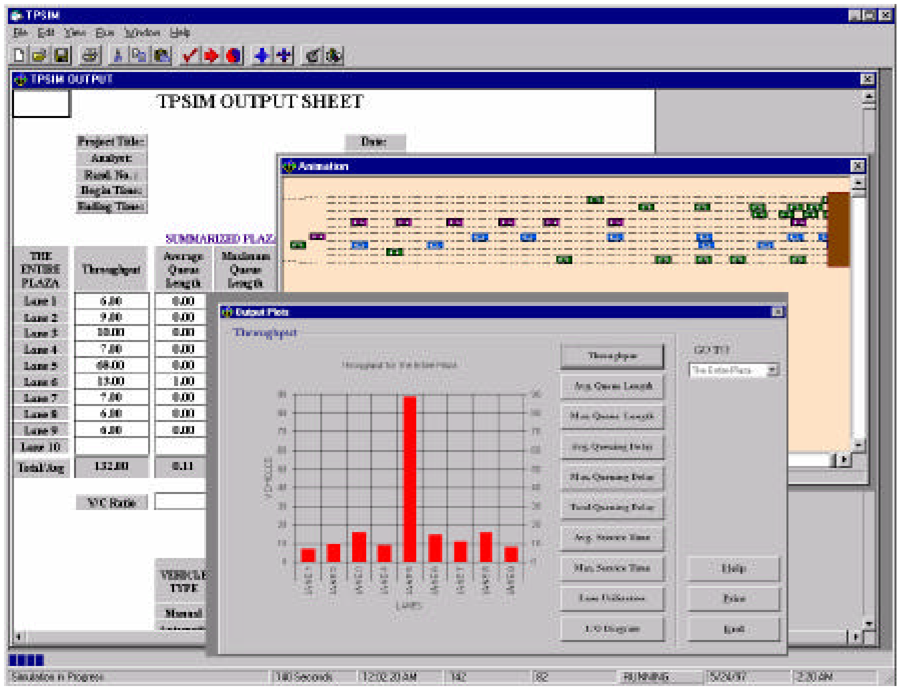


Figure 1.3: Sample of TPSIM© Output Data Representation

CHAPTER 2

EVALUATION OF TPSIM© MODEL

After developing TPSIM© simulation package in accordance with the concepts described in the previous chapter to represent a complex real-life traffic behavior at toll plazas, it is essential to test how close the model behavior corresponds to the actual toll plaza operation before its further applications. Without conducting such task, TPSIM© may be worthless. Verification and validation are the traditional methods to assure model correctness. Each of these methods consists of comparative tests that measure the model consistency. This chapter focuses on verification and validation of TPSIM© model to assess the realism and validity of the output data generated by the model. The main objective of TPSIM© verification and validation is to measure the credibility of the model and its applicability as an accurate substitute for the actual system for the purpose of experimentation.

2.1 MODEL VERIFICATION

Verification is defined as the process of testing how the model programming codes perform the calculations and logical sequences as the model developer formulated them. This includes checking for reasonableness of the model component outputs. Unexplained or unreasonable output from any module within the TPSIM© caused by either an important bug in the model code or flaws in the conceptual structure of the model should be detected and corrected. Verification of TPSIM© model components is quite straightforward due to the advantage of applying the modular structure technique in developing TPSIM©. Utilization of database files to store the outputs generated from each module in TPSIM© was advantageous in detecting and tracing any error. The verification of each individual module was performed with great care during the early stages of TPSIM© development. Whenever the outputs from any module were found to be unexpected, then either the module structure or the computer code, or both, are tested for errors. Further debugging and modifications of the model structure were undertaken until an expected and reasonable performance was assured in every aspect. Coding TPSIM© with Visual Basic programming language eased its verification process due to the advanced debugging tools (e.g., watch, trace, break points, ..etc) included in the VB computer language version 6.0. Figure 2.1 illustrates a snapshot of one of the database files that was generated from a simulation run. This database was structured in such a way to store the characteristics of each individual vehicle in the system every second and the interactions among vehicles within a toll plaza area. Using this database file verification of many TPSIM© algorithms including Car-Following, Lane-Changing and Lane Selection can be conducted. By applying various SQL Statements to this database, the behavior of each individual vehicle in the system at any point of time was monitored. Any unexplained behavior made by any vehicle in the system was analyzed to identify which algorithm(s) within TPSIM© was the reason behind this flaw. Then, this error was corrected and tested. Nemours runs were conducted to verify and correct any debugging or conceptual error.

ASOF	CURRENTPOSX	CURRENTPOSY	CURRENTSPD	CURRENT ACCEL	CURRENT APPLANE	CURRENT TOLLLANE	DESIRED TOLLLANE	LEADPOS	LEADSPD	QUEUE	INDEX	SERVICE TIME	DEPARTURE	DESIRED APPLANE	DELAY	VTYPE
144	2170.394	-6	79.14945	5.933926	2	5	5	2269.682	73.21552	FALSE	29	0	95	2		SunPass
145	2244.019	-6	75.46691	-3.68254	2	5	5	2342.898	73.21552	FALSE	29	0	95	2		SunPass
146	2328.387	-6	81.40084	5.933926	2	5	5	2416.113	73.21552	FALSE	29	0	95	2		SunPass
147	2401.252	-6	75.71004	-5.690803	2	5	5	2489.329	73.21552	FALSE	29	0	95	2		SunPass
148	2485.863	-6	81.64397	5.933926	2	5	5	2562.544	73.21552	FALSE	29	0	95	2		SunPass
149	2557.732	-6	75.12769	-6.516274	2	5	5	2635.76	73.21552	FALSE	29	0	95	2		SunPass
150	2641.761	-6	81.06162	5.933926	2	5	5	2708.976	73.21552	FALSE	29	0	95	2		SunPass
151	2712.812	-6	74.3875	-6.674124	2	5	5	2782.191	73.21552	FALSE	29	0	95	2		SunPass
152	2796.1	-6	80.32143	5.933926	2	5	5	2855.407	73.21552	FALSE	29	0	95	2		SunPass
153	2866.536	-6	73.73127	-6.590158	2	5	5	2928.622	73.21552	FALSE	29	0	95	2		SunPass
154	2949.168	-6	79.6652	5.933926	2	5	5	3001.838	73.21552	FALSE	29	0	95	2		SunPass
155	3019.121	-6	73.19001	-6.47519	2	5	5	3075.053	73.21552	FALSE	29	0	95	2		SunPass
156	3083.607	0	83.24535	0		5	5	3133.353	83.24535	FALSE	29	0	95		0	SunPass
157	3160.94	0	79.30411	-3.941247		5	5	3210.96	79.48619	FALSE	29	0	95		0	SunPass
158	3190.042	0	76.21436	0		5	5	3239.788	76.21436	FALSE	29	0	168		0	SunPass
159	3261.439	0	73.0028	0		5	5	3311.185	73.0028	FALSE	29	0	168		0	SunPass
160	3330.413	0	70.22848	0		5	5	3380.159	70.22848	FALSE	29	0	168		0	SunPass
161	3407.682	0	74.92205	0		5	5	3457.428	74.92205	FALSE	29	0	168		0	SunPass
162	3475.989	0	70.51186	-4.410189		5	5	3526.112	70.76363	FALSE	29	0	168		0	SunPass
163	3539.762	0	66.01919	-4.492673		5	5	3590.151	66.2806	FALSE	29	0	168		0	SunPass
164	3599.58	0	61.88548	-4.133708		5	5	3650.168	62.10496	FALSE	29	0	168		0	SunPass
165	3660.356	0	60.18367	0		5	5	3710.102	60.18367	FALSE	29	0	168		0	SunPass
166	3729.44	0	66.1176	5.933926		5	5	3800	1000000	FALSE	29	0	100		0	SunPass
124	0	-18								FALSE	30					
125	79.27597	-18	79.27597	0	1	4	6	383.8213	95.95531	FALSE	30	0	29	3		SunPass
126	158.5519	-18	79.27597	0	1	4	6	479.7766	95.95531	FALSE	30	0	29	3		SunPass
127	237.8279	-18	79.27597	0	1	4	6	575.7319	95.95531	FALSE	30	0	29	3		SunPass
128	317.1039	-18	79.27597	0	1	4	6	671.6872	95.95531	FALSE	30	0	29	3		SunPass
129	396.3799	-18	79.27597	0	1	4	6	767.6425	95.95531	FALSE	30	0	29	3		SunPass
130	475.6558	-18	79.27597	0	1	4	6	863.5978	95.95531	FALSE	30	0	29	3		SunPass
131	554.9318	-18	79.27597	0	1	4	6	959.5532	95.95531	FALSE	30	0	29	3		SunPass
132	634.2078	-18	79.27597	0	1	4	6	1055.508	95.95531	FALSE	30	0	29	3		SunPass
133	713.4838	-18	79.27597	0	1	4	6	1151.464	95.95531	FALSE	30	0	29	3		SunPass
134	792.7598	-18	79.27597	0	1	4	6	1247.419	95.95531	FALSE	30	0	29	3		SunPass
135	872.0358	-18	79.27597	0	1	4	6	1343.374	95.95531	FALSE	30	0	29	3		SunPass
136	951.3118	-18	79.27597	0	1	4	6	1439.33	95.95531	FALSE	30	0	29	3		SunPass
137	1030.588	-18	79.27597	0	1	4	6	1535.285	95.95531	FALSE	30	0	29	3		SunPass
138	1109.864	-18	79.27597	0	1	4	6	1631.24	95.95531	FALSE	30	0	29	3		SunPass
139	1189.14	-18	79.27597	0	1	4	6	1406.619	94.90553	FALSE	30	0	98	3		SunPass
140	1268.416	-18	79.27597	0	1	4	6	1510.458	100.8616	FALSE	30	0	98	3		SunPass
141	1347.692	-18	79.27597	0	1	4	6	1611.32	100.8616	FALSE	30	0	98	3		SunPass
142	1426.968	-18	79.27597	0	1	4	6	1633.639	97.0655	FALSE	30	0	99	3		SunPass
143	1506.244	-18	79.27597	0	1	4	6	1730.704	97.0655	FALSE	30	0	99	3		SunPass
144	1585.52	-18	79.27597	0	1	4	6	1827.77	97.0655	FALSE	30	0	99	3		SunPass
145	1664.796	-18	79.27597	0	1	4	6	1924.836	97.0655	FALSE	30	0	99	3		SunPass
146	1744.072	-18	79.27597	0	1	4	6	2021.901	97.0655	FALSE	30	0	99	3		SunPass
147	1823.348	-18	79.27597	0	1	4	6	3780.171	0	FALSE	30	0	18	3		SunPass
148	1902.624	-18	79.27597	0	1	4	6	3780.171	0	FALSE	30	0	18	3		SunPass
149	1981.9	-18	79.27597	0	1	4	6	3780.171	0	FALSE	30	0	18	3		SunPass
150	2061.176	-18	79.27597	0	1	4	6	2125.476	85.01905	FALSE	30	0	100	3		SunPass
151	2140.452	-6	79.27597	0	2	5	6	2712.812	74.3875	FALSE	30	0	29	3		SunPass
152	2207.611	6	67.15902	0	3	6	6	2283.407	67.15902	FALSE	30	0	233	3		SunPass
153	2282.306	6	72.18317	5.024144	3	6	6	2350.566	67.15902	FALSE	30	0	233	3		SunPass
154	2348.365	6	68.10074	-4.08243	3	6	6	2417.725	67.15902	FALSE	30	0	233	3		SunPass
155	2424.002	6	73.12489	5.024144	3	6	6	2484.884	67.15902	FALSE	30	0	233	3		SunPass
156	2489.117	6	67.78496	-5.339931	3	6	6	2552.042	67.15902	FALSE	30	0	233	3		SunPass
157	2564.439	6	72.8091	5.024144	3	6	6	2619.201	67.15902	FALSE	30	0	233	3		SunPass
158	2629.038	6	67.33588	-5.47323	3	6	6	2686.36	67.15902	FALSE	30	0	233	3		SunPass
159	2703.843	6	67.15902	0	3	6	6	2753.519	67.15902	FALSE	30	0	233	3		SunPass
160	2771.002	6	67.15902	0	3	6	6	2820.678	67.15902	FALSE	30	0	233	3		SunPass
161	2838.161	6	67.15902	0	3	6	6	2887.837	67.15902	FALSE	30	0	233	3		SunPass
162	2905.32	6	67.15902	0	3	6	6	2954.996	67.15902	FALSE	30	0	233	3		SunPass
163	2972.479	6	67.15902	0	3	6	6	3022.155	67.15902	FALSE	30	0	233	3		SunPass
164	3047.174	6	72.18317	5.024144	3	6	6	3613.62	66.49751	FALSE	30	0	99	3		SunPass
165	3126.894	12	77.20731	5.024144		6	6	3674.247	62.58381	FALSE	30	0	99		0	SunPass
166	3211.637	12	82.23146	5.024144		6	6	3745.374	68.2794	FALSE	30	0	99		0	SunPass
167	3289.636	12	79.40987	-2.821588		6	6	3800	1000000	FALSE	30	0	100		0	SunPass
168	3364.837	12	76.60388	-2.805989		6	6	3800	1000000	FALSE	30	0	100		0	SunPass
169	3437.259	12	73.81599	-2.787895		6	6	3800	1000000	FALSE	30	0	100		0	SunPass
170	3506.926	12	71.04951	-2.766469		6	6	3800	1000000	FALSE	30	0	31		0	SunPass
171	3573.865	12	68.30916	-2.740354		6	6	3800	1000000	FALSE	30	0	100		0	SunPass
172	3638.113	12	65.60201	-2.707145		6	6	3800	1000000	FALSE	30	0	100		0	SunPass
173	3699.722	12	62.94014	-2.661876		6	6	3800	1000000	FALSE	30	0	101		0	SunPass
174	3758.775	12	60.34892	-2.591215		6	6	3800	1000000	FALSE	30	0	101		0	SunPass
127	0	-18								FALSE	31					
128	81.29742	-18	81.29742	0	1	4	3	317.1039	79.27597	FALSE	31	0	30	1		Automatic
129	162.5948	-18	81.29742	0	1	4	3	396.3799	79.27597	FALSE	31	0	30	1		Automatic

Figure 2.1: Snapshot of one of TPSIM© Database Files

2.2 MODEL CALIBRATION

Calibration is the implicit recognition that not all parameters can or will be known or measured with precision, but whose values are bounded or distributed in some reasonable established manner. Calibration is essential to a valid simulation model. Furthermore, the calibration process is highly related to the ability to adjust specific parameters within the model to attain a desired outcome. Within TPSIM©, the primary control resides within the car-following logic and the queuing condition. The car-following model in TPSIM© is based on the premise that drivers desire to follow the car in front of them at a given value of the clearance between them. This distance, however, differs from driver to driver. The clearance distribution assigns a certain desired clearance value to each individual vehicle to designate the driver aggressiveness level. The parameters for this distribution should be calibrated before running any scenario. Another factor should be considered in calibrating TPSIM© is when the vehicle is considered to be in a queuing condition. TPSIM© assumes that if the vehicle reaches a speed of 5 mph, it is considered to be in a queuing condition. Vehicle's start up queue delay and driver's reaction time can also affect the results that TPSIM© produces. Another important factor in TPSIM© calibration is the service time distribution. TPSIM© is very sensitive to this parameter since it is the major control of the toll plaza operation.

2.3 MODEL VALIDATION

After each individual module has been satisfactory debugged and corrected, the major task then is to test the validity of the model. Validation is defined as the process of reaching an acceptable level of confidence that the interference drawn from the model is reliable and accurate to the real-life toll plaza represented before conducting any further applications in planning or evaluating the toll plaza's performance.

The validation process of TPSIM© was conducted using two approaches, conceptual validation and operational validation, each of these approaches consisting of various stages, where tests are performed in a systematic manner. *Conceptual Validation* is a qualitative assessment of the model's theoretical underpinnings and its implementation. Conceptual validation may be reexamined to explain anomalous or inconsistent behaviors detected during operational validation *Rao and Owen, 1997 [4]*. Walkthroughs is the primary method for conceptual validation. By carefully reviewing and revisiting the model logic and its basic structure. *Operational Validation* of any simulation model proceeds through the validation of Measures Of Effectiveness (MOE's), which are part of the simulation output data. In other words, the means of the operational validation is to compare the actual toll plaza's measure of effectiveness observed from the field to those resulted from the simulation package. The MOE's must be representative of the system performance of interest and characterize the essence of the system. In order to accomplish such task, the performance data of a real toll plaza operation must be collected and analyzed prior to conducting the comparison.

2.3.1 Study Site Description

The Holland-East mainline toll plaza is the busiest of the ten OOCEA toll plazas. Figure 2.2 shows the location of the Holland-East Plaza within the OOCEA system. Figure 2.3 illustrates an aerial photograph of the Holland-East Plaza. It has a total of fourteen lanes. Each direction has five stationary lanes and four reversible lanes. The Holland-East Plaza area consists of 4 approach lanes that eventually branch out into 9 individual toll lanes in the peak direction, as shown in Figure 2.4. Due to the significant difference in the peak and off-peak directional traffic volumes the reversible lanes using cones were introduced to provide flexibility in handling these different demands. Before installing the AVI technology (**STAGE 1**), the first two on the right of each direction were manual lanes with the far right lane designed wider for heavy vehicles. The next two lanes were automatic lanes and the fifth lane was a manual lane as well. The four reversible lanes were also manual lanes. After installing an AVI technology known as E-PASS (**STAGE 2**), all lanes became mixed AVI lanes to accept E-PASS customers. After achieving an E-PASS market penetration of 14% in May 1995 (**STAGE 3**), the fifth manual lane was converted into a dedicated E-PASS lane to handle the E-PASS demand. Finally, implementation of a second dedicated lane adjacent to the existing dedicated lane in each direction was accomplished in November 1995 to accommodate the actual growth of the E-PASS subscribers (**STAGE 4**).

The Average Daily Traffic (ADT) volume for Holland-East Plaza was 54000 vpd in 1993, and it has increased to 61000 vpd in 1994. In June 1997, Holland-East Plaza processed an average of 75,000 vehicles per day, 30% of these vehicles were E-PASS users. This daily traffic volume is expected to jump to 132,700 by the year 2015. Analysis of the historical total processed transactions at Holland-East Plaza indicated that the plaza is approaching an annual demand growth of 13-14%, *OOCEA, 1999[5]*.

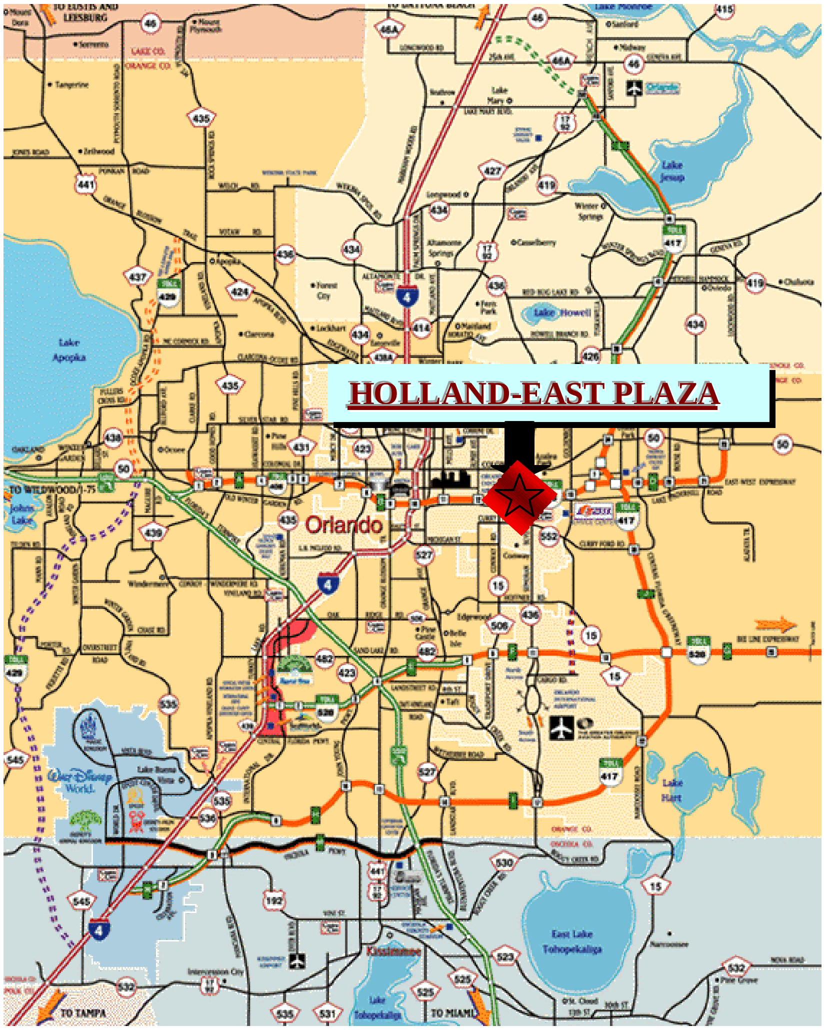
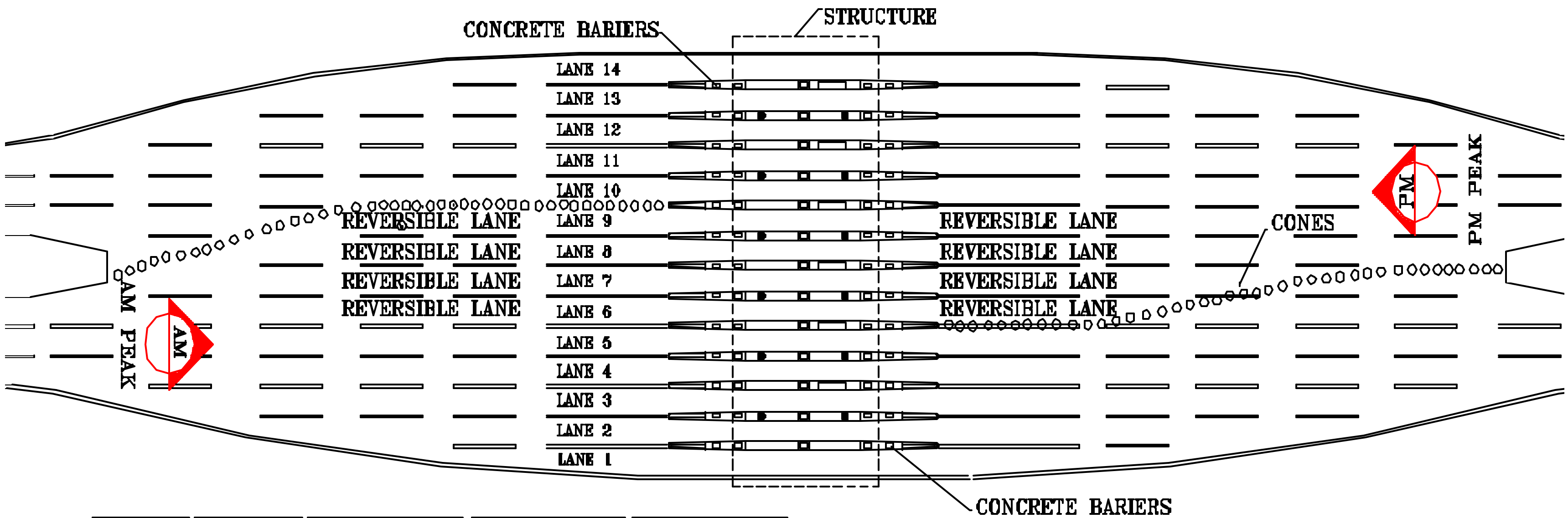


Figure 2.2: Location of Holland-East Plaza

Figure 2.3:Arial Photograph of the Holland-East Plaza



LANE	STAGE 1	STAGE 2	STAGE 3	STAGE 4
LANE 1	MANUAL	MANUAL/AVI	MANUAL/AVI	MANUAL/AVI
LANE 2	MANUAL	MANUAL/AVI	MANUAL/AVI	MANUAL/AVI
LANE 3	AUTOMATIC	AUTOMATIC/AVI	AUTOMATIC/AVI	AUTOMATIC/AVI
LANE 4	AUTOMATIC	AUTOMATIC/AVI	AUTOMATIC/AVI	AUTOMATIC/AVI
LANE 5	MANUAL	MANUAL/AVI	E-PASS	E-PASS
LANE 6	MANUAL	MANUAL/AVI	MANUAL/AVI	E-PASS
LANE 7	MANUAL	MANUAL/AVI	MANUAL/AVI	MANUAL/AVI
LANE 8	MANUAL	MANUAL/AVI	MANUAL/AVI	MANUAL/AVI
LANE 9	MANUAL	MANUAL/AVI	MANUAL/AVI	E-PASS
LANE 10	MANUAL	MANUAL/AVI	E-PASS	E-PASS
LANE 11	AUTOMATIC	AUTOMATIC/AVI	AUTOMATIC/AVI	AUTOMATIC/AVI
LANE 12	AUTOMATIC	AUTOMATIC/AVI	AUTOMATIC/AVI	AUTOMATIC/AVI
LANE 13	MANUAL	MANUAL/AVI	MANUAL/AVI	MANUAL/AVI
LANE 14	MANUAL	MANUAL/AVI	MANUAL/AVI	MANUAL/AVI

MANUAL: CHANGE AND RECIPTS
AUTOMATIC: AUTOMATIC COIN MACHINE (EXACT CHANGE)
AUTOMATIC/AVI: MIXED AVI LANES (AUTOMATIC and E-PASS)
MANUAL/AVI: MIXED AVI LANES (MANUAL and E-PASS)
E-PASS: FOR E-PASS USERS ONLY

Figure 2.4: Holland-East Plaza Layout in Various Stages

2.3.2 Data Acquisition

Generally, field data collection and analysis of toll plaza performance is a very expensive, time consuming, and tedious process. It is, however, an unavoidable task for the purpose of validating the developed model. Many different parameters were required as inputs for the model.

Three synchronized video camcorders were used to tape traffic behavior at the Holland-East Plaza. Two of the camcorders were placed on top of the toll plaza canopy to record vehicle arrivals and queue length. The third camcorder was placed at a vantage point on top of a car on the roadside downstream of the plaza facing the tollbooths to capture the departure time and service time for each vehicle. Data collection was conducted during the morning peak hour (7:00-8:00 AM) in weekdays. One day (June 8, 1995) representing Stage 3 and three days (July 9, 1996, July 28, 1996, and July 24, 1996) representing Stage 4 were selected randomly for data collection to be used in the TPSIM© operational validation process. Preliminary analysis has shown there is no significant differences in service times among different types of lanes, *Al-Deek et al., 1997 [2]*. Therefore, data collection efforts focused on lanes 2 (Manual/Truck), 4 (Automatic), 5 (dedicated AVI), 6 (Manual), and 7 (Manual). The videotapes were viewed for the upstream traffic to extract arrival time for each individual vehicle as well as for downstream traffic to determine the departure time for each vehicle. Those two procedures were matched up and resulted the waiting delay for each individual vehicle. Service time for each individual vehicle was obtained using the downstream camera.

Vehicles that depart the toll plaza in every minute were also counted (lane throughput). These data were collected for each individual lane (2,4,5,6, and 7) and stored in a database format to be used in the simulation validation process. Some of these data were inputs for the TPSIM© model (e.g. service time and arrival rate) and the others were used as real-life performance (vehicle delay, lane throughput, and queue length) to be compared with the TPSIM© model outputs.

Distance Measuring Instruments (DMI) were used for collection of data to compute vehicles approach speed, desired acceleration, and desired deceleration within the toll plaza area. A DMI is a portable device that has the capability of determining the instantaneous time, distance, and speed of the vehicle for which the DMI is connected to, *Klodizinski [6].* A group of five teams collected this data at each lane type. Each team consisted of a driver and a DMI operator. Beginning and ending of data collection section where carefully chosen to allow enough time for the drivers to reach an acceptable cruise speed before approaching the plaza and after departing from the plaza. This allowed for the capture of the platoon speed profile through the toll plaza area. Figure 2.5 illustrates a sample of speed profile for different lane types. A total of five runs were completed during the morning peak hour for seven days, resulting in a total of 35 runs to compute approaching speed, deceleration rate, and acceleration rate data points.

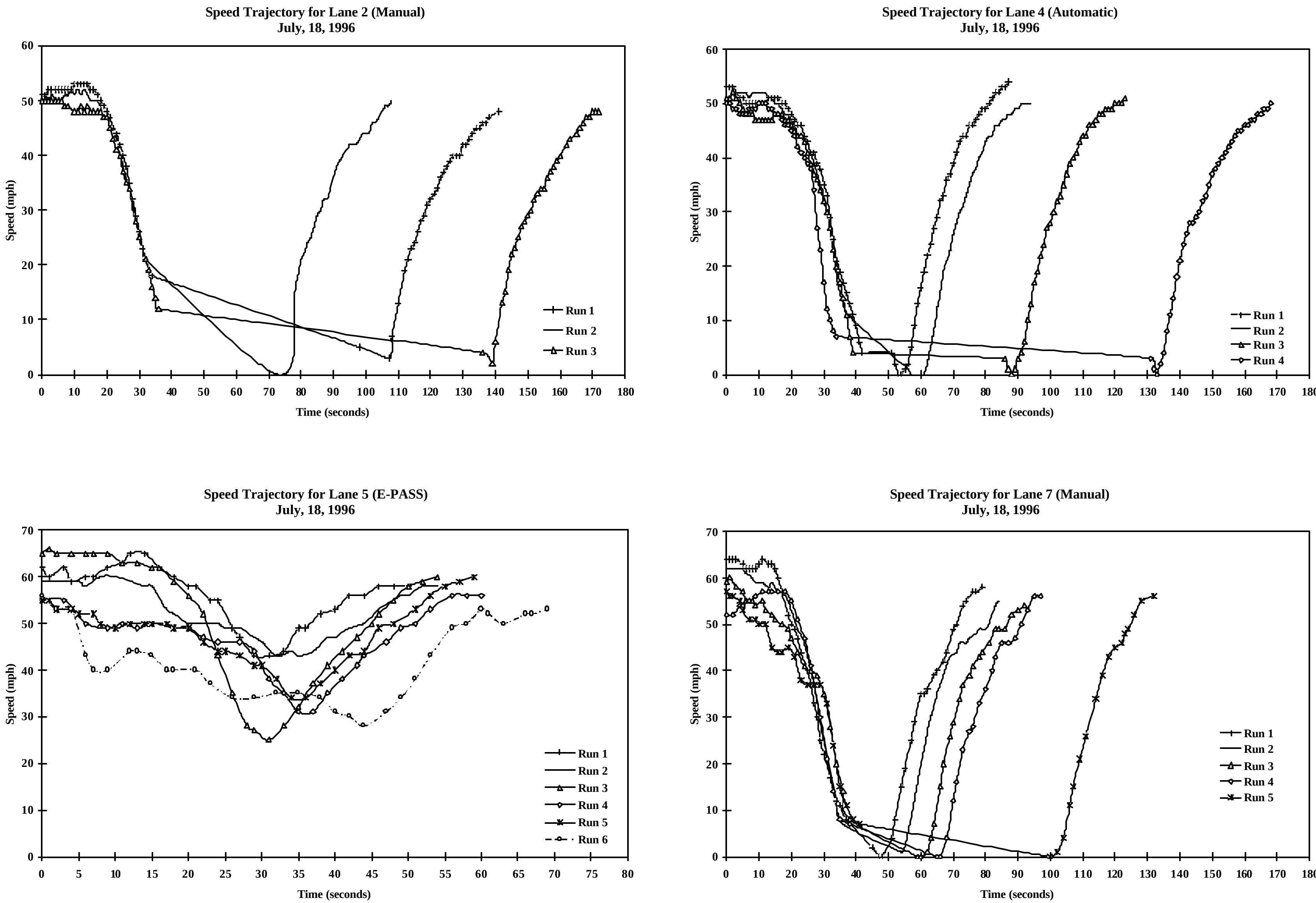


Figure 2.5: Sample of Speed Profile for different Lane Types

2.3.3 Conceptual Validation Process And Results

Conceptual validation is not necessarily a precursor to operational validation. Rather, it is a concurrent and recurring process that takes place in conjunction with operational validation. The best way to confirm some of the conclusions from the conceptual validation is to observe the animation of the simulated real-life case with TPSIM©. Animation was displayed side-by-side with the real-life videotapes collected at the Holland-East Plaza. Figures 2.6 and 2.7 illustrate snapshots of TPSIM© animation and the real-life data collected at the Holland-East Plaza respectively at the same point of time (7:35:32 AM). The comparison of these two figures indicates that traffic condition resulted from simulating the Holland-East Plaza using TPSIM© is very close to the actual real-life traffic condition at Holland-East Plaza.

2.3.4 Operational Validation Process And Results

2.3.4.1 Validation Input Data

Validity of the model should be established by various analyses to see if the model behaves in the expected way when one or more input variables are changed. Therefore, traffic data collected for all four days during both stages 3 and 4 were used to validate TPSIM©. Certain input parameters were held constant for both stages, e.g., plaza geometric and global parameters. However, several other parameters were assigned different values for the two stages, i.e., plaza configurations, traffic characteristics and service time distributions. The following sections introduce input values used to simulate each day in each stage.

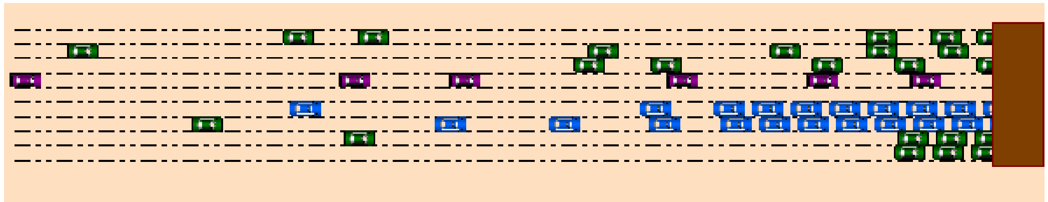


Figure 2.6: Snapshot of the TPSIM© Animation Resulted from Simulating the Holland-East Plaza on July 24, 1996

Figure 2.7: Snapshot of the Real-life Traffic at the Holland-East Plaza Obtained from the Videotape for July 24, 1996

2.3.4.2 <u>Run Specifications Data</u>

Beginning time of simulation were set to be the starting time of the morning peak (7:00 AM), the ending time was set to be 8:00AM. For the purpose of this study, warming up period was assumed to be 5 minutes. Random Offset Number (RON) was changed from run to another for each day. Figure 5.8 illustrates the run specification parameters used to simulate traffic at Holland-East Plaza in both Stages 3 & 4.

2.3.4.3 <u>Plaza Geometric Data</u>

As mentioned before, the Holland-East Plaza consists of 4 approach lanes and 9 toll lanes. It was assumed that the length of the approach lanes is 3000 ft to capture any extended queue that may spill back from the toll lanes and reach the approach lanes. Both lengths of the toll lanes and the transition zone were obtained from the Holland-East Plaza geometric plans and they were 600 ft and 200 ft, respectively. Also, Holland-East Plaza geometric plans indicated that all approach lanes and toll lanes have the same width of 12 ft. Figure 2.9 illustrates the input parameters for plaza geometric in both stages 3 and 4.

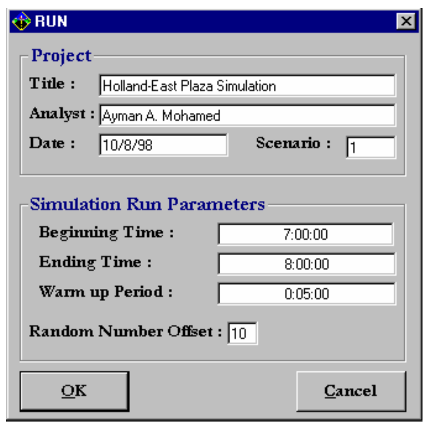


Figure 2.8: Run Specification Input Values

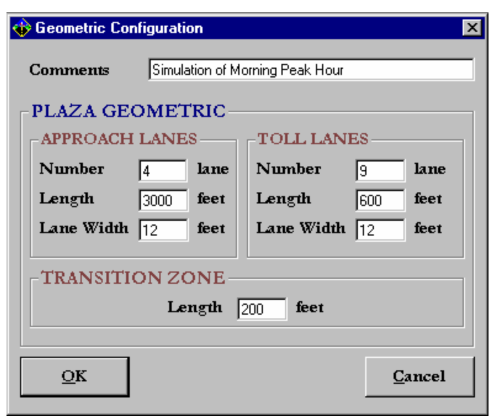


Figure 2.9: Plaza Geometric Input Parameters

During the data collection period for the two days, all toll lanes were opened during the morning peak hour. Therefore, no data were entered for closing time in the lane schedule table, see Figure 5. In July 1996 (stage 4), all toll lanes had the same payment types as in stage 3, except lane number 6 that was changed from a mixed Manual/AVI lane in Stage 3 to a dedicated E-PASS lane in Stage 4. Figures 5.10 and 5.11 illustrate the input parameters for toll lane types and schedules for stages 3 and 4 respectively.

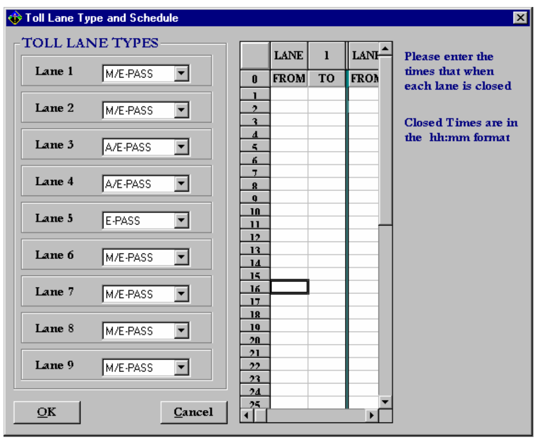


Figure 2.10: Toll Lane Types Input Parameters for Stage 3

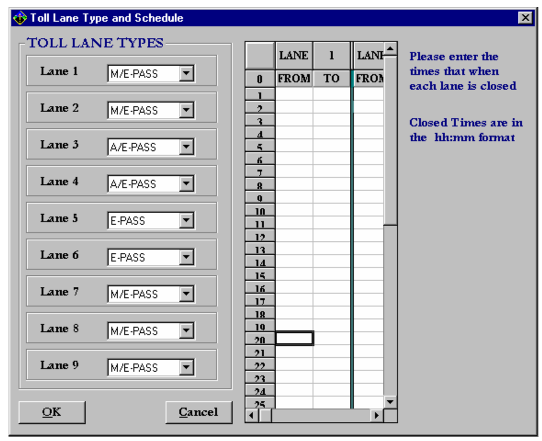


Figure 2.11: Toll Lane Types Input Parameters for Stage 4

2.3.4.4 <u>Global Parameters Data</u>

Inter-arrival time distribution (time between the arrivals of two consecutive vehicles) is an important input for TPSIM©. Using the arrival time for each vehicle obtained from the videotapes, the inter-arrival times were calculated and fitted for each approaching lane to identify which distribution truly represents the inter-arrival time distribution. Figures 5.12 and 5.13 show the observed inter-arrival time distributions. It is clear that, the inter-arrival time distribution follows a shifted negative *exponential* distribution.

Inter-arrival time collected from the field indicated that minimum headway is 1 second as shown in Figures 5.12 and 5.13. The DMI data collected from the field indicated that the average E-PASS speed value is 40 mph, which indicates that E-PASS vehicles have to decelerate to maintain this speed at the toll plaza. Percentage of lane changing was assumed to be 100%. In other words, any vehicle that is being affected by a slower leader will try to change its lane to avoid the slower leader. It was assumed that reaction time among vehicles follow a *uniform* distribution with a minimum of 0.64 second and a maximum of 1.7 second, *AASHTO*, *1990 [7]*.

Approaching speed data was derived from the sample data collected by the DMIs. Approaching speed were collected by using the observation points collected from the DMI before the vehicle was influenced by the toll plaza operation (decelerating to stop or to join the queue). By fitting the approaching speed observations, it was found that, desired speeds for vehicles approaching the toll plaza follow a *normal* distribution with an average of 60 mph (95 km/hr) and a standard deviation of 5 mph (8 km/hr).

Deceleration and acceleration rate distributions were also derived from the sample data collected by the DMIs. Deceleration and acceleration rates were obtained by using the observation points collected from the DMI when the vehicle was not influenced by the toll plaza queues. It was found that, vehicles desired deceleration rates follow a *normal* distribution with an average of 3 ft/s^2 (0.9 m/s^2) and a standard deviation of 0.5 ft/s^2 (0.15 m/ s^2). It was found that, acceleration rates of vehicles approaching Holland-East Plaza follow a *normal* distribution with an average of 5.5 ft/s^2 (0.9 m/s^2) and a standard divination of 0.5 ft/s^2 (0.15 m/ s^2).

Clearance distribution was assumed to be a *uniform* distribution with a minimum of 20 ft and a maximum of 40 ft (one to two car lengths). Figure 5.14 illustrates the default values for the Global Parameters Window.

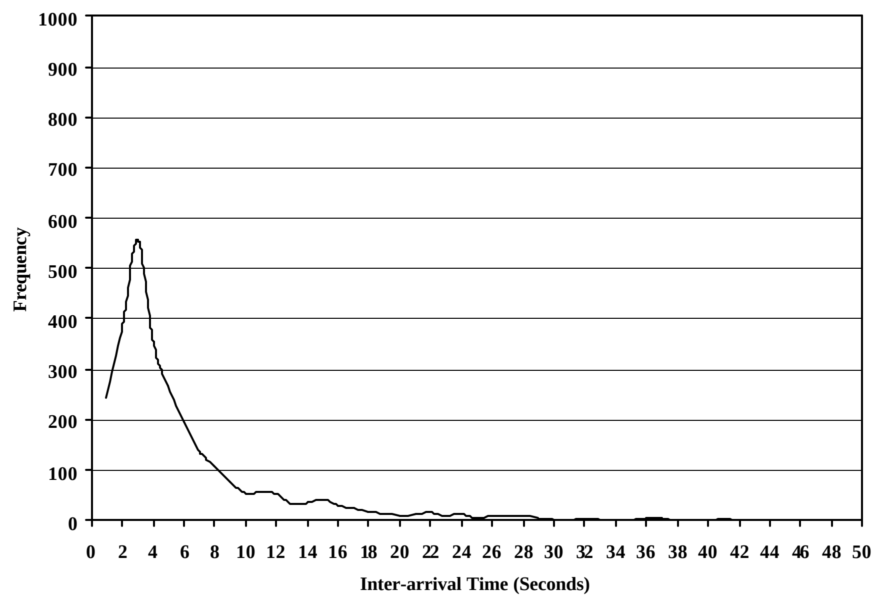


Figure 2.12: Inter-arrival Distribution for Stage 3

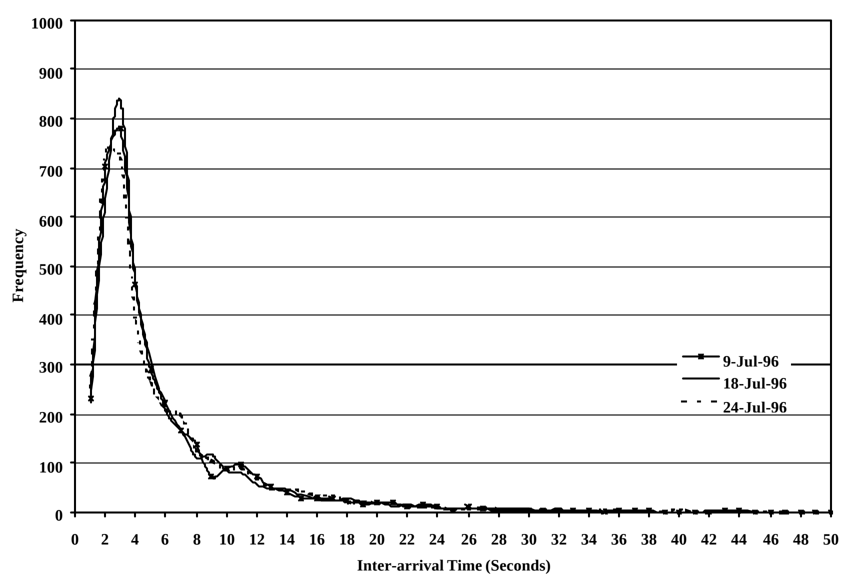


Figure 2.13: Inter-arrival Time Distribution for Stage 4

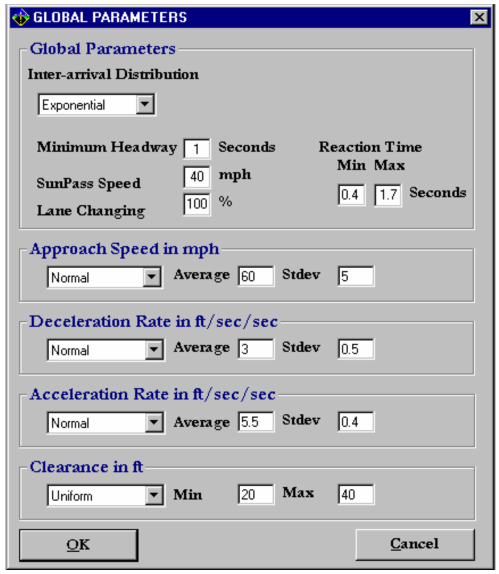


Figure 2.14: Global Parameters Input Values

2.3.4.5 Traffic Characteristics Data

To obtain the inter-arrival time distribution, the database obtained from the video was analyzed. By using the arrival time for each vehicle, traffic volumes were calculated for any selected time interval. Table 2-1 provides traffic volume values for each 5-minutes interval during the morning peak hour for both days under study in Stages 3 and 4.

Table 2-1: Traffic Volume Values During 5-minutes Intervals

Time Interval	June 8, 1995 Stage 3	July 9, 1996 Stage 4	July 18, 1996 Stage 4	July 24, 1996 Stage 4
7:00 - 7:05	345	264	295	229
7:05 – 7:10	376	363	356	352
7:10 - 7:15	417	462	413	373
7:15 – 7:20	429	444	431	494
7:20 – 7:25	400	486	464	419
7:25 – 7:30	445	504	503	496
7:30 – 7:35	511	521	508	499
7:35 – 7:40	534	552	536	529
7:40 – 7:45	510	542	604	563
7:45 – 7:50	462	531	571	565
7:50 – 7:55	410	475	485	485
7:55 – 8:00	274	402	408	454

Percentage of vehicle types (i.e, Manual, Automatic, or E-PASS) was also derived from the videotapes. Table 2-2 provides the vehicle type percentages in each stage. Also, percentages of trucks and passenger cars were extracted from the videotapes. Data analysis shows that 97% of the approaching vehicles are passenger cars and 3% are trucks. Figure 2-15 shows the input parameters for the traffic characteristics in both stages 3 and 4.

Table 2-2: Percentages of Vehicle Types for Both Stages

Vehicle Class	June 8, 1995 Stage 3	July 9, 1996 Stage 4	July 18, 1996 Stage 4	July 24, 1996 Stage 4
Manual	51.48%	39.50%	39.63%	39.72%
Automatic	23.51%	20.22%	20.49%	20.56%
E-PASS	25.01%	40.28%	39.88%	39.72%

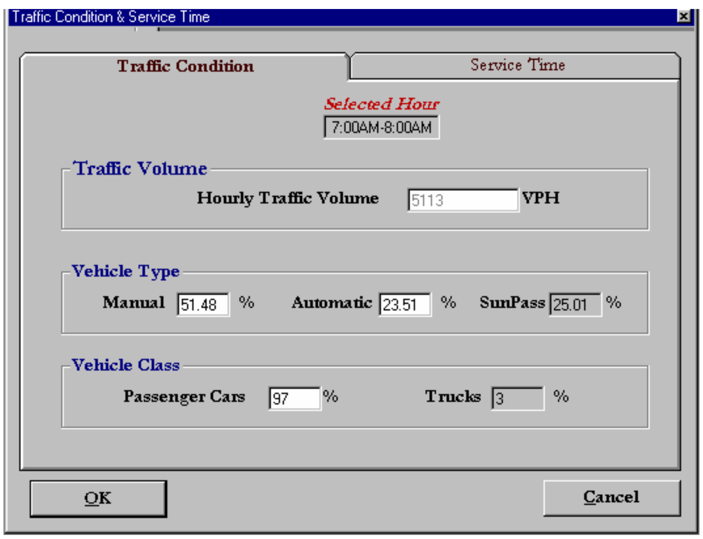


Figure 2.15: Input Parameters for Traffic Characteristics for Stage 3

Service time is the time a vehicle spends to pay toll at the booth. The actual service time may be influenced by a number of factors, such as the number of coins being processed, the experience of the toll collector, and the class of vehicle being serviced. Since the service time value changes from customer to another, fitting a stochastic distribution for service time for each lane is the appropriate way to represent the fluctuation in service time. Service time distribution is a very important parameter in simulating toll plazas. Therefore, fitting the right distribution for each lane was performed with special care. By extracting the service time for each vehicle in each lane from the videotapes, it was found that the best fit for service time is a *discrete* distribution. Tables 2-3, 2-4, and 2-5 provide the parameter for the fitted discrete distribution for each lane type. Since vehicles that are equipped with E-PASS system do not to stop to pay toll, it was assumed that the service time for any E-PASS vehicle is 0 seconds.

Table 2-3: Service Time Distribution for Lane 2 (Manual/AVI)

Service Time	June 8, 1995 Stage 3	July 9, 1996 Stage 4	July 18, 1996 Stage 4	July 24, 1996 Stage 4
0	0%	1%	1%	1%
1	1%	5%	2%	2%
2	2%	11%	6%	8%
3	7%	14%	12%	16%
4	16%	15%	15%	16%
5	19%	16%	14%	12%
6	13%	10%	11%	9%
7	11%	8%	8%	9%
8	8%	6%	8%	8%
9	5%	4%	5%	3%
10	3%	3%	3%	4%
11	4%	3%	3%	5%
12	2%	1%	3%	2%
13	2%	1%	4%	3%
14	2%	1%	3%	2%
15	2%	1%	2%	0%
16	2%	0%	0%	0%
17	1%	0%	0%	0%

Table 2-4: Service Time Distribution for Lane 4 (Automatic/AVI)

Service Time	June 8, 1995 Stage 3	July 9, 1996 Stage 4	July 18, 1996 Stage 4	July 24, 1996 Stage 4
0	2%	0%	2%	4%
1	2%	7%	8%	6%
2	7%	15%	16%	17%
3	20%	24%	24%	21%
4	27%	20%	21%	20%
5	23%	18%	16%	15%
6	10%	9%	8%	10%
7	6%	5%	4%	4%
8	2%	2%	1%	3%
9	1%	0%	0%	0%

Table 2-5: Service Time Distribution Values for Lane 6 (Manual/AVI)

Service Time	June 8, 1995 Stage 3	July 9, 1996 Stage 4	July 18, 1996 Stage 4	July 24, 1996 Stage 4
0	1%	1%	1%	0%
1	1%	3%	4%	5%
2	1%	14%	14%	15%
3	14%	21%	22%	21%
4	24%	16%	15%	19%
5	19%	9%	12%	12%
6	11%	8%	10%	7%
7	7%	8%	5%	5%
8	5%	5%	4%	6%
9	5%	3%	2%	3%
10	3%	3%	2%	2%
11	3%	1%	3%	1%
12	2%	3%	2%	2%
13	1%	3%	1%	1%
14	1%	1%	2%	1%
15	1%	1%	1%	0%

2.3.4.6 Simulation Runs

Since TPSIM© is stochastic in nature and was programmed to use different random number streams to be used in generating different distributions for certain parameters such as arrival times, service times, traffic attributes, ..etc., there was some inherent variation from a simulation run to another. In order to take into account this variability, several simulation runs (replications) were undertaken in the TPSIM© validation process to make a better statistical inference on the simulation results. Ten replications, with different random number streams, for the morning peak hour in each day during both stages 3 and 4 were performed. Results from these runs were averaged macroscopically for the whole-simulated hour and microscopically for each five-minutes interval within the simulated hour. Comparisons between the model outputs and the field observations were conducted at both the macroscopic level and the microscopic level.

2.3.5 Validation Process

After developing any simulation model, it is essential to test how close the model behavior corresponds to the actual operation before its further applications. Validation is defined as the process of reaching an acceptable level of confidence that the inferences drawn from the model are reliable and accurate to the real-world system being represented. One of the major tasks of this study is to validate TPSIM© model before applying the model in conducting any further experiments.

The validation process of TPSIM© was conducted using two approaches, ***Turning Test*** and ***Error Analysis Test***, each of these approaches consists of various stages. These tests are performed in a systematic manner. The ***Turning Test*** is a qualitative assessment of the model's theoretical underpinnings and its implementation. The ***Turning Test*** compares the system performance with real-life observations graphically to detect any unexpected behavior of the model performance during the simulation period. The ***Error***

Analysis Test conducts certain statistical tests to quantify the deviation of the simulated results from their actual values and detect any systematic bias of the simulation results.

2.3.5.1 Measures Of Effectiveness (MOES)

Validation process of any simulation model is basically validation of Measures Of Effectiveness (MOEs), which are part of the simulation output data. In other words, the means of TPSIM© validation is to compare the actual toll plaza's measure of effectiveness observed from the field to those resulted from the simulation package. The MOEs must be representative of the system performance of interest and characterize the essence of the system. For the purpose of TPSIM© validation four different MOEs were selected for each lane. These measures of effectiveness can be summarized as following:

a) Hourly Throughput

This is the vehicle count downstream of the plaza booth during the peak hour.

b) Average Queuing Delay

This is the time a vehicle spends waiting in a queue until it leaves the plaza averaged over all vehicles upstream of the booth during the peak hour.

c) Maximum Queuing Delay

This is the maximum time a vehicle spent in the queue at the toll plaza booth during the peak hour.

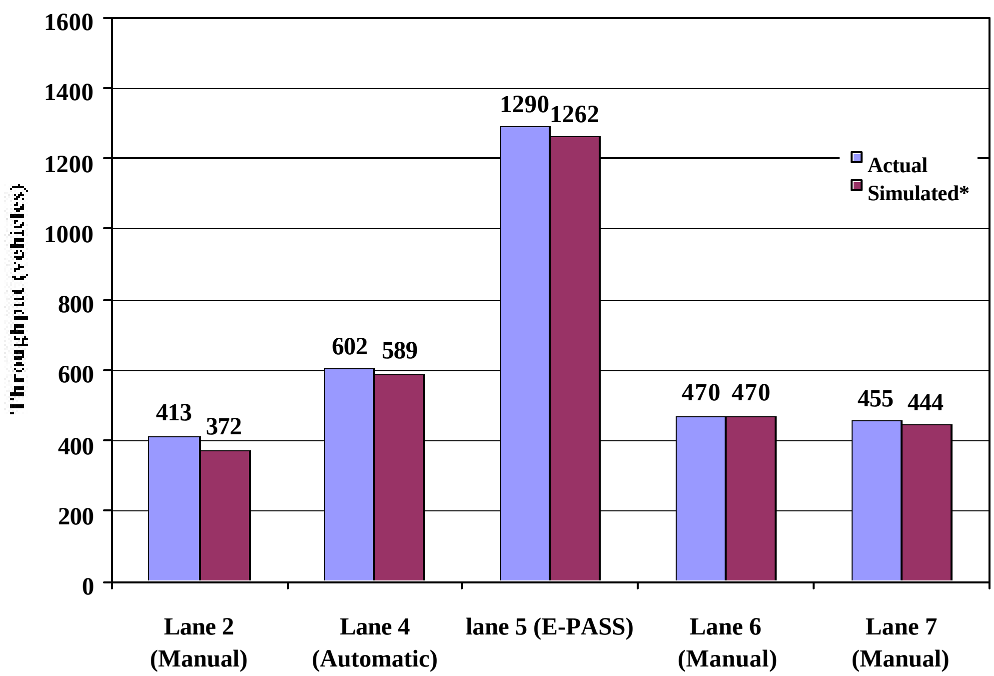
d) Total Queuing Delay

This is the time spent by all vehicles waiting in the queue at the toll plaza booth during the peak hour.

2.3.5.2 Turning Tests Approach

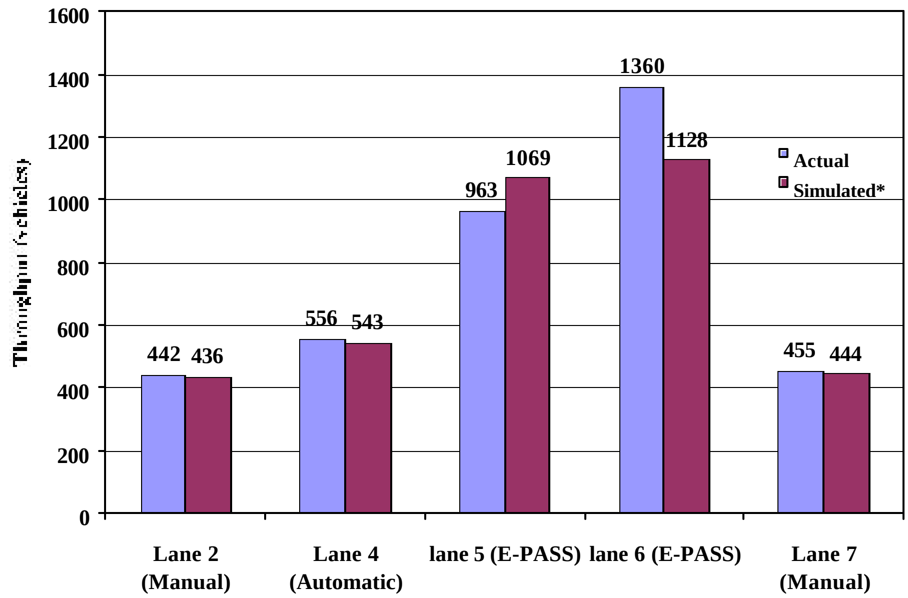
Hourly Throughput

Figures 2-16 through 2-19 show comparisons of the hourly throughput of each tollbooth for each morning peak hour. Even though the simulation outputs are not exactly the observed values, it is clear that TPSIM© outputs are very close to the real-life observations. Appendix A provides a complete set of plots showing the five-minute throughput patterns for the actual observation and the simulation outputs for each simulated day. It is clear that for the two stages, TPSIM© produced satisfactory output results. The differences in tollbooth throughputs are within 10 percent of the actual toll booth throughputs.



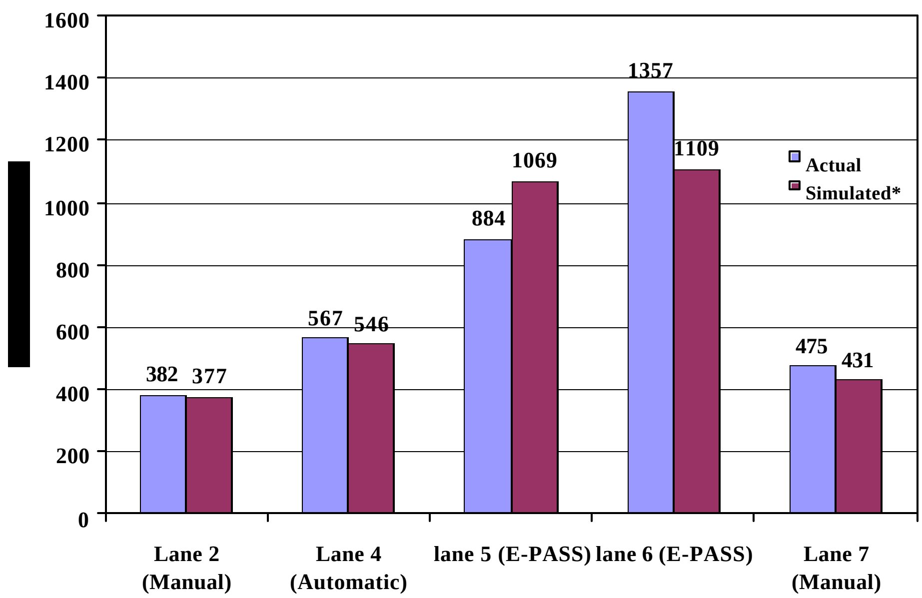
* Based on averages of 10 runs

Figure 2.16: Comparison of Actual and Simulated Hourly Throughput for Thursday June 8, 1995 During Stage 3



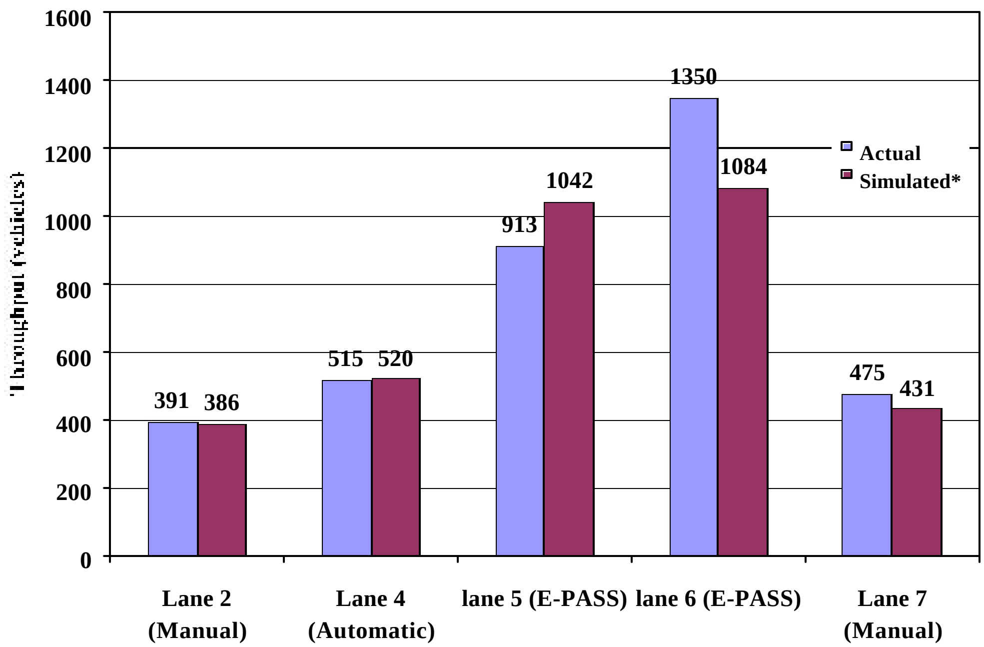
*Based on averages of 10 runs

Figure 2.17: Comparison of Actual and Simulated Hourly Throughput for Tuesday July 9, 1996 During Stage 4



* Based on averages of 10 runs

Figure 2.18: Comparison of Actual and Simulated Hourly Throughput for Thursday, July 18, 1996 During Stage 4



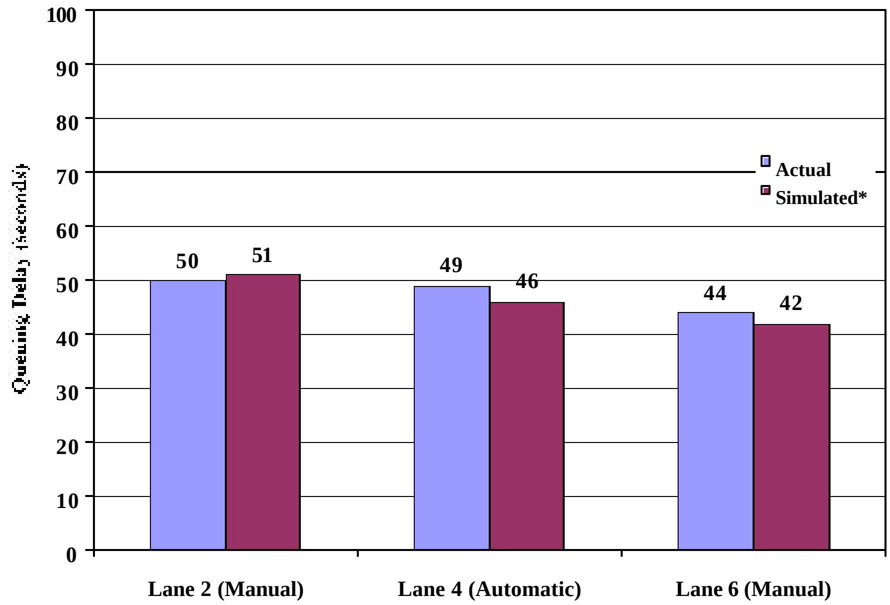
*Based on averages of 10 runs

Figure 2.19: Comparison of Actual and Simulated Hourly Throughput for Wednesday, July 24, 1996 During Stage 4

Average Queuing Delay

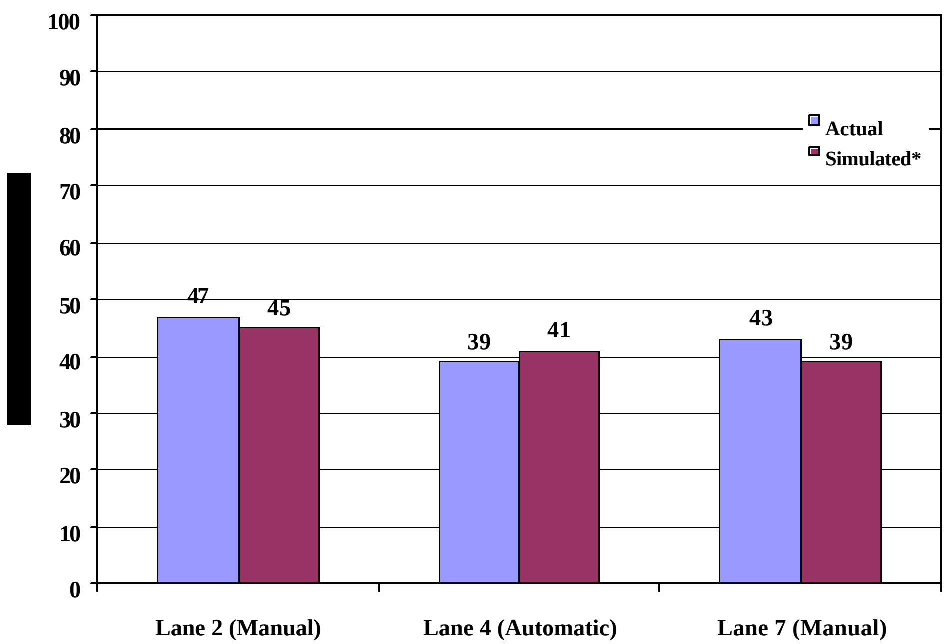
Figures 2.20 through 2.23 illustrate comparisons of the average queuing delay for all vehicles in each lane for each day.

Appendix A provides comparison plots of the average queuing delay per five-minute interval. It is clear that, the simulation results are very close to the real-life average queuing delay observed at the Holland-East Plaza. This result increases the confidence in the TPSIM© model.



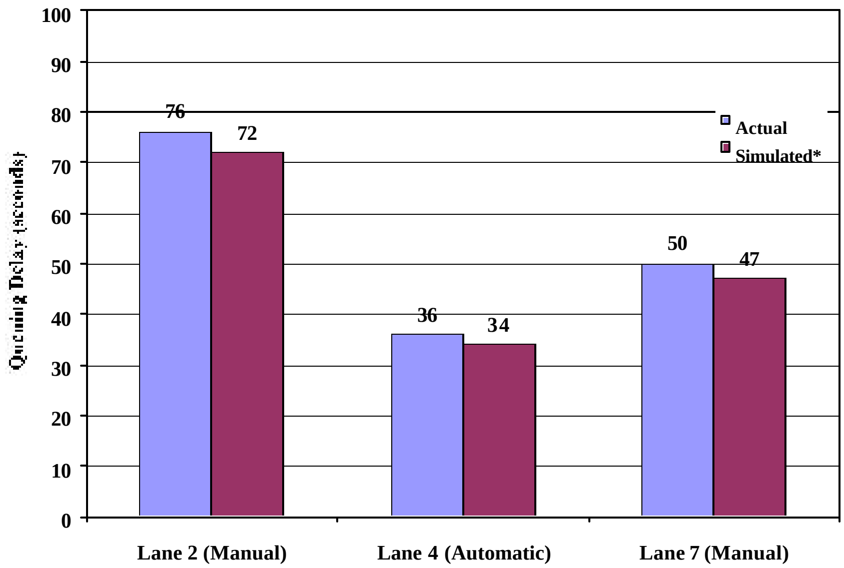
* Based on averages of 10 runs

Figure 2.20: Comparison of Actual and Simulated Average Delay for Thursday June 8, 1995 During Stage 3



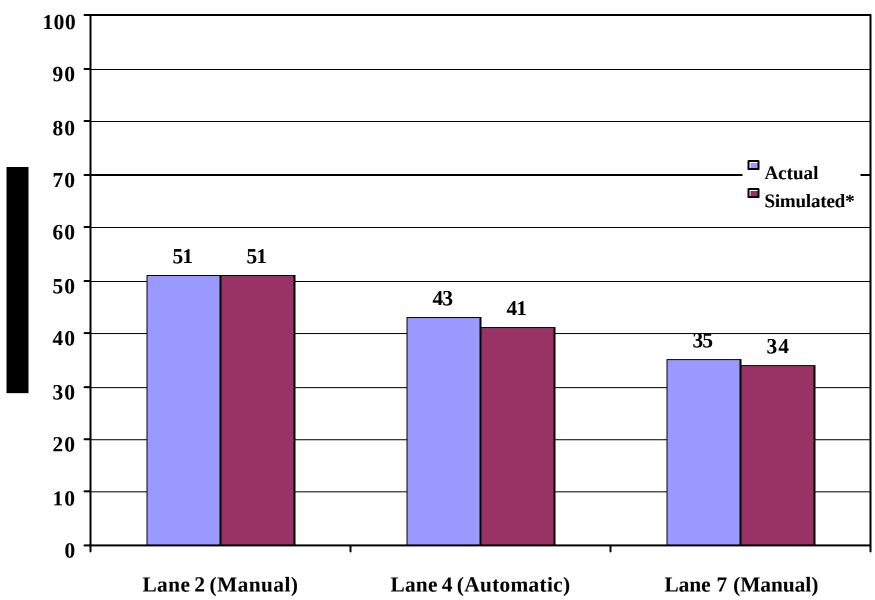
*Based on averages of 10 runs

Figure 2.21: Comparison of Actual and Simulated Average Delay for Tuesday, July 9, 1996 During Stage 4



* Based on averages of 10 runs

Figure 2.22: Comparison of Actual and Simulated Average Delay for Thursday, July 18, 1996 During Stage 4



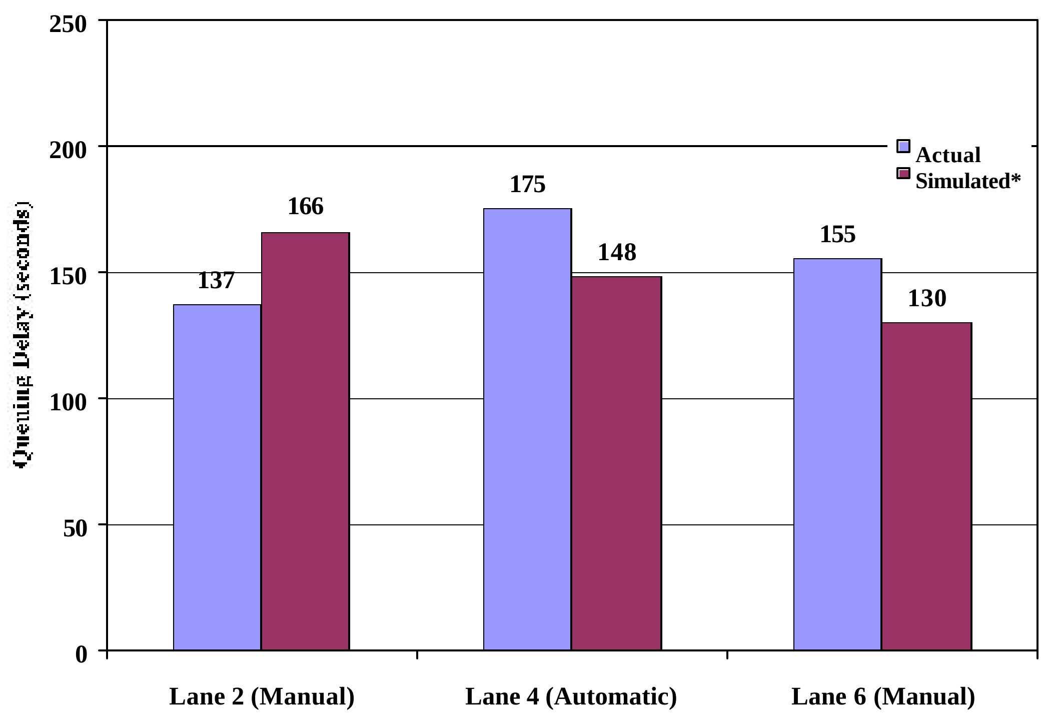
*Based on averages of 10 runs

Figure 2.23: Comparison of Actual and Simulated Average Delay for Wednesday, July 24, 1996 During Stage 4

Maximum Queuing Delay

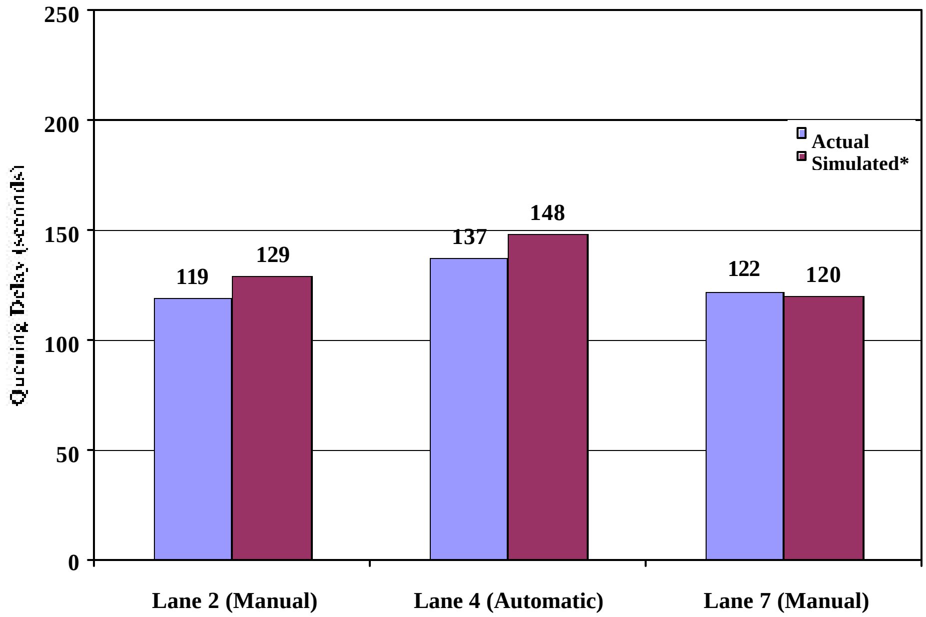
Figures 2.24 through 2.27 illustrate comparisons of real-life and simulated maximum queuing delay during the morning peak hour for each toll lane in each day.

Appendix A provides a complete set of plots for the maximum queuing delay per 5 minutes interval for each toll lane. The simulation outputs for Stage 4 are very close to the real-life observations.



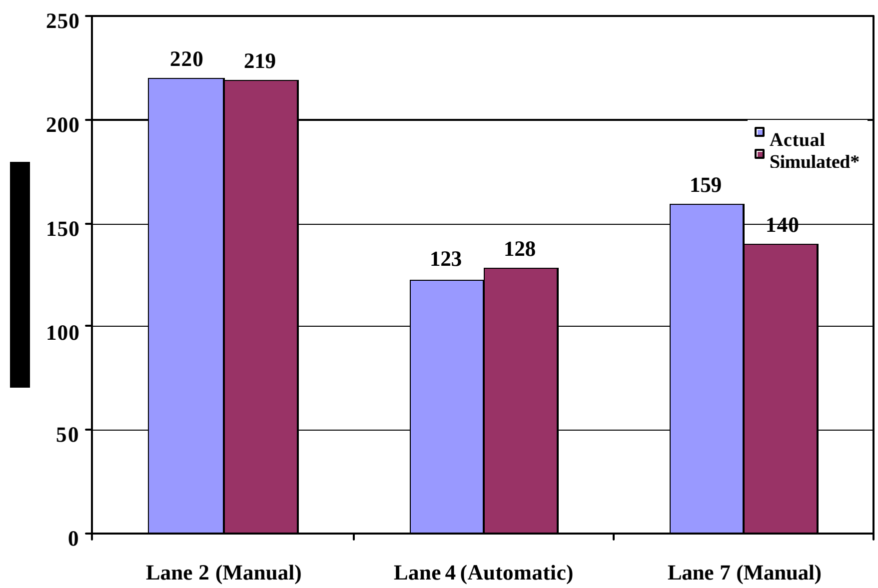
* Based on averages of 10 runs

Figure 2.24: Comparison of Actual and Simulated Maximum Delay for Thursday June 8, 1995 During Stage 3



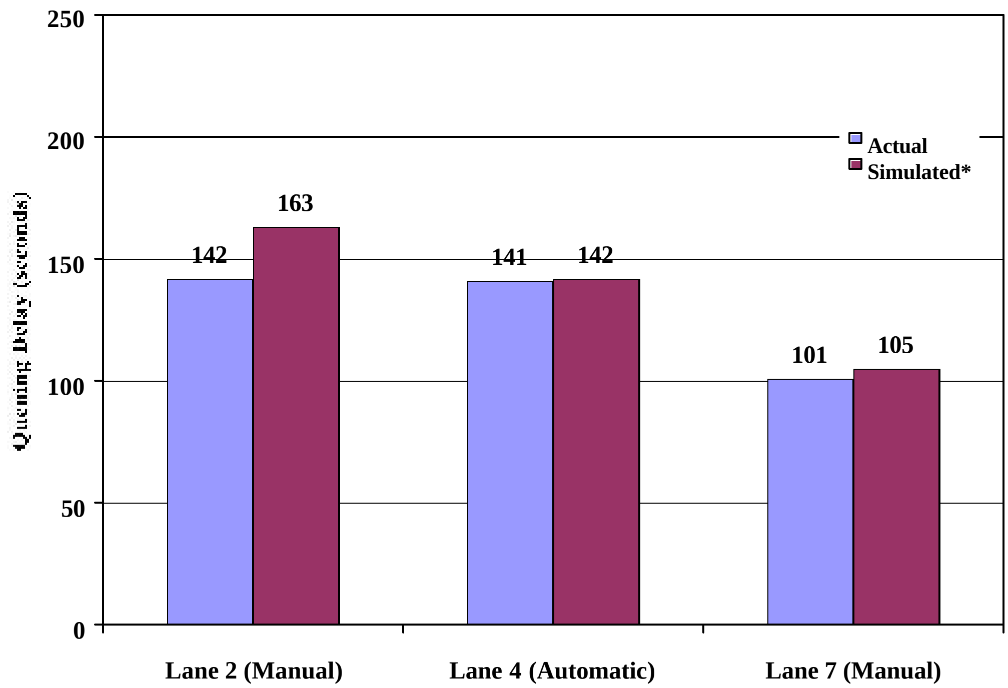
* Based on averages of 10 runs

Figure 2.25: Comparison of Actual and Simulated Maximum Delay for Tuesday July 9, 1996 During Stage 4



* Based on averages of 10 runs

Figure 2.26: Comparison of Actual and Simulated Maximum Delay for Thursday, July 18, 1996 During Stage 4



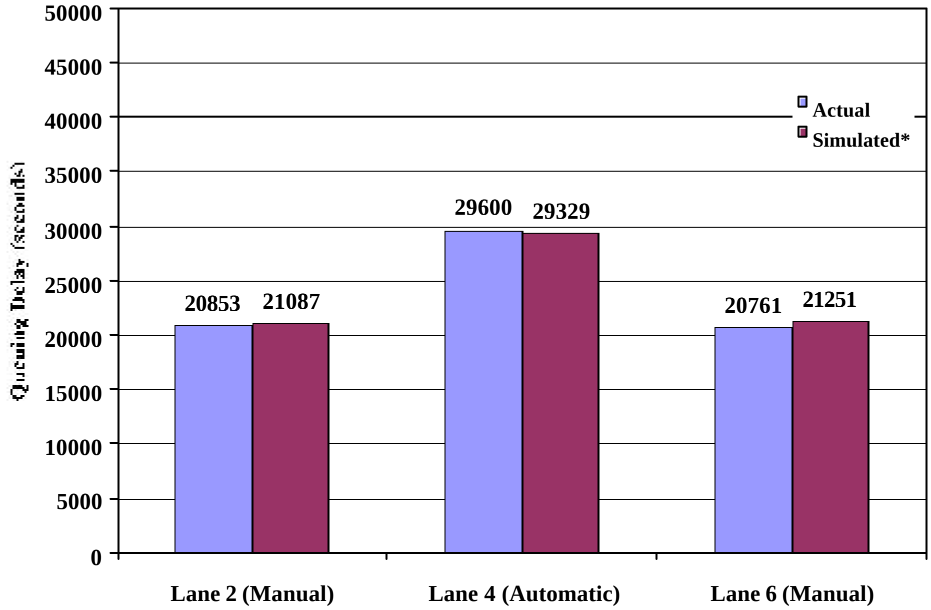
* Based on averages of 10 runs

Figure 2.27: Comparison of Actual and Simulated Maximum Delay for Wednesday, July 24, 1996 During Stage 4

Total Queuing Delay

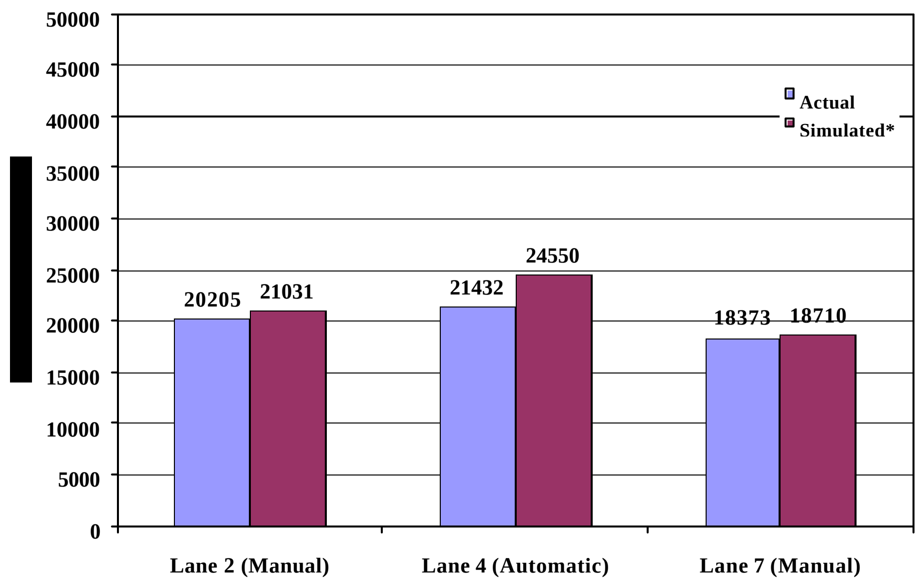
Figures 2.28 through 2-31 illustrate comparisons of real-life and simulated total queuing delay during the morning peak hour in each toll lane in each day.

Appendix A provides plots of the total queuing delay at each lane for 5 minutes interval. It is clear that, for both simulated days, the simulation output patterns are very close to the real-life observations at the Holland-East Plaza.



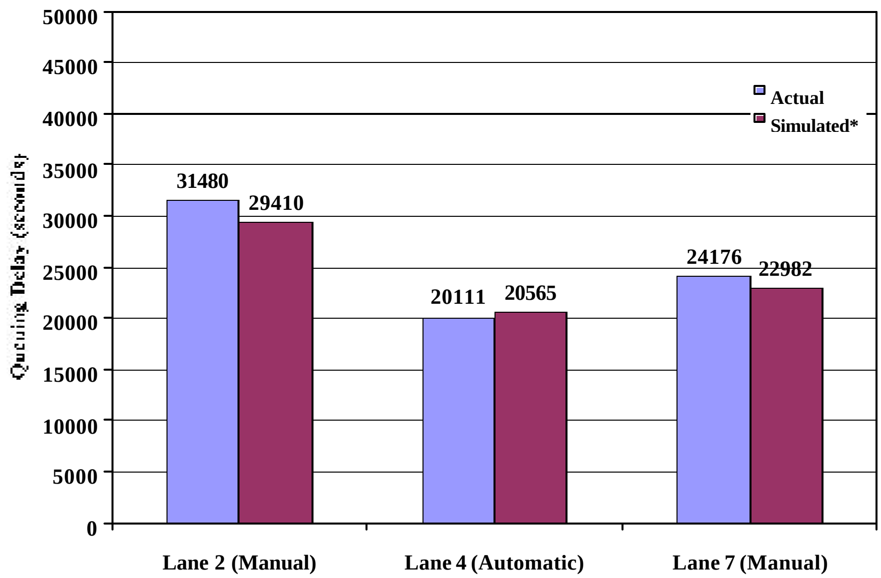
* Based on averages of 10 runs

Figure 2.28: Comparison of Actual and Simulated Total Delay for Thursday June 8, 1995 During Stage 3



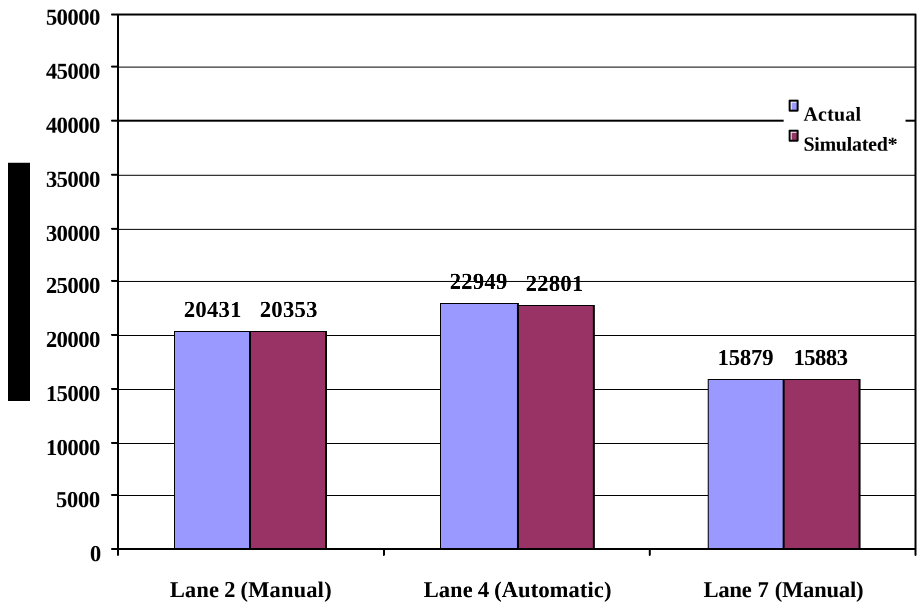
* Based on averages of 10 runs

Figure 2.29: Comparison of Actual and Simulated Total Delay for Tuesday July 9, 1996 During Stage 4



* Based on averages of 10 runs

Figure 2.30: Comparison of Actual and Simulated Total Delay for Thursday, July 18, 1996 During Stage 4



* Based on averages of 10 runs

Figure 2.31: Comparison of Actual and Simulated Total Delay for Wednesday, July 24, 1996 During Stage 4

2.3.6 Error Analysis Tests Approach

The Error Analysis Test involved statistical analysis to quantify the difference in each measure of effectiveness between the field data and the simulation outputs.

Chi-square test was used to compare the tollbooth throughputs. ***Chi-square*** test is used when the observations are numbers counted from the field. Therefore, the ***Chi-square test*** was used in tollbooth throughput rather than applying it in comparing delay observations. The main objective of the ***Chi-square*** test is to check if the distribution of throughput for each lane resulted from TPSIM© is identical to the throughput distribution observed from the field.

The null hypotheses (H_o): the two distributions are identical

The alternative hypotheses (H_a) : the two distributions are different

Table 2-6 shows the Chi-square values for testing the five-minute interval throughput distribution for each lane for both stages. The P-values for all comparisons are larger than 0.05, which indicates that at 95% confidence level there is no significant difference between the simulated average tollbooth throughput and the observed values for all lanes in all validated days under study. Since delays are time base observations that are not counts, ***Chi-square*** test is not an appropriate test to compare the delay observations, a different statistical test was used in comparing the delay measures of effectiveness. The ***Wilcoxon*** *Signed Rank* is non-parametric statistical test. The ***Wilcoxon Signed Rank*** test was used to check if there is a significant difference in average, maximum, and total queuing delay between the simulation results and the real-life data. This test is a matched-pairs design test to analyze the difference between measurements within each pair as follows:

The null hypotheses (H_o): simulated and actual values are identical

The alternative hypotheses (H_a): simulated and actual values are different

Table 2-7 presents the results of the ***Wilcoxon Signed Rank*** test for the average queuing delay for both stages.

Table 2-6: Chi-square Test Results for Tollbooth Throughput

Day	Lane	Chi-square Value	P-Value	Conclusion
June 8, 1995 (Stage 3)	Lane 2	3.85	0.95	*Identical Distributions*
	Lane 4	1.41	0.99	*Identical Distributions*
	Lane 5	15.13	0.29	*Identical Distributions*
	Lane 6	2.95	0.98	*Identical Distributions*
July 9, 1996 (Stage 4)	Lane 2	2.58	0.98	*Identical Distributions*
	Lane 4	3.19	0.96	*Identical Distributions*
	Lane 5&6	7.52	0.6	*Identical Distributions*
	Lane 7	2.21	0.99	*Identical Distributions*
July 18, 1996 (Stage 4)	Lane 2	2.97	0.98	*Identical Distributions*
	Lane 4	4.51	0.92	*Identical Distributions*
	Lane 5&6	15.73	0.11	*Identical Distributions*
	Lane 7	5.85	0.83	*Identical Distributions*
July 24, 1996 (Stage 4)	Lane 2	0.72	0.99	*Identical Distributions*
	Lane 4	4.27	0.93	*Identical Distributions*
	Lane 5&6	10.07	0.43	*Identical Distributions*
	Lane 7	4.44	0.93	*Identical Distributions*

Table 2-7: Wilcoxon Signed Rank Test Results for Average Queuing Delay

Day	Lane	T_+	T_-	T_o	Conclusion (*reject if the smaller of T_- or T_+ £ T_o*)
June 8, 1995 (Stage 3)	Lane 2	43.5	22.5	14	*Identical Distributions*
	Lane 4	14	24	6	*Identical Distributions*
	Lane 6	17.5	18.5	11	*Identical Distributions*
July 9, 1996 (Stage 4)	Lane 2	13	23	6	*Identical Distributions*
	Lane 4	11	4	1	*Identical Distributions*
	Lane 7	12	16	11	*Identical Distributions*
July 18, 1996 (Stage 4)	Lane 2	26.5	27	11	*Identical Distributions*
	Lane 4	27	39	14	*Identical Distributions*
	Lane 7	33.5	32.5	14	*Identical Distributions*
July 24, 1996 (Stage 4)	Lane 2	31.5	23.5	11	*Identical Distributions*
	Lane 4	9	36	8	*Identical Distributions*
	Lane 7	21.5	33.5	14	*Identical Distributions*

T_+ is the rank sum of the positive difference, T_- is the rank sum of negative differences, and T_o is the critical value; *Mendenhall and Sincich, 1994 [8]*. We reject the null hypotheses if the smaller of T_- and $T_+ \leq T_o$. If almost all of the differences are positive (or negative), we have evidence to indicate that the actual value distribution is shifted to the right or to the left of the simulated value distribution. The results from the ***Wilcoxon Signed Rank*** for the average queuing delay indicated that at 95% confidence level there is no significant difference between the simulated average queuing delay and the observed values for all lanes in both stages.

Table 2-8 presents the results of the ***Wilcoxon Signed Rank*** test for the maximum queuing delay for both stages.

Table 2-8: Wilcoxon Signed Rank Test Results for Maximum Queuing Delay

Day	Lane	T_+	T_-	T_o	**Conclusion** (*reject if the smaller of T_- or T_+ £ T_o*)
June 8, 1995 (Stage 3)	Lane 2	42.5	23.5	14	*Identical Distributions*
	Lane 4	11.5	54.5	14	*Different Distributions*
	Lane 6	48	18	14	*Identical Distributions*
July 9, 1996 (Stage 4)	Lane 2	52	3	14	*Different Distributions*
	Lane 4	9.5	26.5	6	*Identical Distributions*
	Lane 7	49	6	11	*Different Distributions*
July 18, 1996 (Stage 4)	Lane 2	41	25	14	*Identical Distributions*
	Lane 4	10.5	44.5	14	*Identical Distributions*
	Lane 7	63	3	14	*Different Distributions*
July 24, 1996 (Stage 4)	Lane 2	56.5	9.5	14	*Identical Distributions*
	Lane 4	37	29	6	*Identical Distributions*
	Lane 7	37	18	11	*Identical Distributions*

The results drawn from the ***Wilcoxon Signed Rank*** test for the average queuing delay indicated that at 95% confidence level there is no significant difference between the simulated maximum queuing delay and the observed values for all lanes except for lanes 2 and 7 in stage 4 and lane 4 in Stage 3. It must be emphasized that maximum queuing delay is not a critical measure for judging the plaza efficiency since it is a one-observation value for unlucky vehicle. Table 2-9 presents the results of the ***Wilcoxon Signed Rank*** test for the total queuing delay for both stages.

Table 2-9: Wilcoxon Signed Test Results for Total Queuing Delay

Day	Lane	T_+	T_-	T_o	**Conclusion** (*reject if the smaller of* T_- *or* T_+ £ T_o)
June 8, 1995 (Stage 3)	Lane 2	32	34	14	*Identical Distributions*
	Lane 4	31	**35**	14	*Identical Distributions*
	Lane 6	38.5	27.5	14	*Identical Distributions*
July 9, 1996 (Stage 4)	Lane 2	27	28	14	*Identical Distributions*
	Lane 4	37	18	14	*Identical Distributions*
	Lane 7	34	27.5	11	*Identical Distributions*
July 18, 1996 (Stage 4)	Lane 2	30	36	14	*Identical Distributions*
	Lane 4	29.5	36.5	14	*Identical Distributions*
	Lane 7	22	44	14	*Identical Distributions*
July 24, 1996 (Stage 4)	Lane 2	30	36	14	*Identical Distributions*
	Lane 4	22	44	14	*Identical Distributions*
	Lane 7	31.5	34.5	14	*Identical Distributions*

The results from the ***Wilcoxon Signed Rank*** for the average queuing delay indicated that at 95% confidence level there is no significant difference between the simulated total queuing delay and the observed values for all lanes in both stages.

2.4 MODEL EVALUATION CONCLUSIONS

Both the conceptual and operational validation process of TPSIM© indicated that TPSIM© has reached an acceptable level of validity and reliability to represent traffic condition at toll plazas with a 95% confidence level. This indicates that TPSIM© can be utilized for further extermination and application on toll plaza operations.

CHAPTER 3

MODEL APPLICATIONS

This Chapter highlights the TPSIM© model applications for toll plaza system design and operations. The demonstration herein provides valuable insight into the usefulness of TPSIM© to prospective toll plaza operators and planners. Since TPSIM© is a tool, it will not directly state the optimum plaza management strategies. However, this can be done through performing various scenarios and analysis of the model outputs. It will be possible to conduct this sensitivity analysis, now that the model has been validated and calibrated in the previous Chapter.

TPSIM© can evaluate the existing operational toll plaza and predict the future performances of toll plazas given the forecasted plaza configurations and traffic characteristics. The effects on traffic operation at any toll plaza when one or more of the input parameters are changed can be quantified using TPSIM©.

The main objective of the TPSIM© applications presented in this chapter is to identify the best configuration for the existing nine lanes of the Holland-East Plaza at various levels of traffic volume with different percentages of AVI market penetration. Given a specific traffic volume and threshold values for the AVI usage rate, the results drawn from this experiment provide the management operators of the Holland-East Plaza certain recommendations on when and which lane to convert from the conventional payment type to a dedicated AVI.

3.1 EXPERMINTAL DESIGN

The experiment conducted in this study employs multi-level factorial design in which there are three qualitative variables and three response quantitative variables. The three quantitative variables are the E-PASS market penetration, the plaza configuration, and the traffic volume. The three response variables include the plaza throughput, the average queuing delay, and the total plaza queuing delay. This experiment focuses only on the traffic peak direction (which is westbound) at the morning peak hour from 7:00 to 8:00. Each of the three-quantitative variables has a fixed number of levels. The E-PASS market penetration variable includes 7 different levels, (i.e., 20%, 30%, 40%, 50%, 60%, 70%, and 80%). The plaza configuration variable consists of 4 different levels based on the number of dedicated E-PASS lanes, (i.e., two E-PASS lanes, three E-PASS lanes, four E-PASS lanes, and five E-PASS lanes). Finally, the traffic volume variable has three levels (i.e., 5000 vph, 6000 vph, and 7000 vph). The experiment performs all possible combination scenarios of these variables and their associated levels. The experiment is 7 x 4 x 3 factorial design resulting in 84 different scenarios. Table 3-1 tabulates all possible scenarios associated with each level of the traffic volume variable. In other words, each of these scenarios is investigated at three different levels of traffic volumes, 5000, 6000, and 7000 vph. The *base case scenario* is the existing scenario at the Holland-East Plaza in Stage4. The present configuration of the Holland-East Plaza in the westbound morning peak direction of traffic (five manual lanes, two automatic lanes, and two E-PASS lanes) was used as the *base case scenario*. This scenario is compared to all other scenarios to investigate the effect of plaza configurations and the E-PASS market penetration on the plaza performance.

Table 3-1: Experiment Design for Each Level of the Traffic Volume Variable [a]

		Percentage of vehicle Types			Number of Lanes		
Scenario	**Run**	**E-PASS**	**Manual**	**Automatic**	**Manual**	**Automatic**	**E-PASS**
5M-2A-2E[b]	1	20%	60%	20%	5	2	2
	2	30%	50%	20%	5	2	2
	3[c]	***40%***	***40%***	*20%*	***5***	***2***	***2***
	4	50%	30%	20%	5	2	2
	5	60%	20%	20%	5	2	2
	6	70%	10%	20%	5	2	2
	7	80%	0%	20%	5	2	2
4M-2A-3E	1	20%	60%	20%	4	2	3
	2	30%	50%	20%	4	2	3
	3	40%	40%	20%	4	2	3
	4	50%	30%	20%	4	2	3
	5	60%	20%	20%	4	2	3
	6	70%	10%	20%	4	2	3
	7	80%	0%	20%	4	2	3
3M-2A-4E	1	20%	60%	20%	3	2	4
	2	30%	50%	20%	3	2	4
	3	40%	40%	20%	3	2	4
	4	50%	30%	20%	3	2	4
	5	60%	20%	20%	3	2	4
	6	70%	10%	20%	3	2	4
	7	80%	0%	20%	3	2	4
2M-2A-5E	1	20%	60%	20%	2	2	5
	2	30%	50%	20%	2	2	5
	3	40%	40%	20%	2	2	5
	4	50%	30%	20%	2	2	5
	5	60%	20%	20%	2	2	5
	6	70%	10%	20%	2	2	5
	7	80%	0%	20%	2	2	5

[a] These scenarios are conducted for each level of the traffic volume variable.
[b] M is Manual, A is Automatic, and E is E-PASS
[c] Base Case Scenario at the traffic volume level of 6000 vph.

3.1.1 *Scenarios Assumptions*

Several assumptions were considered in conducting the simulation scenarios as follows:

⇒ In this experimental design, the percentage of automatic vehicles was held constant at 20% for all scenarios. This indicates that any shifts among vehicles would be from manual to E-PASS or vise versa. In other words, the accumulated percentage of manual and E-PASS vehicles is always 80% of total traffic volume for all simulation scenarios.

⇒ The introduction of a new dedicated E-PASS lane was achieved by converting one of the manual lanes to the left of the existing dedicated E-PASS lanes (Lanes 5 &6) in the *base case scenario* into an E-PASS lane. In other words, this analysis investigates the benefits gained by shifting manual users to ETC lanes.

⇒ Lanes 1& 2 are fixed to be manual lanes and lanes 3 & 4 are fixed to be automatic lanes throughout all the simulation runs. However, lanes 5 through 9 can be alternated from manual to E-PASS based on the simulation scenario.

⇒ All toll lanes are open during the simulated morning peak hour for all scenarios.

⇒ For all the simulation scenarios, all other parameters including service time distributions, vehicle characteristics and percentages of vehicle class are assigned to typical default values collected from the field in Stage 4 for all simulation scenarios.

The following section discusses in detail the input values for all conducted simulation scenarios in this experiment.

3.1.2 Input Values For Scenarios

3.1.2.1 <u>Plaza Geometric</u>

As mentioned before, the Holland-East Plaza consists of 4 approach lanes and 9 toll lanes. It was assumed that the length of the approach lanes is 3000 ft for certain scenarios to capture any extended queue that may spill back from the toll lanes and reach the approach lanes. In other rare scenarios where the queues back up more than 3000 ft, the length of the approach lanes were set to 10000 ft. Lengths of the toll lanes and the transition zone obtained from the existing Holland-East Plaza geometric plans indicated that they are 600 ft and 200 ft, respectively. Also, Holland-East Plaza geometric plans indicated that all approach lanes and toll lanes have the same width of 12 ft. Figure 3.1 illustrates the input parameters for plaza geometric for some simulated scenarios

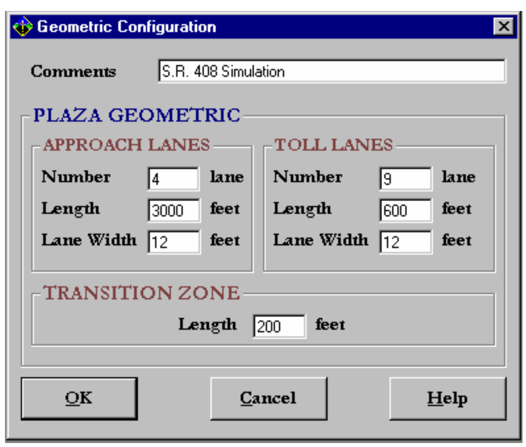


Figure 3.1: Plaza Geometric Input Parameters

As mentioned before, it was assumed that all toll lanes are open during the simulated morning peak hour for all scenarios. Therefore, no data were entered for the closing times schedule for all simulation scenarios, see Figure 3.2. Since the plaza configuration is one of the experiment variables, four levels of plaza configuration were investigated in this study. These levels are *Two E-PASS lanes*, *Three E-PASS lanes*, *Four E-PASS lanes*, and *Five E-PASS lanes*. The toll lane types were selected depending on the level of plaza configuration under investigation in each scenario. Figure 3.2 illustrates the input parameters for toll lane types for the *Two E-PASS lanes* level scenarios.

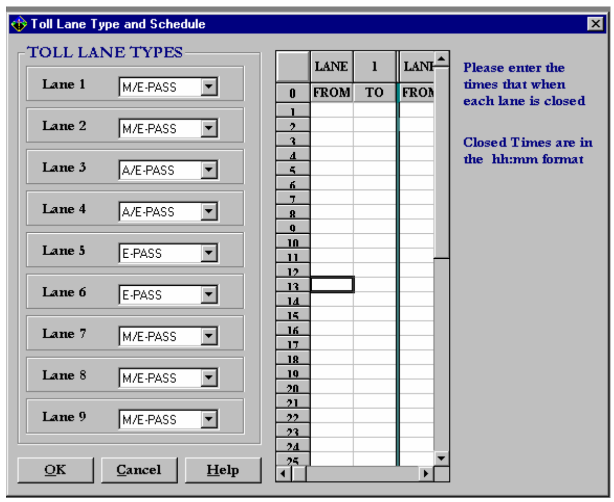


Figure 3.2: Toll Lane Types Input Parameters for the Two E-PASS Lanes Level

3.1.2.2 <u>Global Parameters</u>

Using the arrival time for each vehicle obtained from the videotapes collected in 1996, the inter-arrival times were calculated and fitted for each approaching lane to identify which distribution truly represents the inter-arrival time distribution. This analysis showed that the inter-arrival time distribution follows a shifted negative *exponential* distribution for all simulation scenarios, see the “Validation Input Data” section in Chapter 2.

Inter-arrival time collected from the field indicated that minimum headway is 1 second as mentioned previously in Chapter 2. The DMI data collected from the field also indicated that the average E-PASS speed value is 40 mph, which indicates that E-PASS vehicles have to decelerate to maintain this speed at the toll plaza. Percentage of lane changing was assumed to be 100%. In other words, any vehicle that is being affected by a slower leader will try to change its lane to avoid the slower leader. It was assumed that the reaction time among vehicles follow a *uniform* distribution with a minimum of 0.64 second and a maximum of 1.7 seconds.

Approaching speed data was derived from the sample data collected by the DMIs as described in the previous progress report. By fitting the approaching speed observations, desired speeds for vehicles approaching the toll plaza follow a *normal* distribution with an average of 60 mph (95 km/hr) and a standard divination of 5 mph (8 km/hr).

Deceleration rate and acceleration rate distributions were also derived from the sample data collected by the DMIs as also described earlier. Vehicles desired deceleration rates were found to follow a *normal* distribution with an average of 3 ft/s^2 (0.9 m/s^2) and a standard divination of 0.5 ft/s^2 (0.15 m/ s^2). The acceleration rates of vehicles approaching Holland-East Plaza follow also a *normal* distribution with an average of 5.5 ft/s^2 (0.9 m/s^2) and a standard divination of 0.5 ft/s^2 (0.15 m/ s^2).

Clearance distribution was assumed to be a *uniform* distribution with a minimum of 20 ft and a maximum of 40 ft (one to two car length). Figure 3.3 provides the input values for the global parameters for all simulation scenarios.

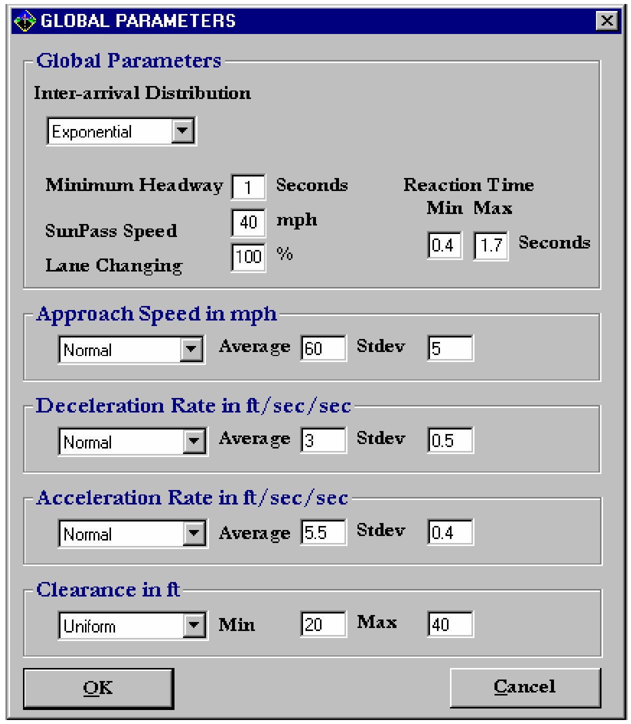


Figure 3.3: Global Parameters Input Values for all Scenarios

3.1.2.3 <u>Traffic Characteristics</u>

To obtain arrival rate and the inter-arrival time distribution, the database obtained from the video collected in 1996 was analyzed as described in Chapter 2. Since all scenarios have two or more dedicated ETC lanes. Distribution of five-minute traffic volume during the morning peak hour in all simulation runs were calculated by averaging the five-minute traffic volume for the three days collected in 1996 (Stage 4).

Table 3-2 presents the traffic volume values for each five-minute interval within the simulated morning peak hour for the three traffic volume levels under study.

Table 3-2: Traffic Volume Values During 5 minute Intervals

5 minute Interval	July 9, 1996	July 18, 1996	July 24, 1996	Average	Volume per Interval for the 5000 vph Traffic Volume Level	Volume per Interval for the 6000 vph Traffic Volume Level	Volume per Interval for the 7000 vph Traffic Volume Level
7:00-7:05	6%	6%	5%	**6%**	300	360	420
7:05:7:10	7%	6%	7%	**7%**	350	420	490
7:10-7:15	8%	7%	8%	**8%**	400	480	560
7:15-7:20	8%	9%	8%	**8%**	400	480	560
7:20-7:25	8%	8%	10%	**9%**	450	540	630
7:25-7:30	9%	9%	9%	**9%**	450	540	630
7:30-7:35	9%	9%	9%	**9%**	450	540	630
7:35-7:40	10%	10%	10%	**10%**	500	600	700
7:40-7:45	11%	10%	10%	**10%**	500	600	700
7:45-7:50	10%	10%	10%	**10%**	500	600	700
7:50-7:55	8%	9%	8%	**8%**	400	480	560
7:55-8:00	6%	7%	6%	**6%**	300	360	420
Total	**100%**	**100%**	**100%**	**100%**	**5000**	**6000**	**7000**

Percentages of trucks and passenger cars were extracted from the videotapes. Data analysis shows that 97% of the approaching vehicles are passenger cars and 3% are trucks.

Since the percentage of E-PASS market penetration is one of the variables of this experiment, the values for both the E-PASS and manual vehicle percentages were changed from scenario to another depending on the level of the E-PASS market penetration. However, the percentage of automatic vehicles was kept constant of 20% for all scenarios. For Example, if we are simulating the 30% E-PASS level scenario, the input values for the vehicle type field are 50% manual, 20% automatic and 30% E-PASS as shown in Figure 3.4. However, if we are simulating the 50% E-PASS level Scenario, the input values would be 30% manual, 20% automatic and 50% E-PASS. Figure 3.4 shows the input parameters for the traffic characteristics in all scenarios.

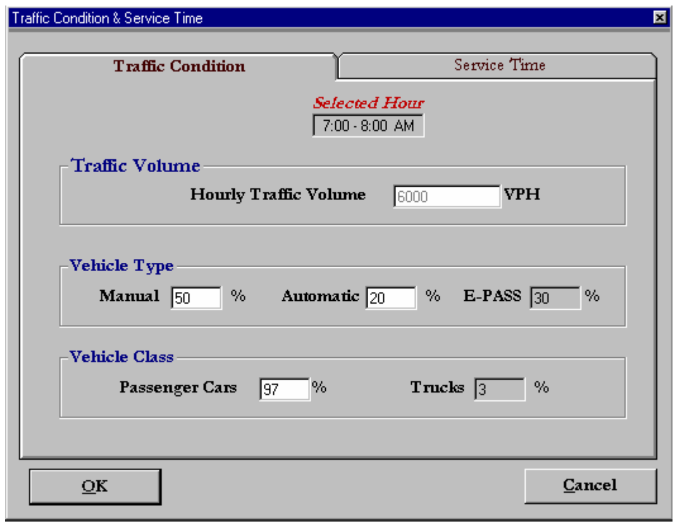


Figure 3.4: Input Parameters for Traffic Characteristics

Service time is the time a vehicle spends to pay toll at the booth. By extracting the service time for each vehicle in each lane from the videotapes, it was found that the best fit for service time is a discrete distribution, see Chapter 2. Tables 3-3, 3-4, and 3-5 provide the parameters for the fitted discrete distribution for each lane type for all collected days in Stage 4 during 1996. These values were averaged to obtain the service time distribution parameters for all scenarios in this experiment. Since vehicles that are equipped with E-PASS system do not to stop to pay toll, it was assumed that the service time for any E-PASS vehicle is 0 seconds.

Table 3-3: Service Time Distribution for Lane 2 (Manual/AVI)

Service Time	July 9, 1996	July 18, 1996	July 24, 1996	Average
0	1%	1%	1%	**1%**
1	5%	2%	2%	**3%**
2	11%	6%	8%	**8%**
3	14%	12%	16%	**14%**
4	15%	15%	16%	**15%**
5	16%	14%	12%	**14%**
6	10%	11%	9%	**10%**
7	8%	8%	9%	**9%**
8	6%	8%	8%	**7%**
9	4%	5%	3%	**4%**
10	3%	3%	4%	**3%**
11	3%	3%	5%	**4%**
12	1%	3%	2%	**2%**
13	1%	4%	3%	**3%**
14	1%	3%	2%	**2%**
15	1%	2%	0%	**1%**

Table 3-4: Service Time Distribution for Lane 4 (Automatic/AVI)

Service Time	July 9, 1996	July 18, 1996	July 24, 1996	Average
0	0%	2%	4%	**2%**
1	7%	8%	6%	**7%**
2	15%	16%	17%	**16%**
3	24%	24%	21%	**23%**
4	20%	21%	20%	**20%**
5	18%	16%	15%	**17%**
6	9%	8%	10%	**9%**
7	5%	4%	4%	**4%**
8	2%	1%	3%	**2%**

Table 3-5: Service Time Distribution Values for Lane 6 (Manual/AVI)

Service Time (Seconds)	July 9, 1996	July 18, 1996	July 24, 1996	Average
0	1%	1%	0%	**1%**
1	3%	4%	5%	**4%**
2	14%	14%	15%	**14%**
3	21%	22%	21%	**21%**
4	16%	15%	19%	**17%**
5	9%	12%	12%	**11%**
6	8%	10%	7%	**8%**
7	8%	5%	5%	**6%**
8	5%	4%	6%	**5%**
9	3%	2%	3%	**3%**
10	3%	2%	2%	**2%**
11	1%	3%	1%	**2%**
12	3%	2%	2%	**2%**
13	3%	1%	1%	**2%**
14	1%	2%	1%	**1%**
15	1%	1%	0%	**1%**

3.1.2.4 Simulation Runs

For the purpose of sensitivity analysis and comparing the plaza performance with different plaza configurations, the random number stream was fixed to a specific value for all scenarios under the experiment. This allows fixing the arrival times for all vehicles among scenarios with same traffic volume. Therefore, any change in the plaza performance among scenarios would result from the change in the plaza configuration rather than the vehicles' characteristics. Results from these scenarios were compared for the whole-simulated hour for all scenarios. The following section presents the findings drawn from comparing these scenarios to evaluate the Holland-East Plaza under different configurations and traffic characteristics.

3.2 DELAY SENSITIVITY ANALYSIS

3.2.1 Traffic Volume

Several simulation scenarios were conducted to investigate the impact of traffic volume on the toll plaza operation. In this analysis, three different volume levels (5000, 6000, and 7000 vph) representing the morning peak hour with different plaza configurations were investigated. Estimated morning peak hour total delay was used to evaluate each scenario.

Figures 3.5 through 3.8 demonstrate the smooth and expected increase of the estimated peak hour plaza delay with the increase of the traffic volume demand regardless of the plaza configuration. Sensitivity to the plaza traffic demand increases more rapidly with higher traffic volumes. In other words, the increase in the estimated peak hour delay is not linear, but more exponential in nature. This is simply attributed to the queuing condition at the plaza. When the plaza operates over its capacity, and approaches more traffic demand, more queues build up behind the existing queues and the queuing delays associated with these queues increase exponentially.

Figures 3.5 through 3.8 also show that plaza delay sensitivity to E-PASS user percentage is also affected by the number of dedicated E-PASS lanes. It is more sensitive for scenarios with high number of dedicated E-PASS lanes (i.e., delay goes down quickly)

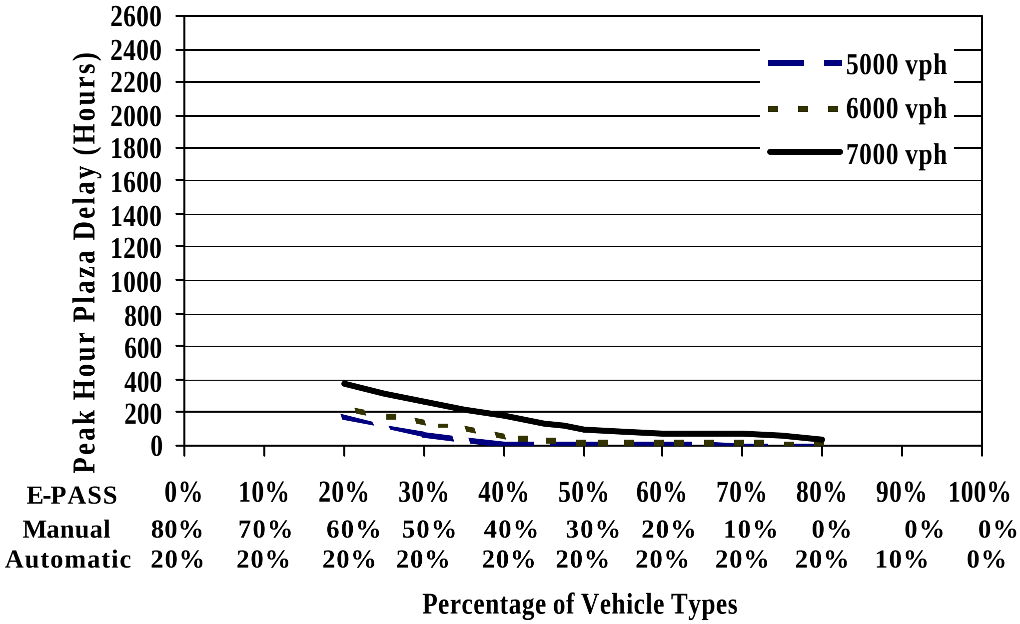


Figure 3.5: Traffic Volume Effects for Scenario 5M-2A-2E

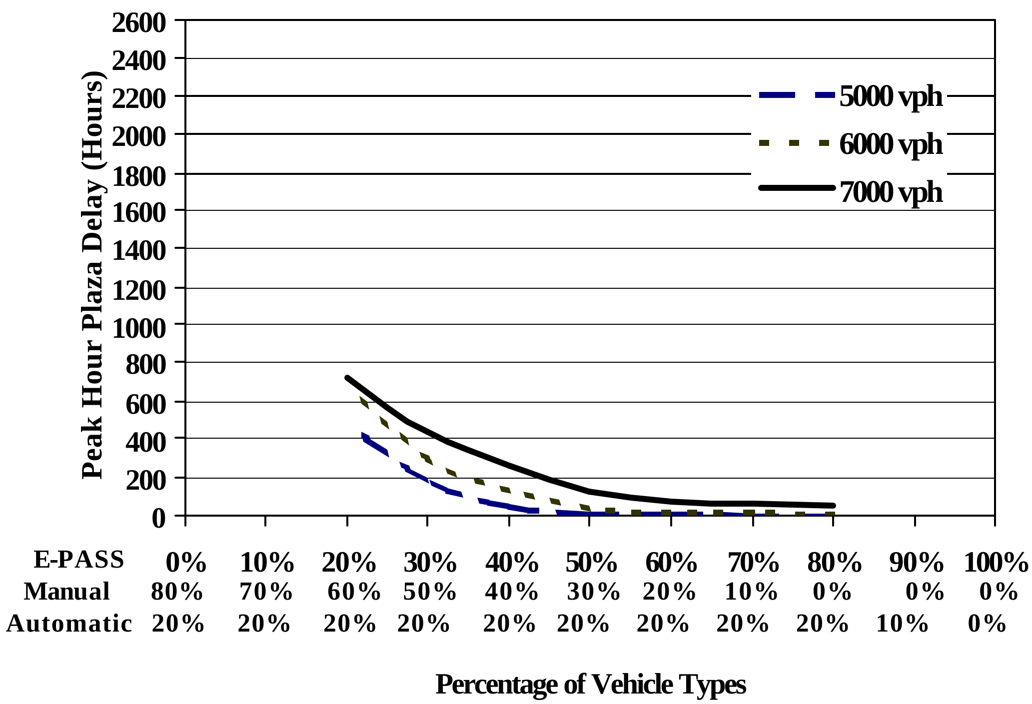


Figure 3.6: Traffic Volume Effects for Scenario 4M-2A-3E

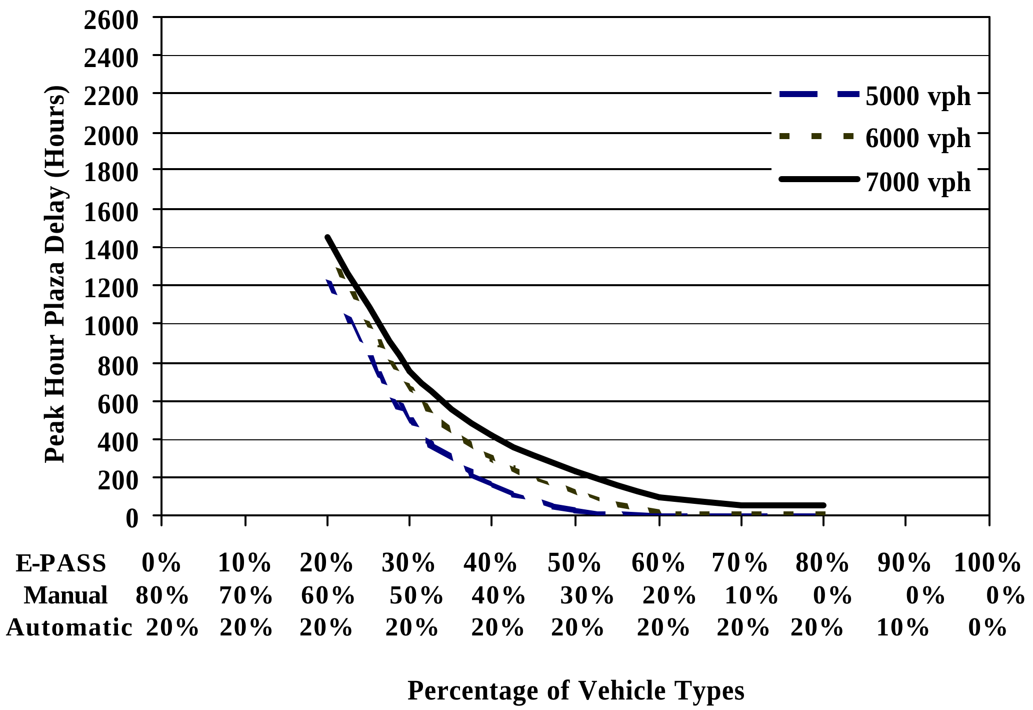


Figure 3.7 Traffic Volume Effects for Scenario 3M-2A-4E

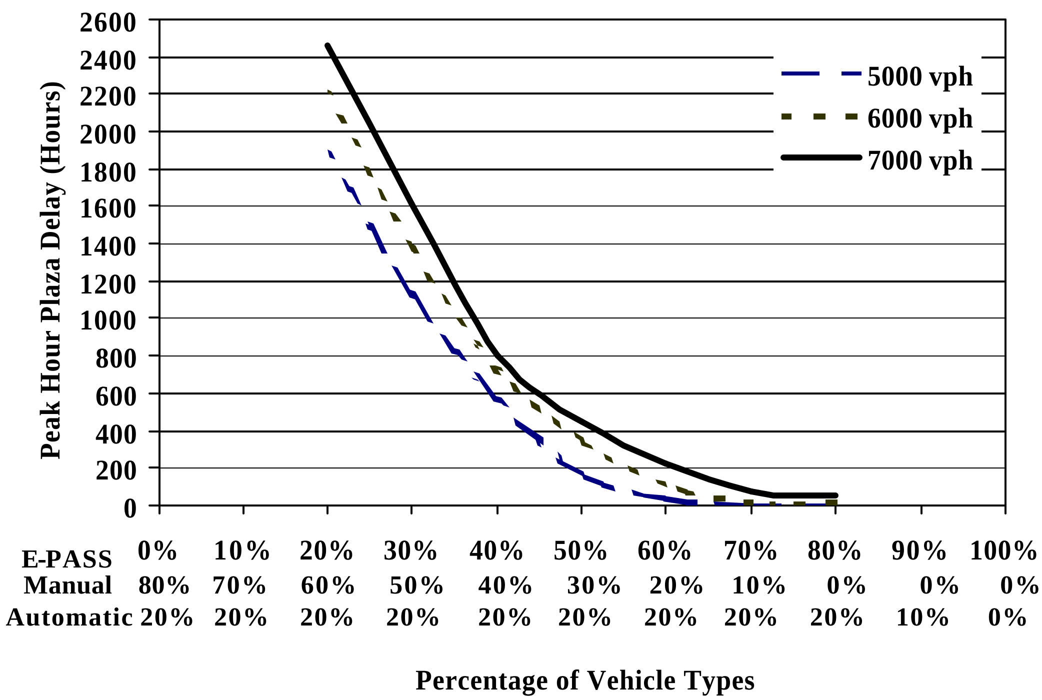


Figure 3.8: Traffic Volume Effect for Scenario 2M-2A-5E

3.3 AVI MARKET PENETRATION

Several simulation scenarios were conducted to investigate the impact of E-PASS market penetration variable on the plaza operational performance. The present configuration of the Holland-East Plaza in the westbound morning peak direction of traffic (five manual lanes, two automatic lanes, and two E-PASS lanes) was used in the *base case scenario*. Traffic volume on the approach lanes of the Holland-East Plaza during the morning peak hour was 6000 vph; 20% of this volume used automatic coin machine tollbooths, 40% used E-PASS tollbooths, and 40% used manual tollbooths. The *base case scenario* was modified by increasing or decreasing the E-PASS market penetration in steps of 10%, see Table 3-1. To accommodate for the volume increase in E-PASS vehicles, additional dedicated E-PASS lanes were introduced to the left of the two existing E-PASS lanes in the *base case scenario*. Estimated total plaza queuing delay, average queuing delay per vehicle and the plaza throughput during the morning peak hour were used as measures of effectiveness to compare the plaza operational performance among scenarios.

3.3.1 Total Plaza Queuing Delay

Figures 3.9 through 3.11 depict the estimated peak hour total plaza queuing delay for each scenario at the three levels of traffic demand, i.e., 5000, 6000, and 7000 vph respectively. This experiment illustrates that vehicles switching from manual to E-PASS lanes reduce the total plaza queuing delay specially when manual lanes are operating over capacity. This can be easily demonstrated by a shift from left to right within *Zone A* of all the three figures. Note that *Zone A* defines the boundaries within which manual lanes operate under queuing or over capacity conditions. Also, it is clear that the benefits of E-PASS are sensitive to the plaza configuration, i.e., each curve in this figure is a scenario with a different plaza configuration. Figures 3.9 through 3.11 present also an interesting finding in this simulation experiment. Regardless of the plaza configuration and traffic volumes, the total plaza delay can be reduced in half (about 50%) if only as little as 10% of the vehicles can switch from manual lanes to E-PASS lanes in *Zone A*, where the manual lanes operate over capacity. These figures also illustrate that the increase in E-PASS usage does not have a significant impact on the plaza delay when manual lanes operate under capacity, i.e., *Zone B*.

It is obvious from these figures that adding more dedicated E-PASS lanes immaturely, i.e., without an increase in the level of E-PASS subscription, can cause an increase in the total plaza queuing delay. This is equivalent to moving vertically within *Zone A*. For example, adding more E-PASS lanes to the *base case scenario* (with configuration 5M-2A-2E and the same percentages of E-PASS vehicles mentioned earlier) would be ineffective. By converting one of the manual lanes to a dedicated E-PASS lane, the demand for manual lanes that is already exceeding manual capacity would have one less lane to use. A natural result of this strategy is more queuing delay for the entire the plaza. Figure 3.12 illustrates a snapshot of the TPSIM© animation representing the condition at the Holland-East Plaza with the immature E-PASS lanes strategy. In this figure the configuration of the plaza is 2M-2A-5E serving a traffic volume of 7000 vph with 40% of this volume being manual vehicles, 20% is automatic vehicles and 40% E-PASS vehicles. It is obvious from this figure that the two manual lanes exceeded their

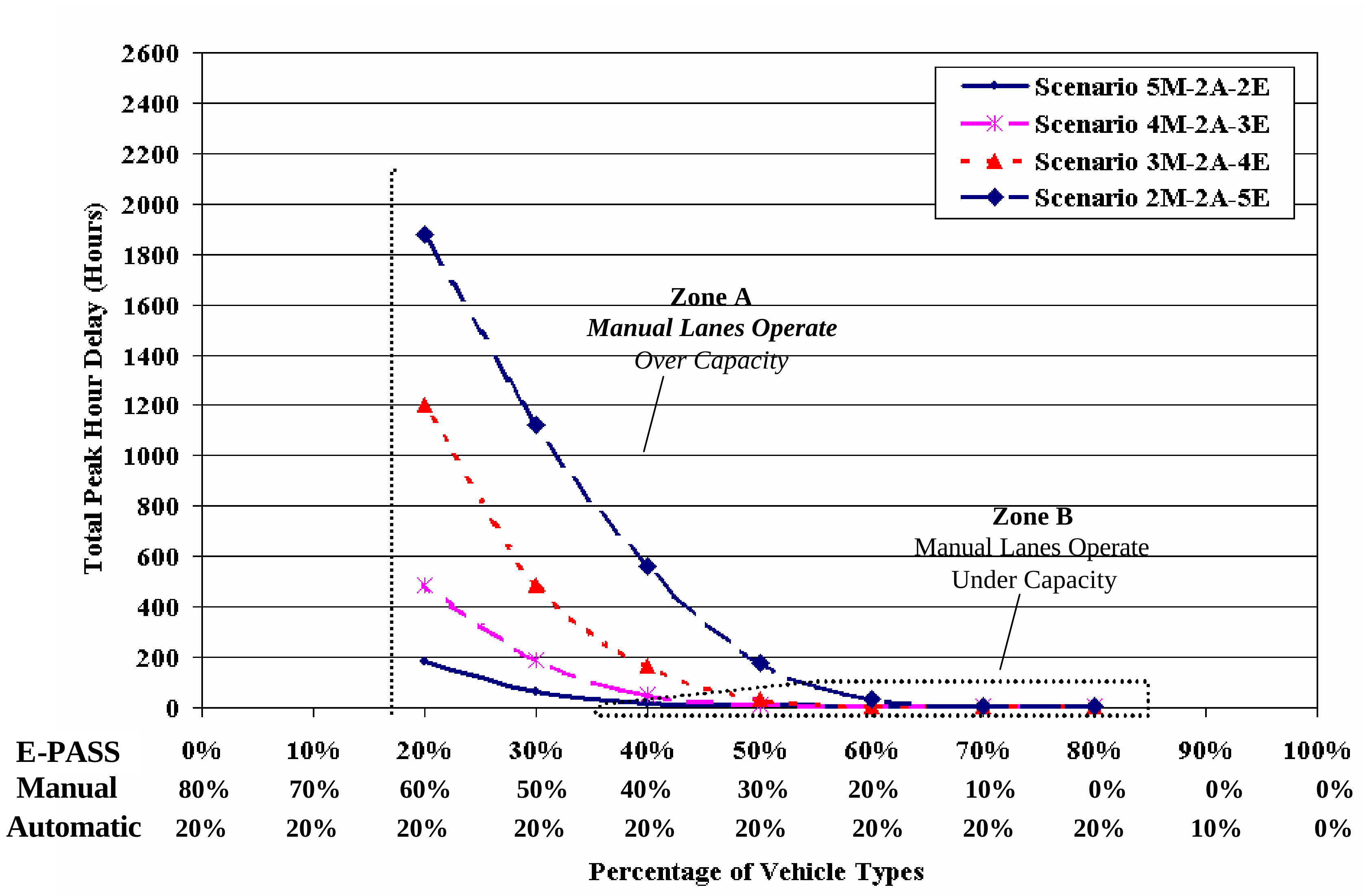


Figure 3.9: Sensitivity Analysis of E-PASS Market Penetration at 5000 vph Level

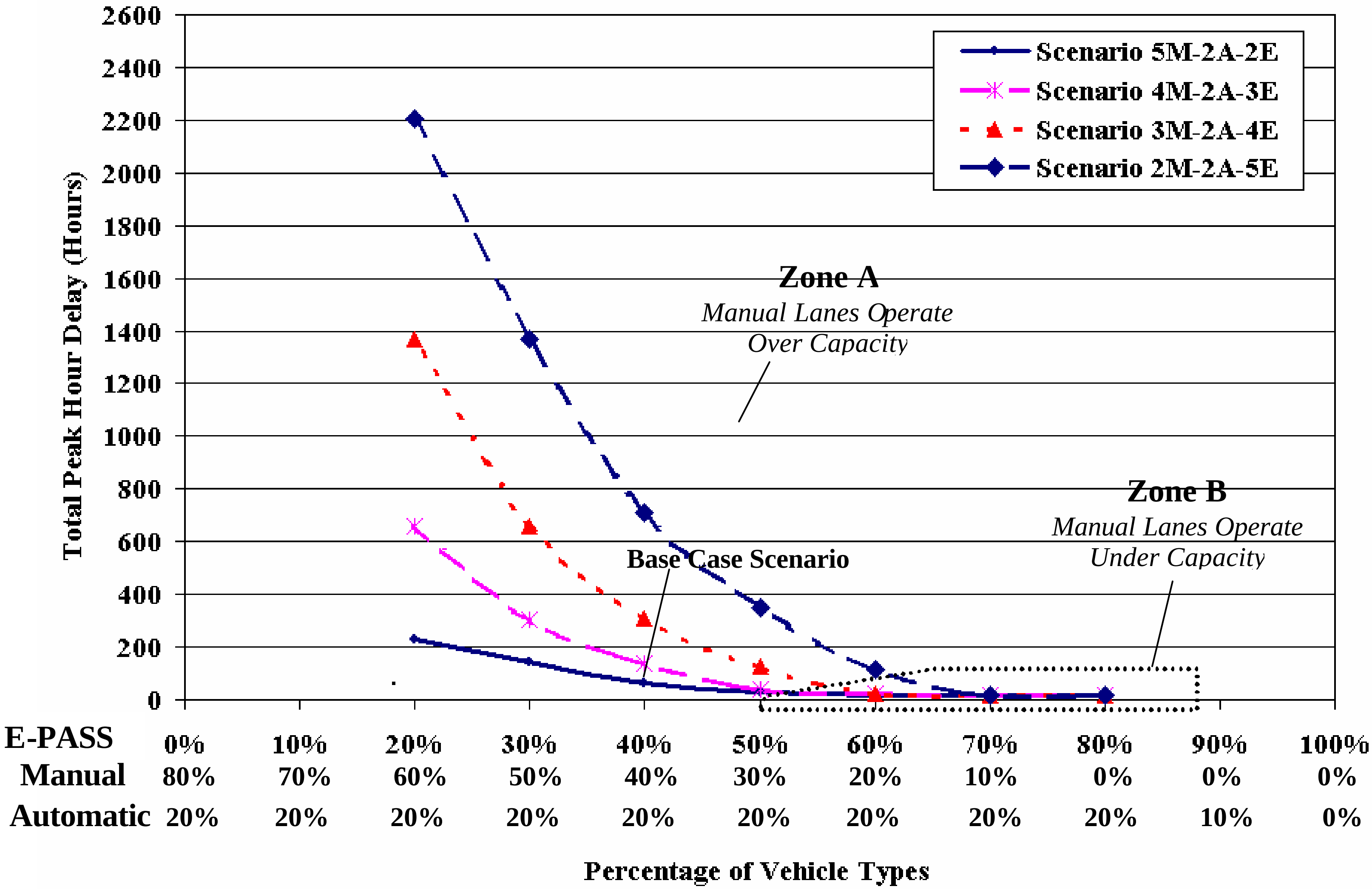


Figure 3.10: Sensitivity Analysis of E-PASS Market Penetration at 6000 vph Level

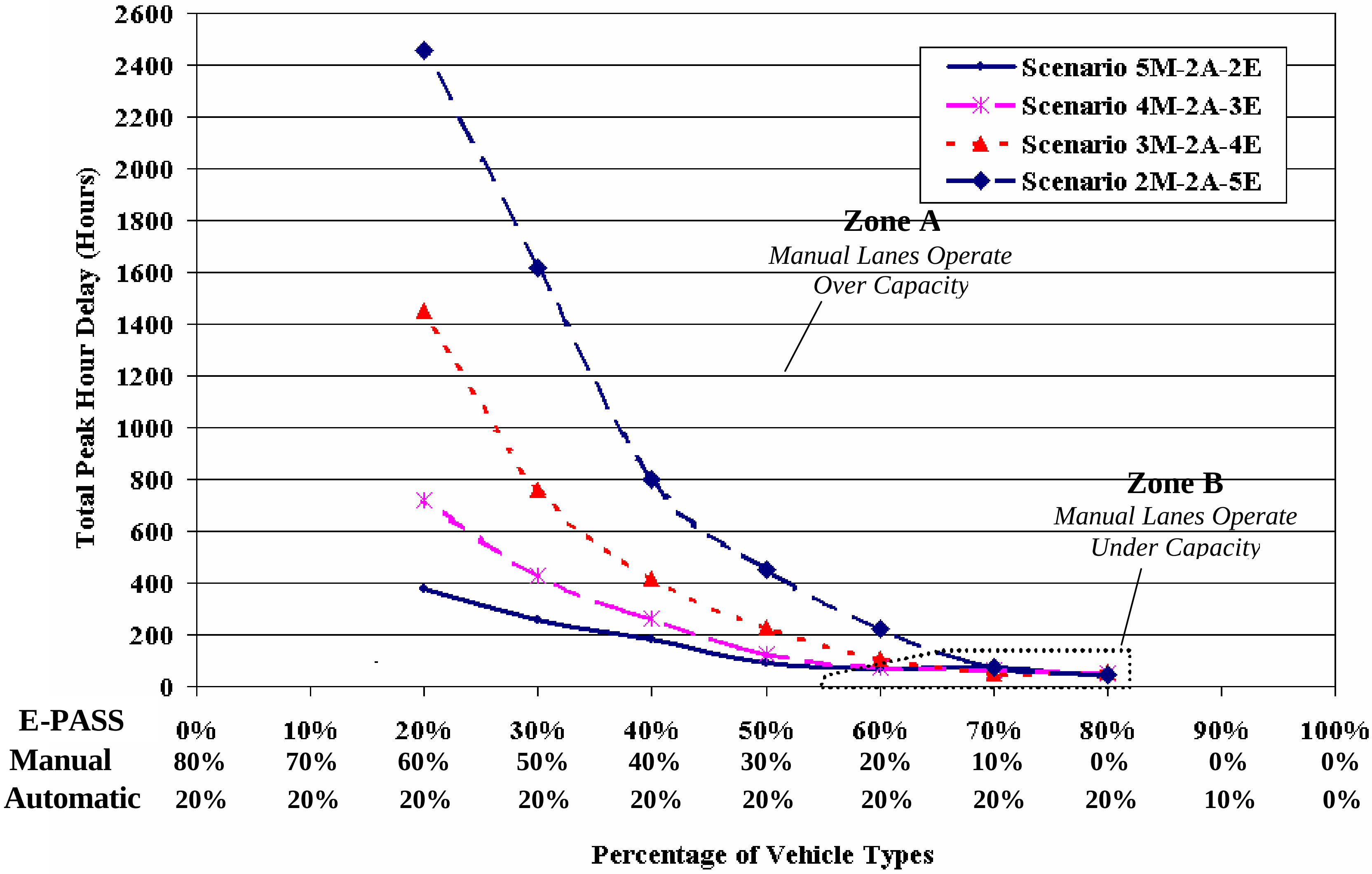
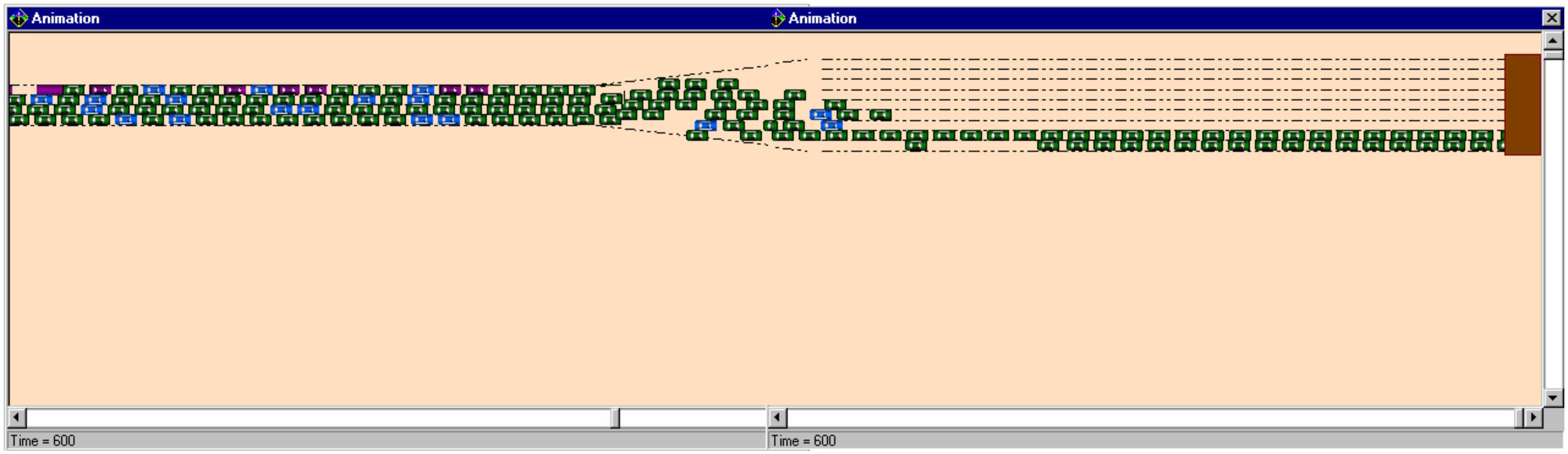


Figure 3.11: Sensitivity Analysis of E-PASS Market Penetration at 7000 vph Level



 **Manual Vehicle**

 **Automatic Vehicle**

 **E-PASS Vehicle**

Figure 3.12: TPSIM© Animation Snapshot of the 2M-2A-5E Scenario

capacities and experienced more demand. Therefore, manual vehicles are queued in both the transition and approach zones trying to get into one of the two over saturated manual lanes. As a result of that, a significant number of automatic and E-PASS vehicles are blocked behind the queued manual vehicles within the approach and transition zones, and therefore they experience more queuing delay. This indicates that, the total queuing delay resulted from this strategy does not come only from manual vehicles but also resulted from queued automatic and E-PASS vehicles.

3.3.2 Average Queuing Delay Per Vehicle

Figures 3.13 through 3.15 show the trend of average queuing delay per vehicle for each scenario at the three levels of traffic volume i.e., 5000, 6000, and 7000 vph respectively. This experiment illustrates the same conclusion drawn from the total plaza delay measure of effectiveness. Vehicles switching from manual to E-PASS lanes reduce the average queuing delay per vehicle specially when manual lanes are operating over capacity. It is clear that the E-PASS benefits are sensitive to the plaza configuration. Regardless of plaza configuration, the average queuing delay can be reduced by more than a *90 seconds* for most scenarios if only as little as 10% of the vehicles can switch from manual lanes to E-PASS lanes in *Zone A*, where the manual lanes operate over capacity. These figures also indicate that the increase in E-PASS usage does not have a significant impact on the average queuing delay per vehicle when manual lanes operate under capacity, *Zone B*.

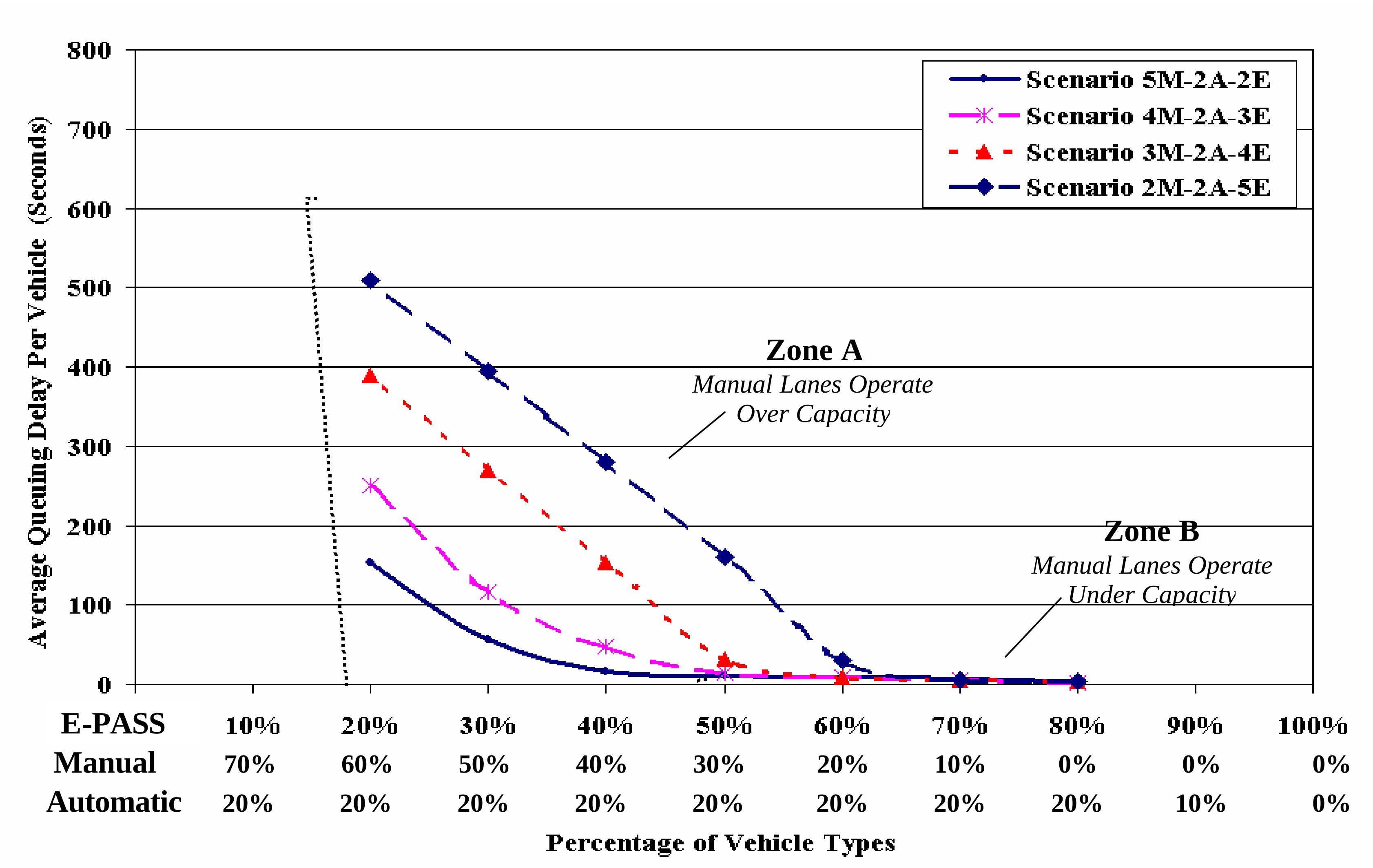


Figure 3.13: Sensitivity Analysis of ETC Market Penetration and Average Queuing Delay at Traffic Volume Level of 5000 vph

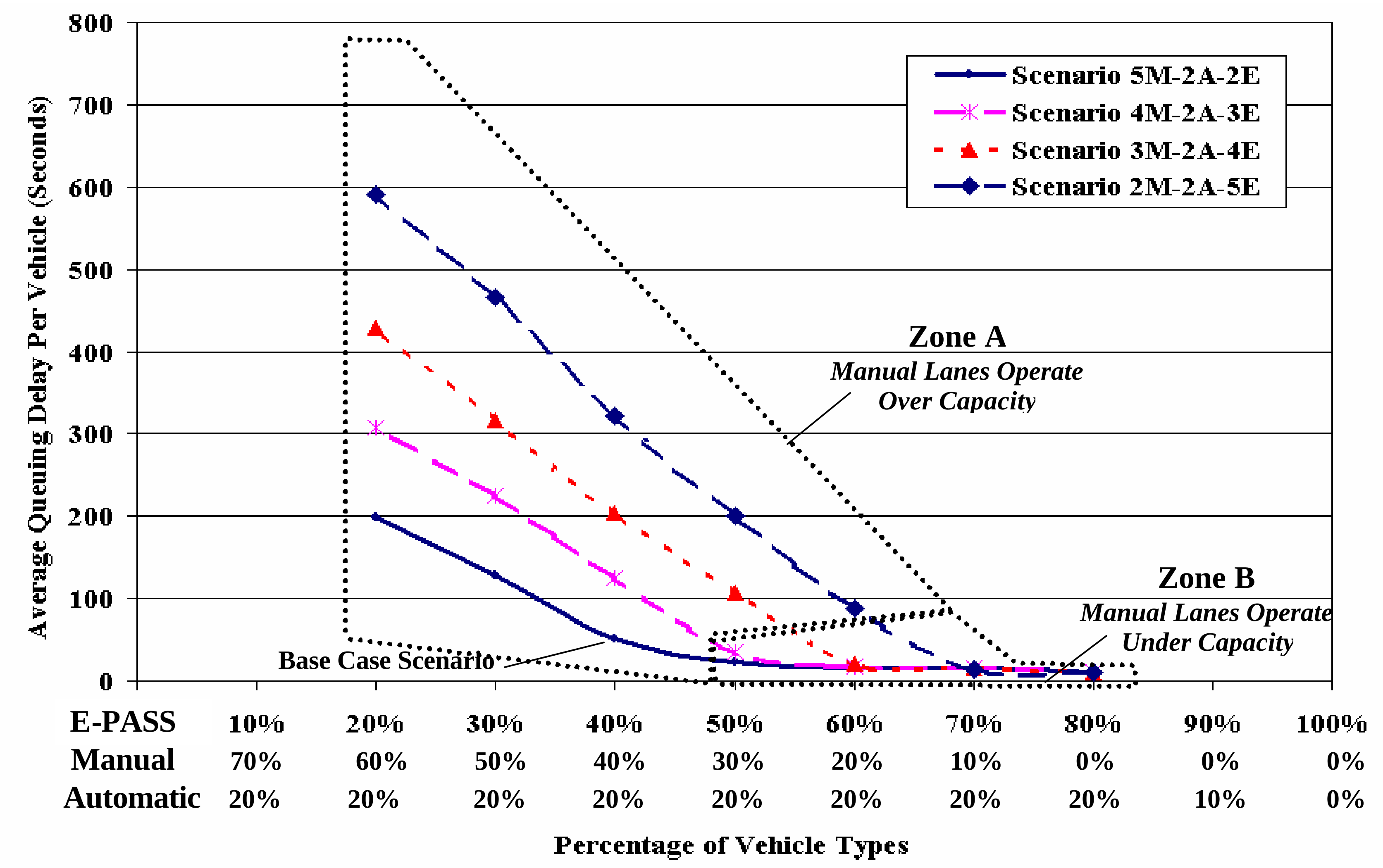


Figure 3.14: Sensitivity Analysis of ETC Market Penetration and Average Queuing Delay at Traffic Volume Level of 6000 vph

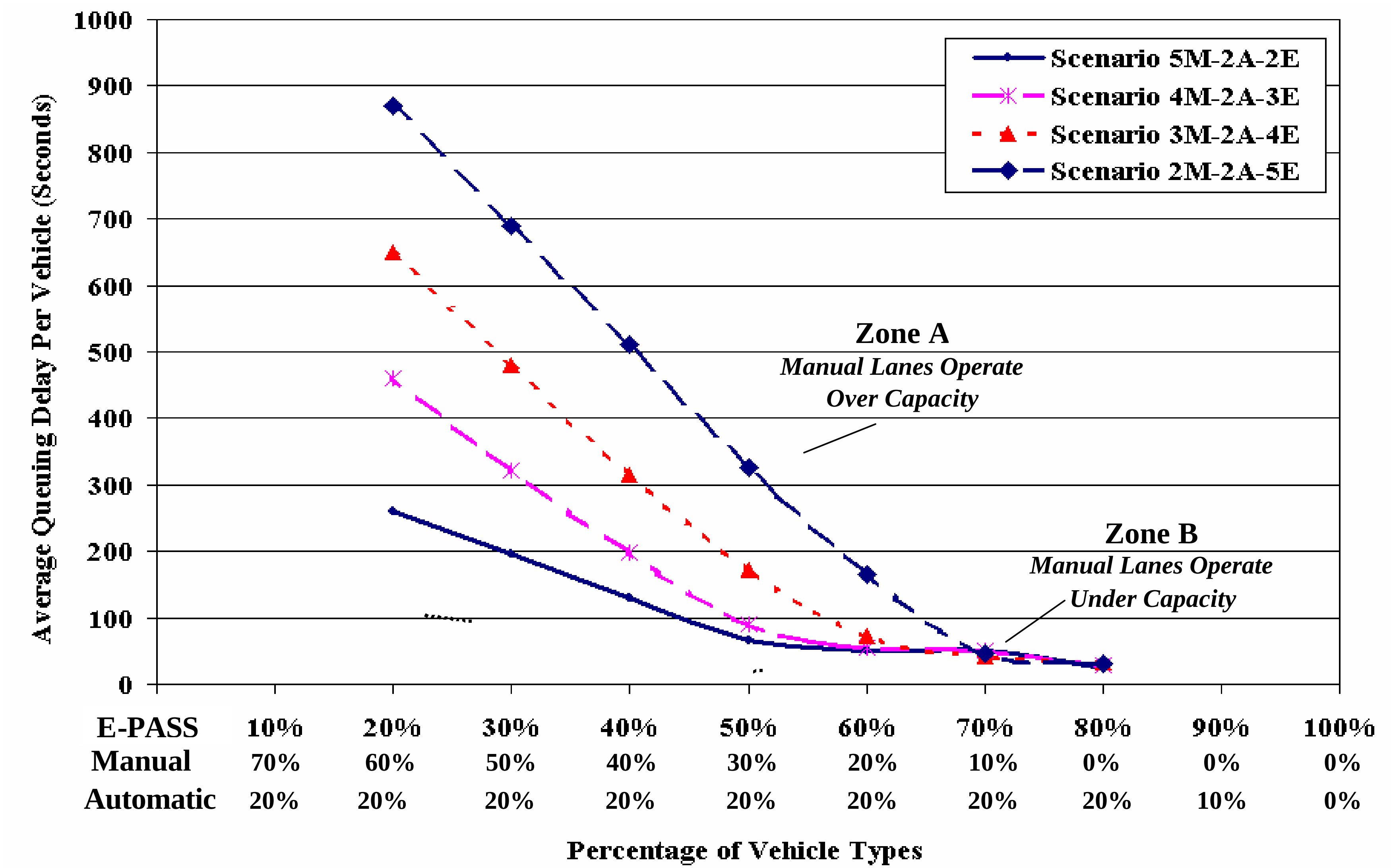


Figure 3.15: Sensitivity Analysis of ETC Market Penetration and Average Queuing Delay at Traffic Volume Level of 7000 vph

Also, adding more dedicated E-PASS lanes immaturely increases the average queuing delay per vehicle. By converting one of the manual lanes to a dedicated E-PASS lane when manual lanes are already exceeding their capacities would have one less lane to accommodate the same manual vehicles demand. A natural result to this is more queuing delays for all vehicles within the plaza area.

3.3.3 Hourly Plaza Throughput

Figures 3.16 through 3.18 illustrate the trend of estimated hourly plaza throughput for each scenario at the three levels of traffic volume, i.e., 5000, 6000, and 7000 vph respectively. This experiment indicates that vehicles switching from manual to E-PASS lanes increase the peak hour plaza throughput significantly specially when manual lanes are operating over capacity.

It is clear that the E-PASS benefits are sensitive to the plaza configuration. Regardless of plaza configuration and traffic volume, the plaza hourly throughput can be increased by more than 20% for most scenarios if only as little as 10% of the vehicles can switch from manual lanes to E-PASS lanes in *Zone A*, where the manual lanes operate over capacity. This 10% decrease in the manual users shortened the queue length significantly at the manual toll lanes which in many cases reached the approach lanes. Therefore, many E-PASS and automatic vehicles that would have been stuck behind the long queues at the approach lanes are now able to reach their desired lanes in more expedient manner and increase the plaza throughput. These figures also indicate that the increase in E-PASS usage does not have a significant impact on the plaza throughput when manual lanes operate under capacity, i.e., *Zone B*.

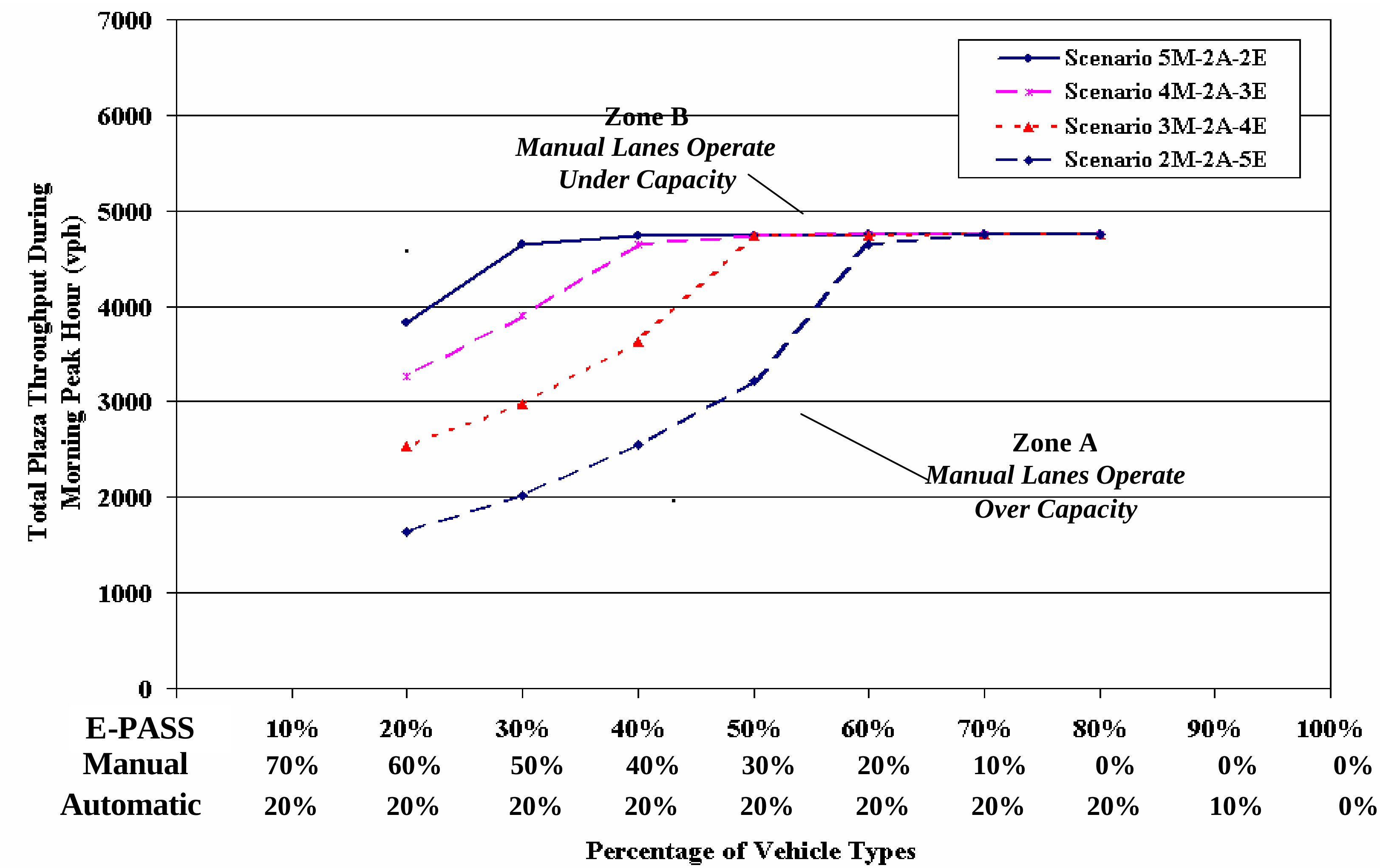


Figure 3.16: Sensitivity Analysis of ETC Market Penetration and Total Plaza Throughput per Peak Direction for 5000 vph Traffic Volume Level

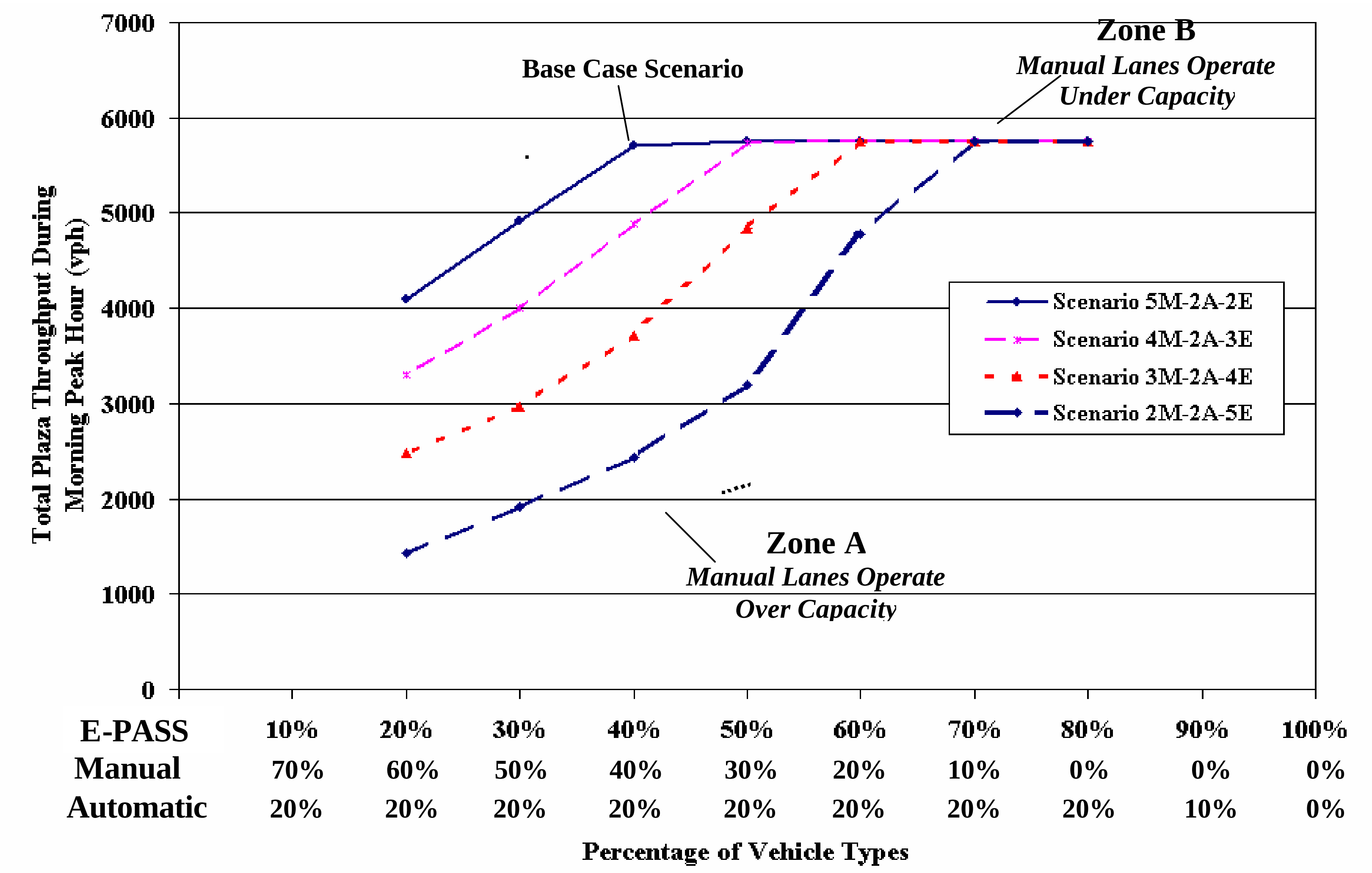


Figure 3.17: Sensitivity Analysis of ETC Market Penetration and Total Plaza Throughput per Peak Direction for 6000 vph Traffic Volume Level

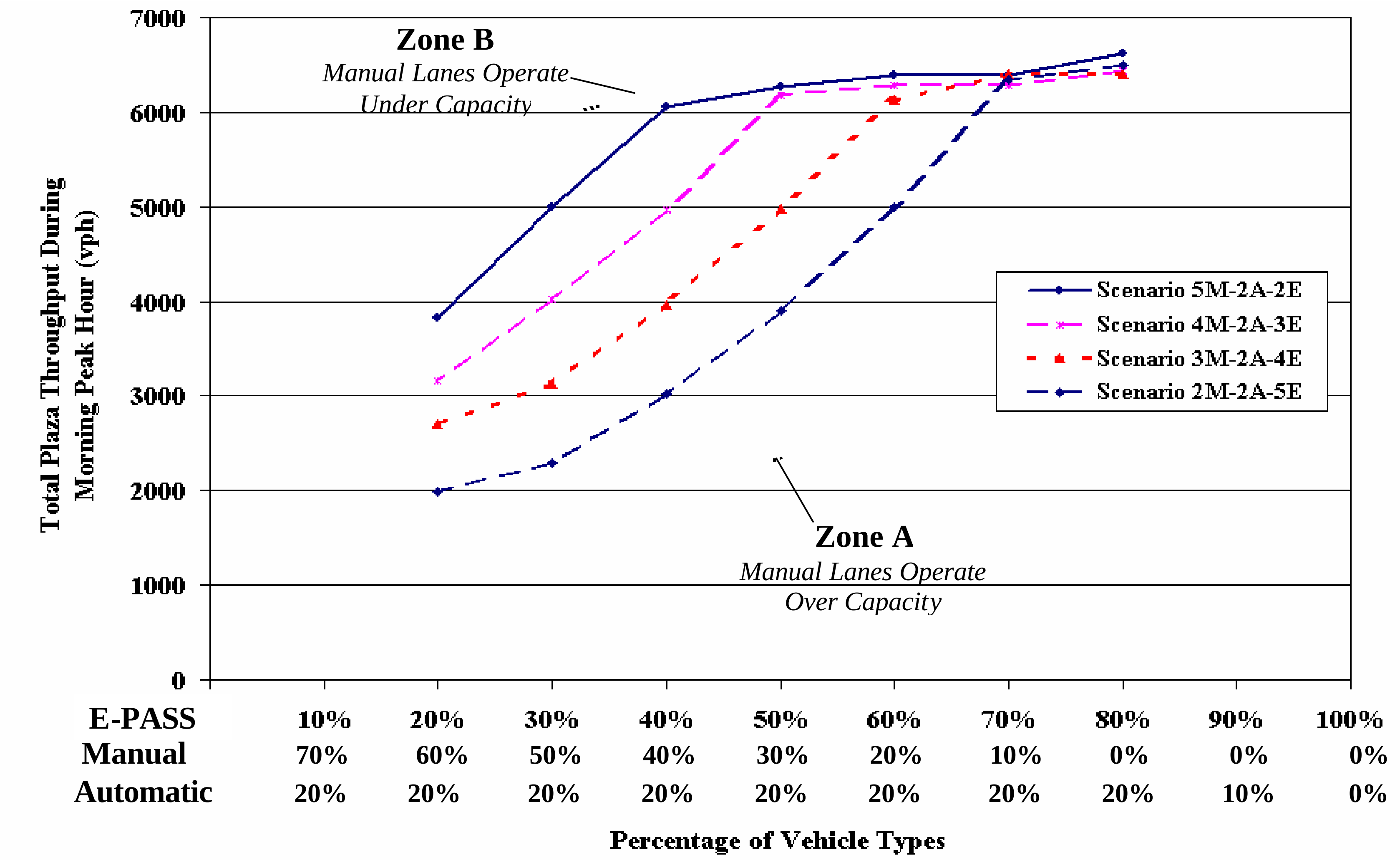


Figure 3.18: Sensitivity Analysis of ETC Market Penetration and Total Plaza Throughput per Peak Direction for 7000 vph Traffic Volume Level

It is also clear from these figures that adding more dedicated E-PASS lanes immaturely decreases the plaza throughput. This is equivalent to moving vertically within *Zone A* in all figures. For example adding more E-PASS lanes to the *base case scenario,* see Figure 3.17, (with configuration 5M-2A-2E and the same percentages of E-PASS vehicles mentioned earlier) would be ineffective and decrease the plaza throughput by about 20%.

3.4 IMPLEMENTATION OF NEW DEDICATED ETC LANES

One of the important needs for the toll agencies to operate their toll plazas is determining the optimum time to convert one of the existing conventional lanes to a dedicated ETC lane. Figure 3.19 zooms on *Zone B* where manual lanes operate under capacity and compare the total plaza delay among different scenarios with various numbers of dedicated E-PASS lanes, i.e., two , three, four, and five dedicated ETC lanes at the Holland-East Plaza. It is clear from the figure that, there is no significant difference among scenarios at same level of E-PASS market penetration. This is equivalent to moving vertically in this figure. This indicates that adding more dedicated E-PASS lanes at the same percentages of E-PASS vehicles would be ineffective on decreasing the total plaza delay during the peak hour.

It must be emphasized that once the level of ETC market penetration becomes high, plaza delay may no longer be an important factor that determines whether or not introducing a new dedicated ETC lane is appropriate. When ETC usage during the peak hour at the Holland-East Plaza is high (>60%), delays have already been considerably reduced due to that manual lanes operate under their capacities at this level. Capacity of the dedicated ETC lanes may be on of the most important factors in this decision process. *Al-Deek et al, 1997 [2]* provide a methodology to measure and calculate the capacity of the dedicated ETC lane using real-life observations. Other contributing factors such as traffic demand characteristics, driver comfort level and safety considerations may weigh more heavily upon the decision of introducing a new dedicated ETC lane. However further evaluation for these factors is recommended.

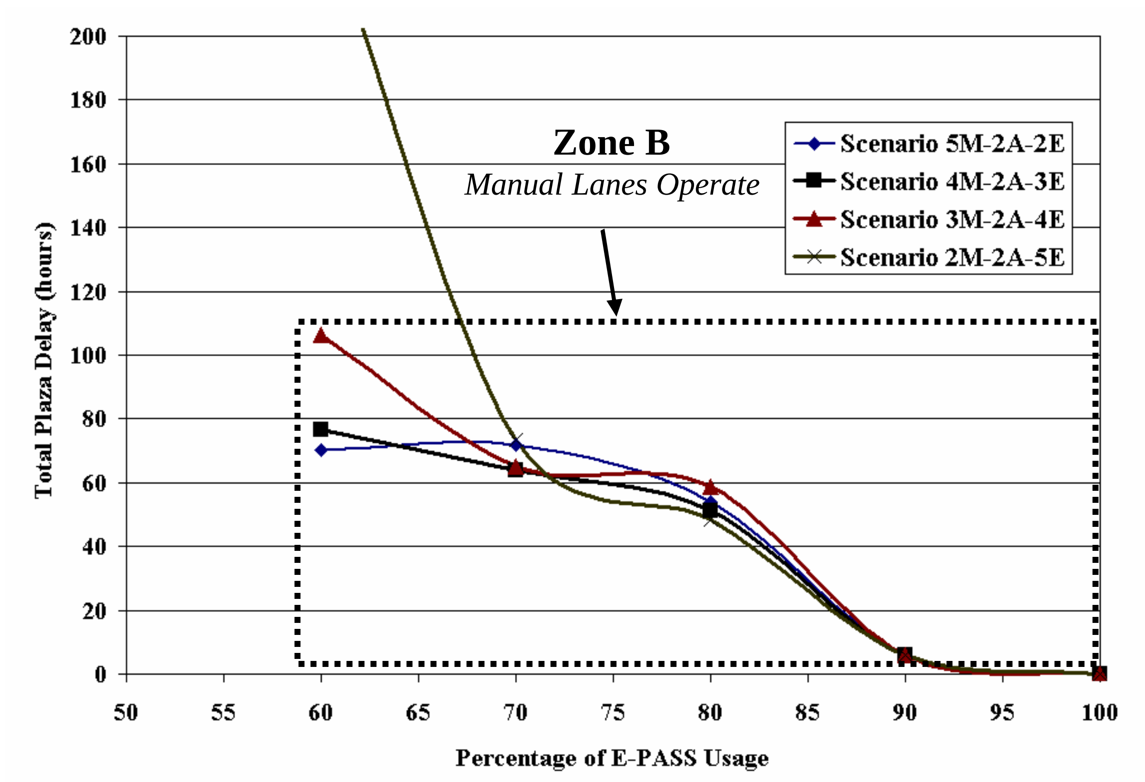


Figure 3.19: Sensitivity Analysis of ETC Market Penetration and Total Plaza Delay within *Zone B* at Traffic Volume Level of 7000 vph

3.5 LOCATIONS OF THE DEDICATED ETC LANES

Several simulation scenarios were conducted to investigate the appropriate location(s) of the dedicated ETC lane(s) within the toll plaza. In this analysis, three different levels of dedicated ETC lanes i.e., *one E-PASS lane, two E-PASS lanes, and three E-PASS lanes* were investigated. Estimated morning peak hour total delay was used to evaluate each scenario. It was assumed in this experiment that lanes 1& 2 are fixed to be manual lanes and lanes 3 & 4 are fixed to be automatic lanes throughout all the simulation scenarios. However, lanes 5 through 9 can be alternated from manual to E-PASS based on the objective of each simulation scenario. For plaza configuration with more than one E-PASS lane, all E-PASS lanes are adjacent to each other. In other words, there is no conventional lane between two or more dedicated E-PASS lane. A total of 12 scenarios were conducted in this experiment. All scenarios were conducted at the traffic volume level of 7000 vph with 50% manual vehicles, 20% automatic and 30% E-PASS vehicles. Table 3-6 provides all possible scenarios and plaza configurations under this experiment. The findings of this experiment can be summarized as follows:

3.5.1 One E-PASS Lane

Sensitivity to the dedicated ETC lane location increases very slightly with moving the ETC lane to the left of the toll plaza. Figure 3.20 demonstrates an insignificant increase (5%) in the estimated peak hour plaza delay associated with moving the dedicated ETC lane from the middle of the plaza to the left of the plaza.

Table 3-6 Experimental Design for Location of the Dedicated E-PASS Lanes Scenarios at Traffic Volume Level of 7000 vph for the Holland-East Plaza

		Plaza Configuration									Percentage of vehicle Types		
		Lane Number											
Number of AVI lanes	**Scenario Name**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**M**	**A**	**E**
One E-PASS Lane	***1E-5***	M	M	A	A	**E**	M	M	M	M	50%	20%	30%
	1E-6	M	M	A	A	M	**E**	M	M	M	50%	20%	30%
	1E-7	M	M	A	A	M	M	**E**	M	M	50%	20%	30%
	1E-8	M	M	A	A	M	M	M	**E**	M	50%	20%	30%
	1E-9	M	M	A	A	M	M	M	M	**E**	50%	20%	30%
Two E-PASS Lanes	***2E-5&6***	M	M	A	A	**E**	**E**	M	M	M	50%	20%	30%
	2E-6&7	M	M	A	A	M	**E**	**E**	M	M	50%	20%	30%
	2E-7&8	M	M	A	A	M	M	**E**	**E**	M	50%	20%	30%
	2E-8&9	M	M	A	A	M	M	M	**E**	**E**	50%	20%	30%
Three E-PASS Lanes	***3E-5&6&7***	M	M	A	A	**E**	**E**	**E**	M	M	50%	20%	30%
	3E-6&7&8	M	M	A	A	M	**E**	**E**	**E**	M	50%	20%	30%
	3E-7&8&9	M	M	A	A	M	M	**E**	**E**	**E**	50%	20%	30%

M is Manual, A is Automatic, and E is E-PASS.

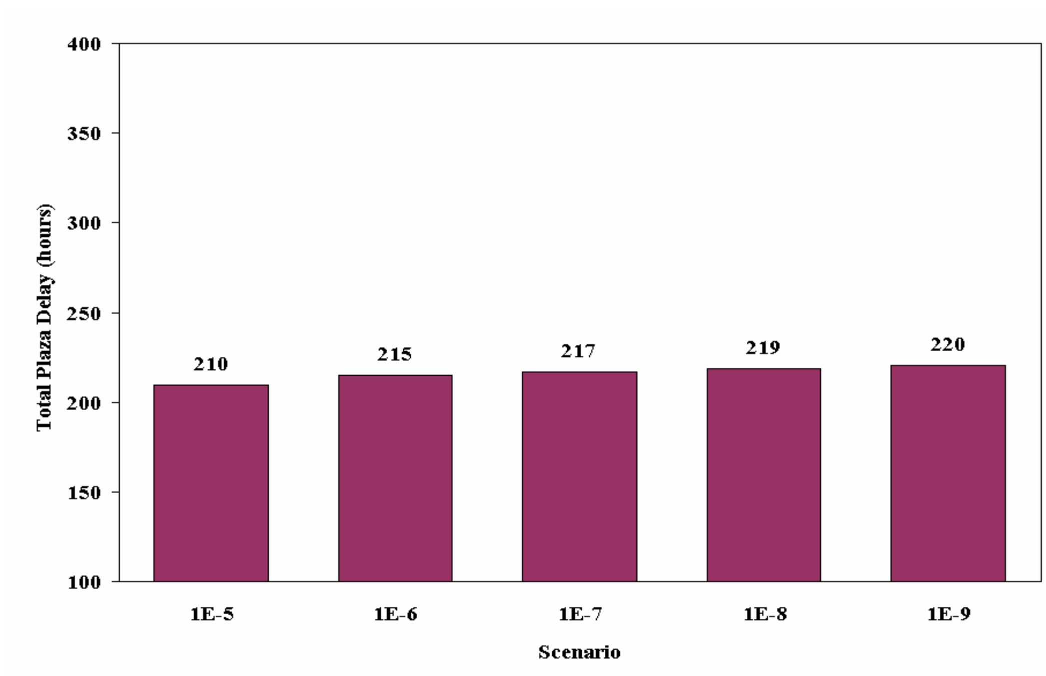


Figure 3.20: Total Plaza Delay at Various Locations of the Dedicated AVI Lane

3.5.2 Two E-PASS Lanes

Figure 3.21 illustrates an increase trend in the estimated peak hour plaza delay with moving the two dedicated ETC lanes from the middle of the plaza to the left of the plaza. This significant increase (30%) could be attributed to ETC vehicle accessibility to the dedicated ETC lanes. In a plaza configuration with two dedicated ETC lanes being in the middle of the plaza and the plaza operates over its capacity, the queues of manual and automatic lanes do not reach the approach lanes and the dedicated lanes are accessible from all approach lanes, see Figure 3.22. However, every time these two lanes are moved to the left of the plaza, i.e., lanes 6&7 and 7&8, E-PASS vehicle accessibility is weakening gradually, see Figures 3.23 and 3.24.

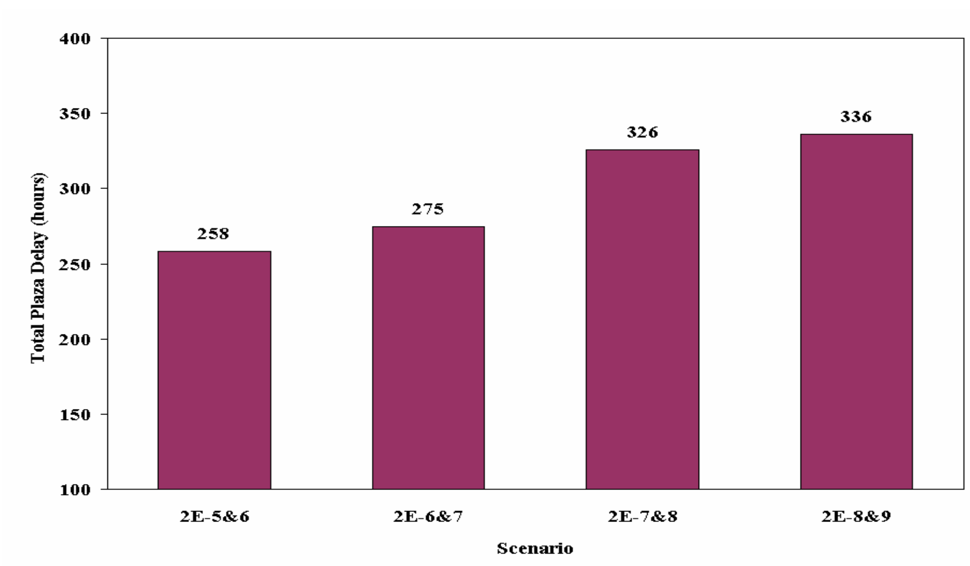


Figure 3.21: Total Plaza Delay at Various Locations of Two Dedicated AVI Lanes

Finally, as these two dedicated ETC lane located to the most far left lanes of the toll plaza, the E-PASS vehicle accessibility of these dedicated lanes would be only from

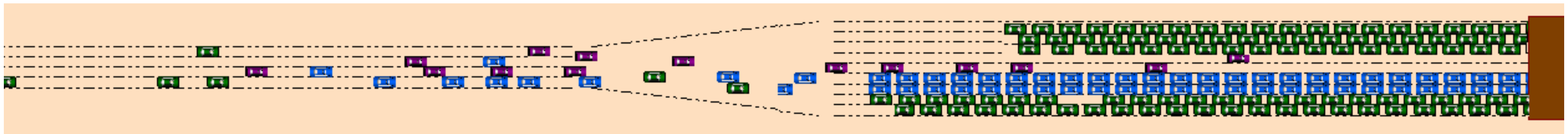


Figure 3.22: Snapshot of the TPSIM© Animation Window for the 2E-5&6 Scenario (Middle)

Figure 3.23: Snapshot of the TPSIM© Animation Window for the 2E- 6&7 Scenario

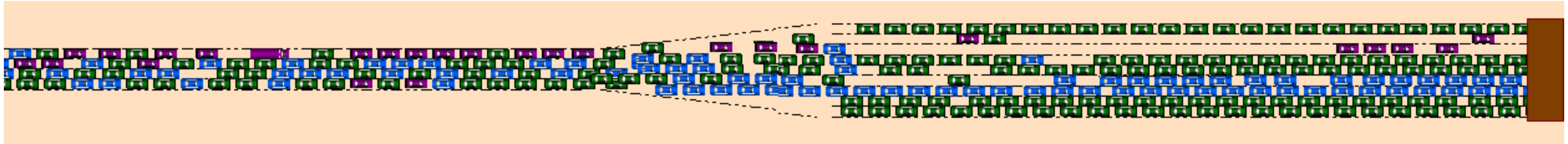


Figure 3.24: Snapshot of the TPSIM© Animation Window for the 2E-7&8 Scenario

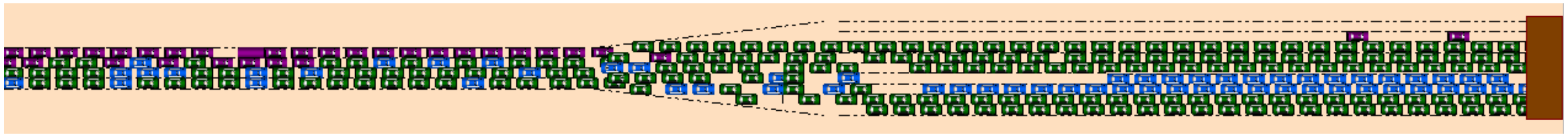


Figure 3.25: Snapshot of the TPSIM© Animation Window for the 2E- 8&9 Scenario (Far Left)

Manual Vehicle **Automatic Vehicle** **E-PASS Vehicle**

the far left approach lanes. Since these approach lanes experience queuing resulted from the extension of the long queue associated with both manual lanes 5 and 6, E-PASS vehicles that are stuck behind these queues would not be able to reach their desired lanes and experience significant delays, see Figure 3.25.

3.5.3 Three E-PASS Lanes

Unlike the conclusion from the two dedicated ETC lanes plaza configuration, Figure 3.26 illustrates a slight decrease trend in the estimated peak hour plaza delay with moving the three dedicated ETC lane from the middle of the plaza to the left of the plaza. This could be also attributed to the ETC vehicle accessibility to the dedicated ETC lanes. In a plaza configuration with three dedicated ETC lanes being in the middle of the plaza and the plaza operates over its capacity, the dedicated ETC lanes are surrounded by conventional lanes associated with long queues. In many cases, the extended queues from these conventional lanes located to the right and to the left of the three E-PASS lanes, block E-PASS vehicles to reach their desired lanes and experience significant delays, see Figure 3.27. However, every time these there lanes are moved to the left of the plaza, i.e., lanes 6&7&8 and 7&8&9, E-PASS vehicle accessibility is improving, see Figures 3.28 and 3.29. By grouping the lanes with the same payment types, manual and automatic vehicles would try to maintain the approach lanes located to the right to achieve their desired conventional toll lanes. However, E-PASS vehicles maintain the approach lanes located to the left to approach their dedicated E-PASS lanes. This strategy creates a well-organized traffic flow pattern approaching the plaza, see Figures 3.28 and 3.29. Since the far left approach lane does not experience any extended queue associated with a conventional toll lane, therefore, most of the time this approach lane would be clear for E-PASS vehicles to reach their desired dedicated lanes located to the left of the plaza. This well-organized traffic pattern decreases the delays associated with the E-PASS vehicles. It must be emphasized that, in all conducted simulation scenarios in this experiments, a significant number of E-PASS vehicles experienced delays resulting from manual vehicles that traveled in the dedicated E-PASS lanes to avoid the long queue in the adjacent conventional lanes. As soon as these vehicles reach a close distance to the tollbooth, they try to squeeze themselves in the queue associated with the adjacent conventional lanes.

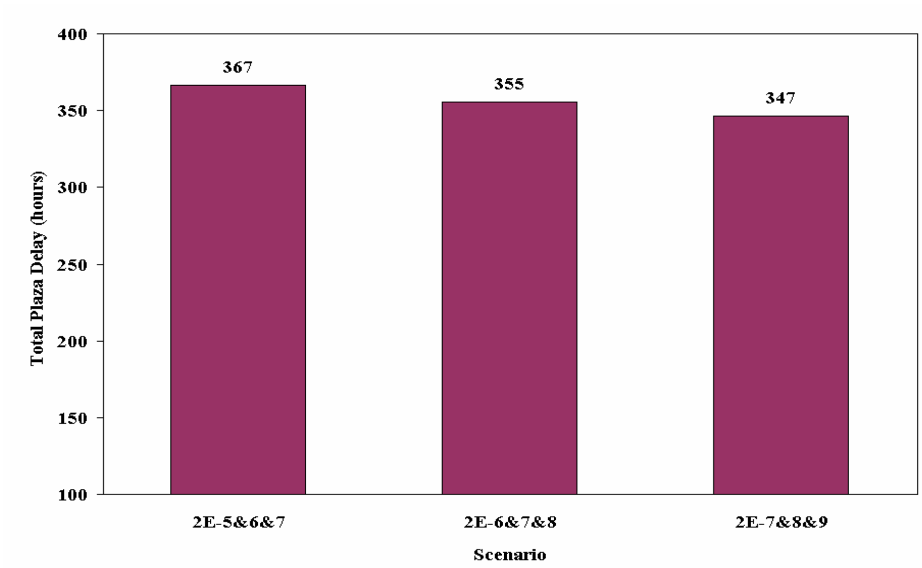


Figure 3.26: Total Plaza Delay at Various Locations of Three Dedicated AVI Lanes

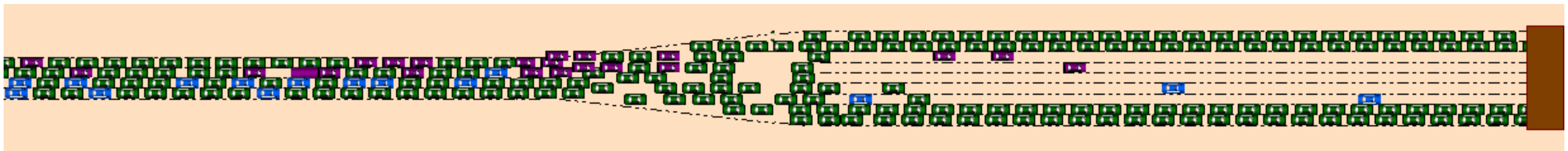


Figure 3.27: Snapshot of the TPSIM© Animation Window for the 3E-5&6&7 Scenario (Middle)

Figure 3.28: Snapshot of the TPSIM© Animation Window for the 3E-6&7&8 Scenario

Figure 3.29: Snapshot of the TPSIM© Animation Window for the 3E-7&8&9 Scenario (Far Left)

Manual Vehicle   Automatic Vehicle   E-PASS Vehicle

CHAPTER 4

CONCLUSIONS AND FUTURE RESEARCH

Computer simulation provides an excellent means for evaluating a wide spectrum of traffic management schemes within the framework of controlled experiments. In recognition of the need for a more detailed understanding of the effect of toll plazas on toll roads, this study was performed to develop a new methodology for evaluating toll plaza operational performance with different configurations.

The main goal of this research is to evaluate current and future traffic conditions at a toll plaza with different configurations and traffic characteristics in order to recommend the most appropriate (and near optimal) plaza configuration. The specific objectives of this research include:

1. Testing and assuring the reliability of the TPSIM© model in predicting performance of toll plazas.
2. Quantifying the traffic operational benefits with various levels of E-PASS.
3. Setting the criteria for optimization of traffic operations at toll plazas as applied to OOCEA plazas and extending this to FDOT Turnpike plazas in the near future.

4.1 CONCLUSIONS

Field study was conducted as a means of testing the validity of the model for making reasonable and accurate predictions of behavior on the system being simulated. Several tests were performed to investigate the reliability of the developed model in representing the real-world situation at toll plazas.

TPSIM© validation was performed using data collected at one of the busiest toll plazas in the Orlando-Orange County Expressway system, i.e., Holland-East Plaza, Orlando, Florida. Data collection was conducted during the morning peak hour (7:00-8:00 AM) in weekdays. One day (June 8, 1995) representing one dedicated E-PASS plaza configuration level and three days (July 9, 1996, July 28, 1996, and July 24, 1996) representing two dedicated E-Pass lanes level were selected randomly for data collection to be used in the TPSIM© validation process. The validation process of TPSIM© was conducted using two approaches, *Conceptual Validation* and *Operational Validation.*

Conceptual Validation observes the animation of the simulated real-life case with the model output. Animation was displayed side-by-side with the real-life videotapes collected at the Holland East Plaza. The comparison of the TPSIM© animation and the videotapes indicates that simulated traffic condition resulted from TPSIM© is close to the actual real-life traffic condition at Holland-East Plaza.

Operational Validation of TPSIM© was performed by inputting the real-life data collected at the Holland-East Plaza into the model and comparing the simulated results with observed measures of effectiveness macroscopically and microscopically. These measures of effectiveness included plaza throughput, average queuing delay, maximum queuing delay, and total queuing delay.

Operational Validation process of TPSIM© was conducted using two tests, ***Turning Test*** and ***Error Analysis Test***. The ***Turning Test*** compares the system performance with real-life observations graphically to detect any unexpected behavior of the model performance during the simulation period. This test concludes that there is no difference between the real-life observations and the simulation performance. The ***Error Analysis Test*** conducts certain statistical tests to quantify the deviation of the simulated results from their actual values and detect any systematic bias of the simulation results. The ***Error Analysis Test*** indicated that for all measures of effectiveness TPSIM© has reached an acceptable level of validity and reliability to represent traffic condition at toll plazas with a 95% confidence level.

Using the newly developed model in this study, TPSIM©, a simulation experiment was designed to study the impact of ETC market penetration on the benefits of this technology. This experiment focused on the Holland-East Plaza condition during the morning peak hour. The experiment employs 7 x 4 x 3 multi-level factorial design resulted in 84 different scenarios. Three qualitative variables including the ETC market penetration, the plaza configuration, and the traffic volume and three response quantitative variables including the plaza throughput, the average queuing delay, and the total plaza queuing delay were used in conducting the experiments. The ETC market penetration variable includes 7 different levels, (i.e., 20%, 30%, 40%, 50%, 60%, 70%, and 80%). The plaza configuration variable consists of 4 different levels based on number of dedicated ETC lanes, (i.e., two ETC lanes, three ETC lanes, four ETC lanes, and five ETC lanes). Finally, the traffic volume variable has three levels (i.e., 5000 vph, 6000 vph, and 7000 vph). The experiment performs all possible combination scenarios of these variables and their associated levels. Several conclusions were drawn from the results of this experiment as following:

⇒ Plaza delay sensitivity to the traffic demand increases more rapidly with higher traffic volumes. This increase in the estimated peak hour delay is not linear, but more exponential in nature.

⇒ Delay sensitivity to the ETC market penetration indicated a decrease in the estimated peak hour delay when the percentage of ETC usage increases. This decrease is not linear, but more exponential in nature. Clearly, the benefits of ETC depend on the plaza configuration. However, the most interesting of the ETC sensitivity analysis finding is that, for all plaza configurations simulated with the manual lanes operating over capacity, the total plaza queuing delay can be reduced *in half* if only as little as 10% of the users can switch from manual to

ETC lanes. Also, the ETC Sensitivity analysis indicated a decrease in the average queuing delay per vehicle as the percentage of ETC usage increases. For all plaza configurations simulated with the manual lanes operating over capacity, the average queuing delay per vehicle can be reduced by *more than 90 seconds* if only as little as 10% of the users can switch from manual to ETC lanes.

⇒ An increase of 20%-30% of the plaza throughput can be achieved by switching only 10% of the manual users to ETC users during the morning peak hour when the manual lanes operate over their capacities.

⇒ Adding more dedicated ETC lanes immaturely, i.e., without an increase in the level of ETC subscription, can cause an increase in the plaza queuing delay and decrease in the total plaza throughput. By converting one of the manual lanes to a dedicated ETC lane when the ETC lanes are operating under capacity, the demand for manual lanes that is already exceeding manual capacity would have one less lane to use. A natural result of this strategy is more queuing delay for manual vehicles and less plaza throughput since the ETC dedicated lanes operate under capacity.

⇒ Since ETC vehicles do not experience any delays when the dedicated ETC lanes operate under capacity, total plaza delay does not have any impact on the decision of converting one of the manual lanes to a dedicated ETC lane. Sensitivity analysis of the ETC market penetration supported this conclusion and showed that when ETC usage during the rush hour is high (> 60%), delays reach a considerably reduced level for all plaza configurations, and any additional dedicated ETC lane does not have any impact on the plaza operational performance. Other contributing factors such as ETC lane capacity, traffic demand characteristics, safety factors, and driver comfort may weigh more heavily upon the decision process of introducing a new dedicated ETC lane

Several simulation scenarios were conducted to investigate the impact of various dedicated ETC lane locations on traffic operations of the Holland-East Plaza. This experiment investigated three levels of plaza configuration including *one dedicated ETC lane*, *two dedicated ETC lanes*, and *three dedicated ETC lanes*. In this analysis, traffic demand was set to 7000 vph with 50% manual vehicles, 20% automatic and 30% ETC vehicles. Estimated morning peak hour total delay was used to evaluate each scenario. The findings of this experiment indicated that ETC vehicles accessibility to the dedicated ETC lane from the approach lane is the key factor in selecting the appropriate location of the dedicated ETC lane. Sensitivity analysis to the dedicated ETC lanes indicated the following:

- ⇒ For plaza configuration with a one dedicated ETC lane, there is no significant differences in plaza delay among locating the dedicated ETC lane in the middle of the plaza or moving it to the far left of the plaza.

- ⇒ For plaza configuration with two dedicated ETC lanes, a significant decrease (30%) in the estimated peak hour delay was observed when these lanes were located in the middle of the plaza rather to the far left of the plaza. This could be contributed to the fact that these dedicated lanes are accessible from all approach lanes.

- ⇒ For plaza configuration with three dedicated ETC lanes, a slight decrease (5%) in the estimated peak hour delay was observed when these lanes were located to the far left of the plaza. This could be due to the increase in ETC vehicle accessibility to three dedicated lanes from the approach lanes. Another reason for this decrease is the well-organized traffic pattern within the approach zone resulted from grouping conventional payment types (manual and automatic) associated with queued vehicles to the right of the plaza and payment type (ETC) associated with high speed vehicles to the left of the plaza.

4.2 FUTURE RESEARCH

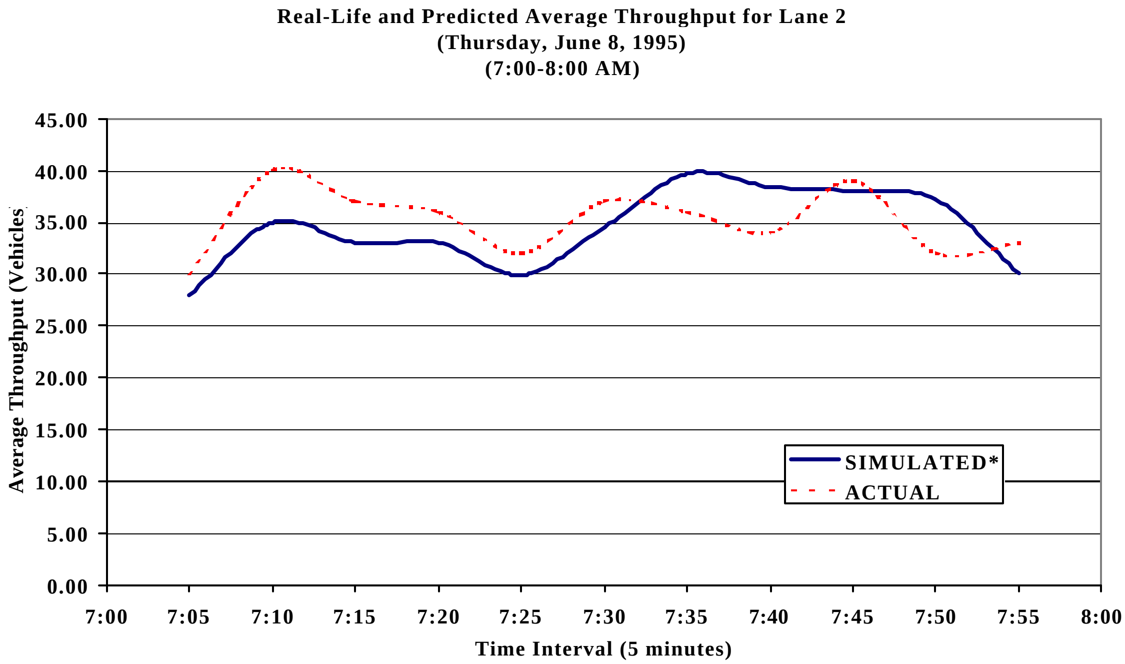
Validation of TPSIM© using traffic data at the Holland-East Plaza indicated that TPSIM© has reached an acceptable level of reliability to represent traffic condition at toll plazas with a 95% confidence level. This conclusion opens the door for further experimentation and application on toll plaza operations. Sensitivity analysis for a second OOCEA plaza may generalize the findings drawn from the analysis of this study. The E-PASS sensitivity analysis conducted at the selected plaza may be compared to the results from the Holland-East Plaza sensitivity analysis. The conclusion of this comparison may band the E-PASS sensitivity analysis findings for all OOCEA mainline toll plazas. Data collection for certain input parameters for the selected plaza is needed to accurately simulate traffic behavior at the plaza. A limited number of scenarios for existing and future growth conditions will be evaluated for the second plaza.

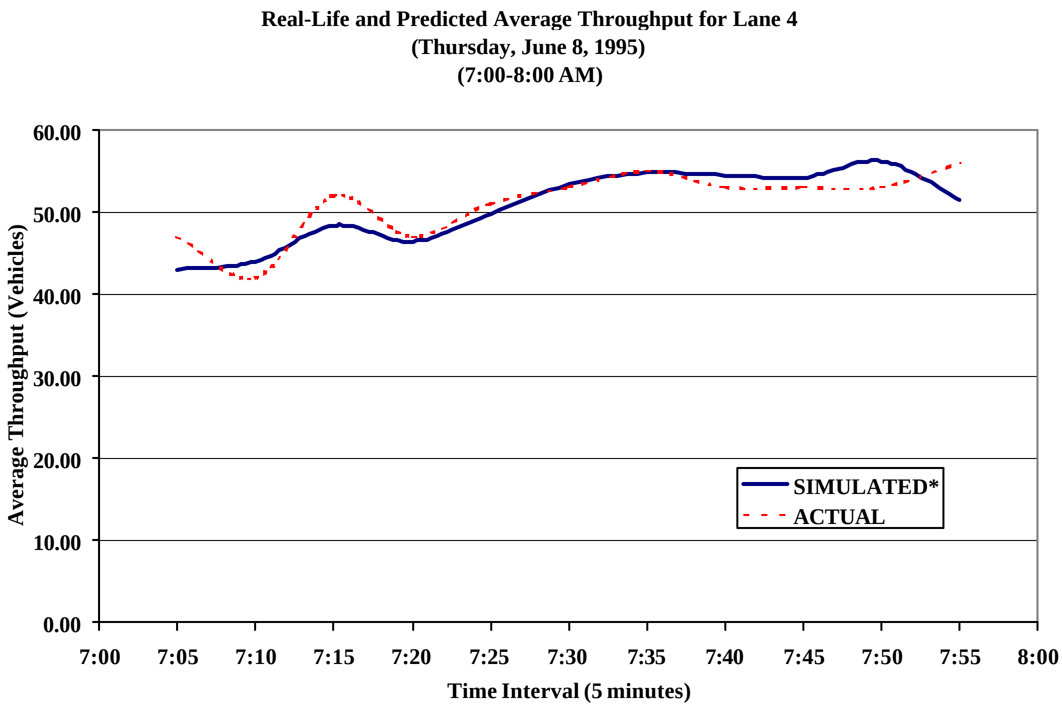
APPENDIX A

VALIDATION RESULTS

Five-minute Intervals Comparisons

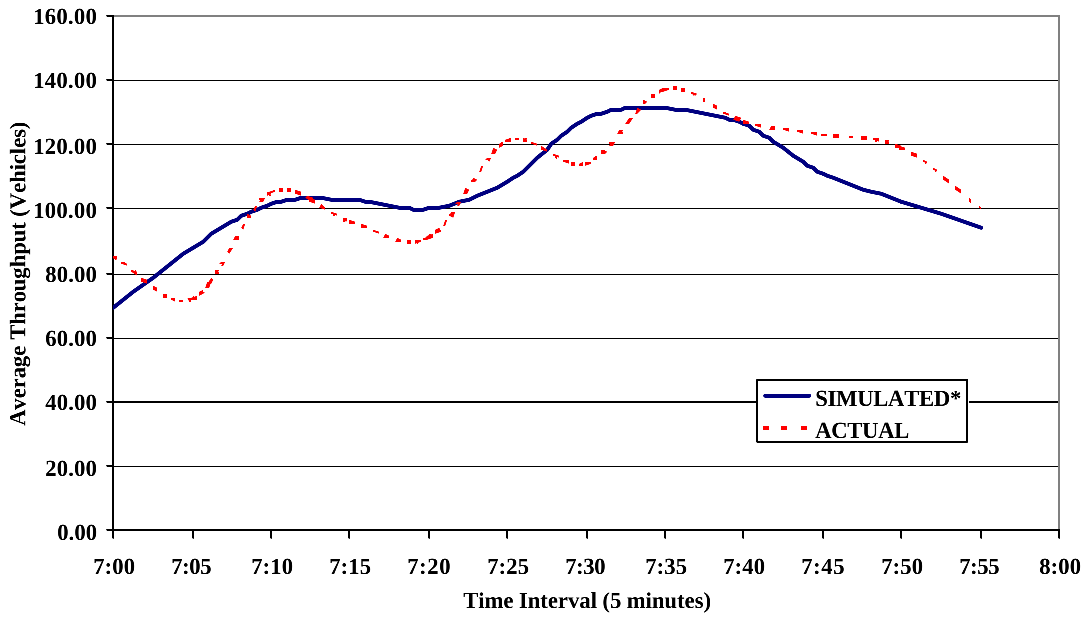
1- LANE THROUGHPUT





* Based on averages of 10 runs

Real-Life and Predicted Average Throughput for Lane 5
(Thursday, June 8, 1995)
(7:00-8:00 AM)



Real-Life and Predicted Average Throughput for Lane 6
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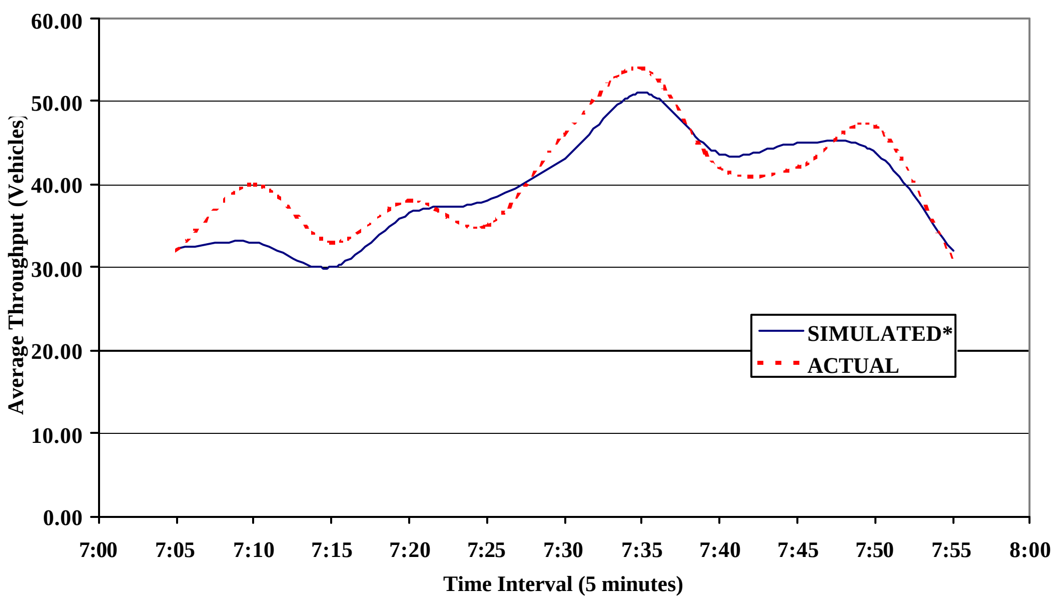
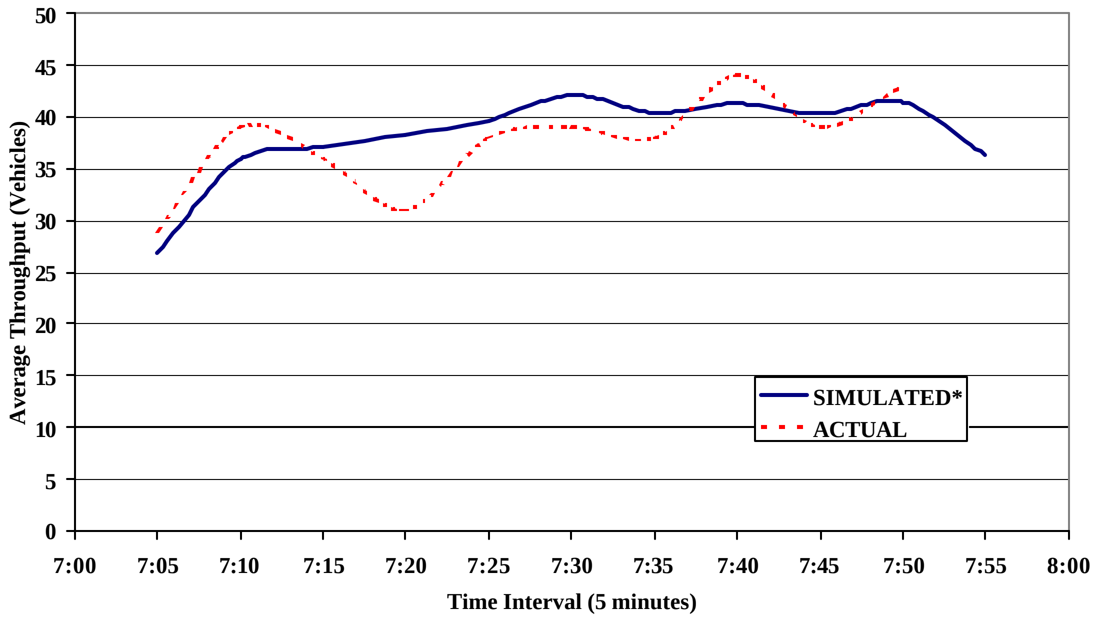
(7:00-8:00 AM)

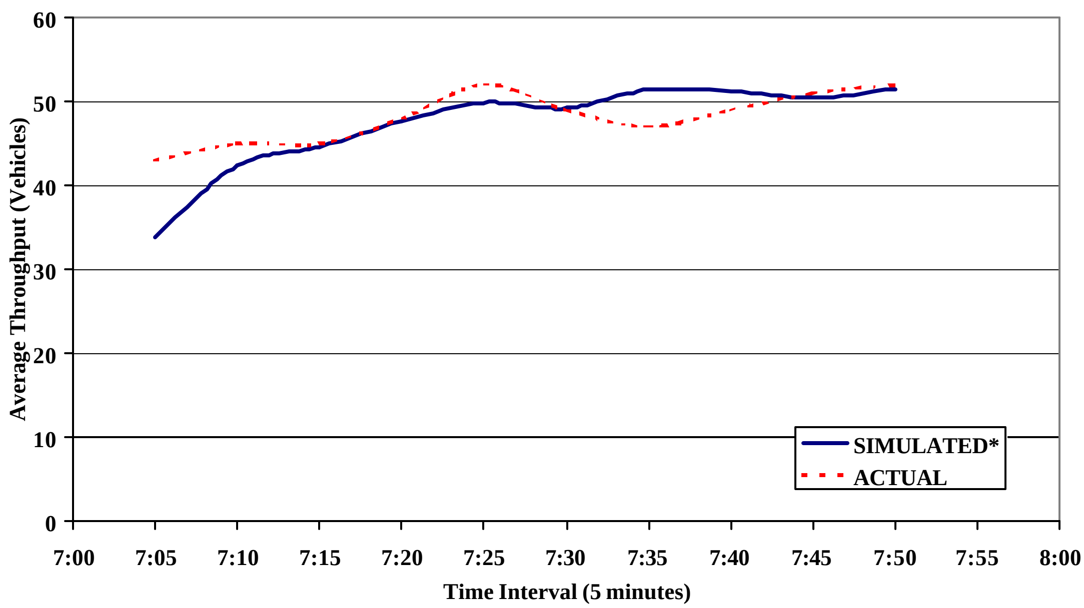


* Based on averages of 10 runs

Real-Life and Predicted Average Throughput for Lane 2
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

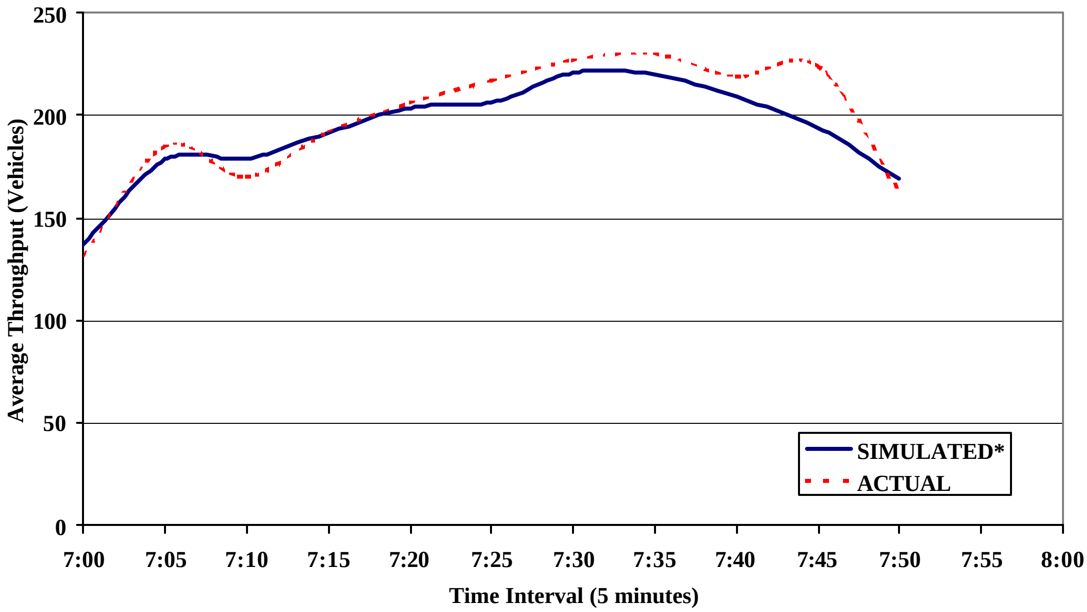


Real-Life and Predicted Average Throughput for Lane 4
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

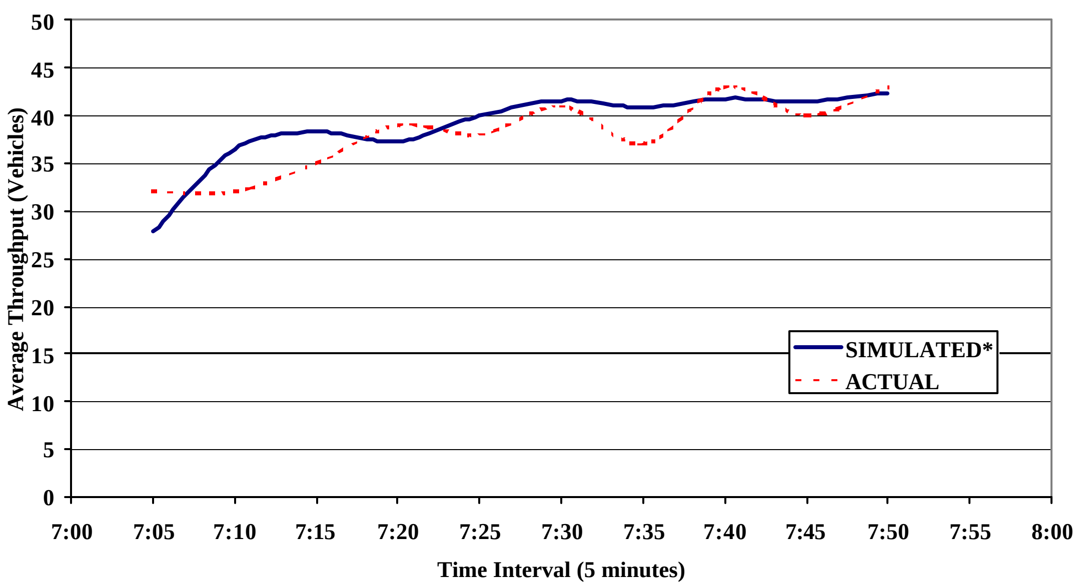


* Based on averages of 10 runs

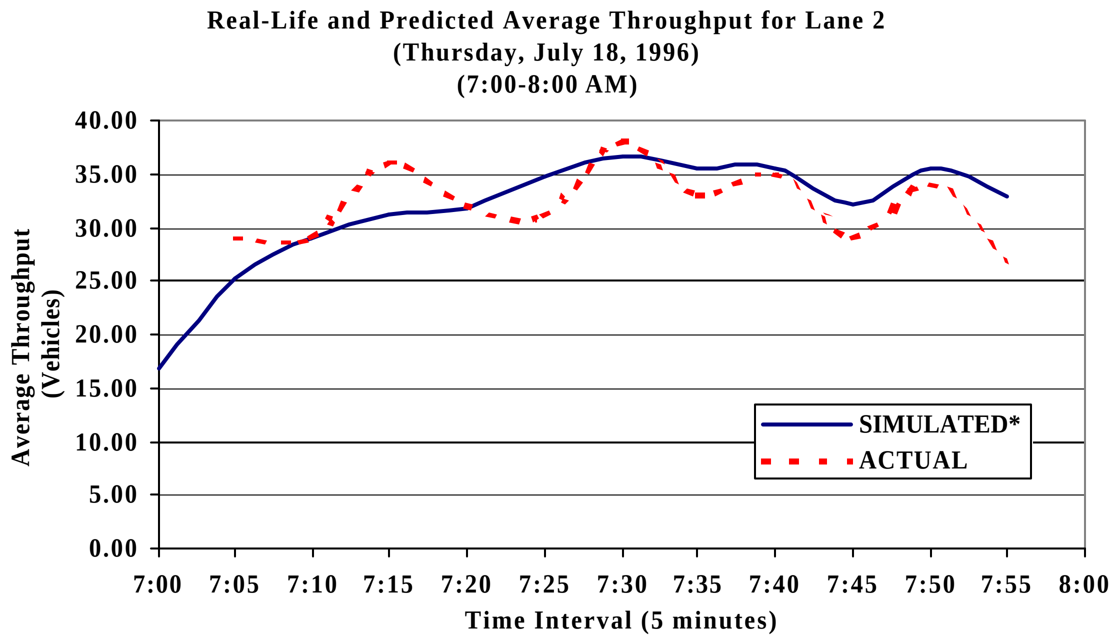
Real-Life and Predicted Average Throughput for Both Lanes 5 & 6
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

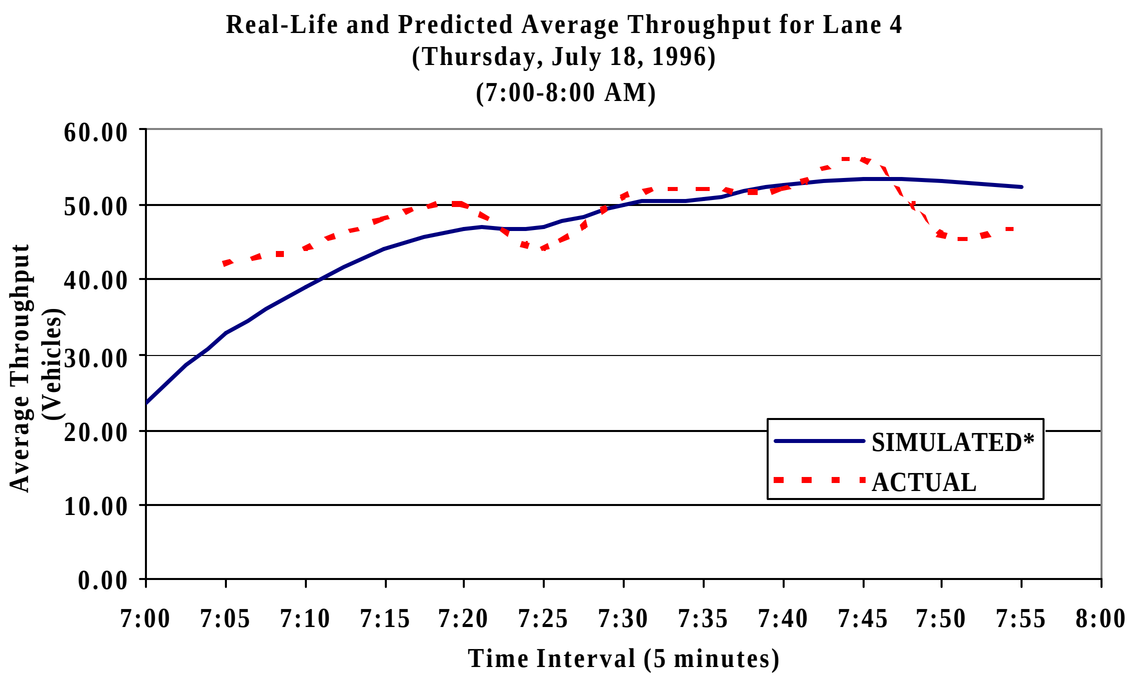


Real-Life and Predicted Average Throughput for Lane 7
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

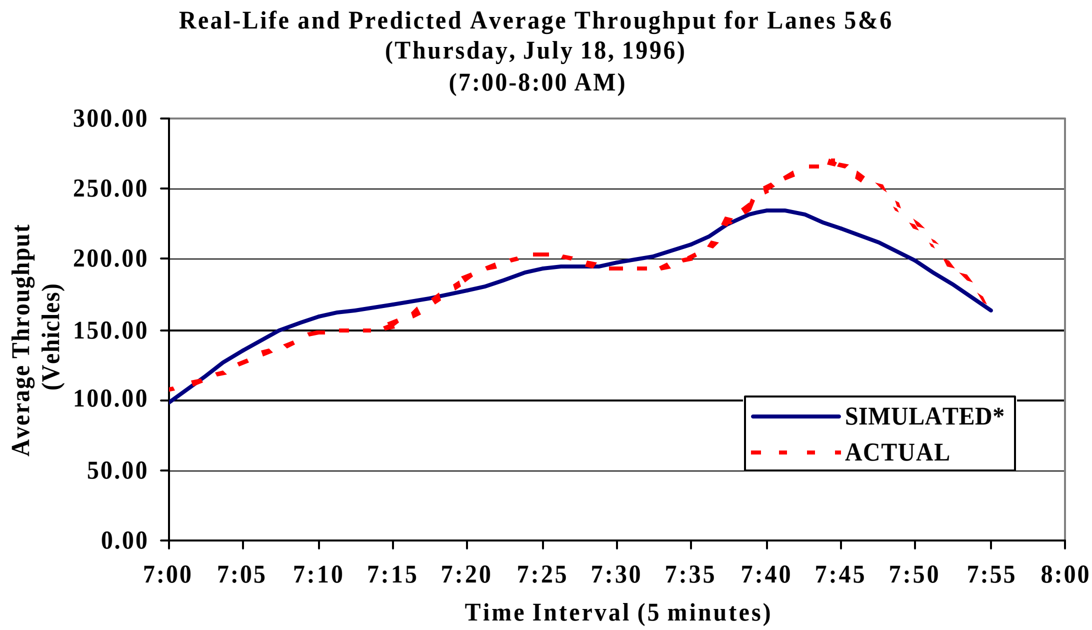


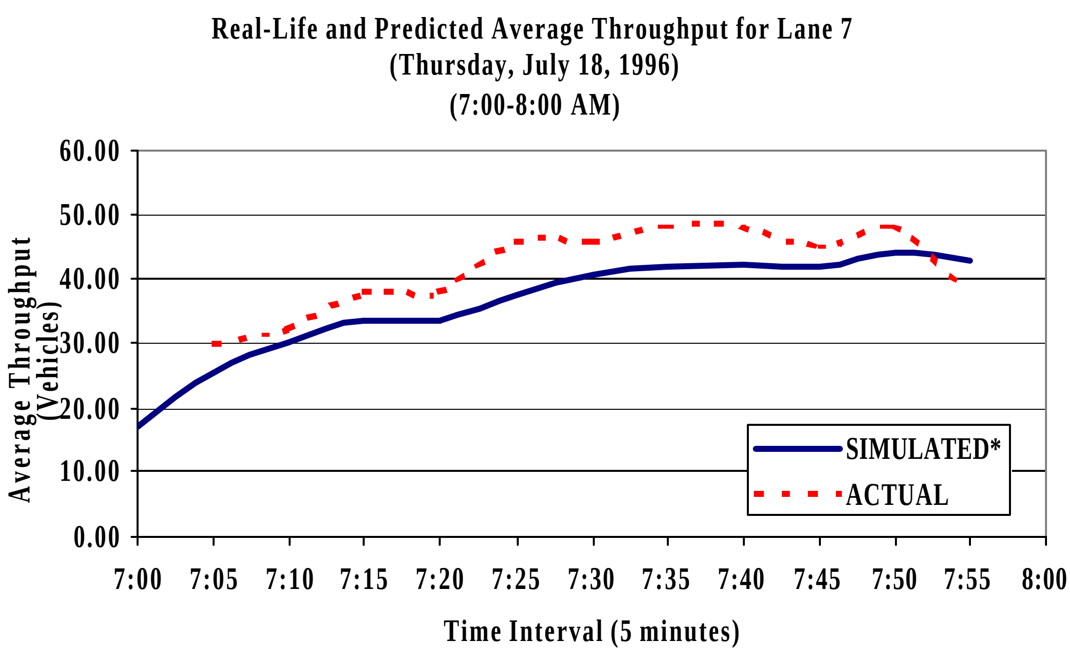
* Based on averages of 10 runs





* Based on averages of 10 runs





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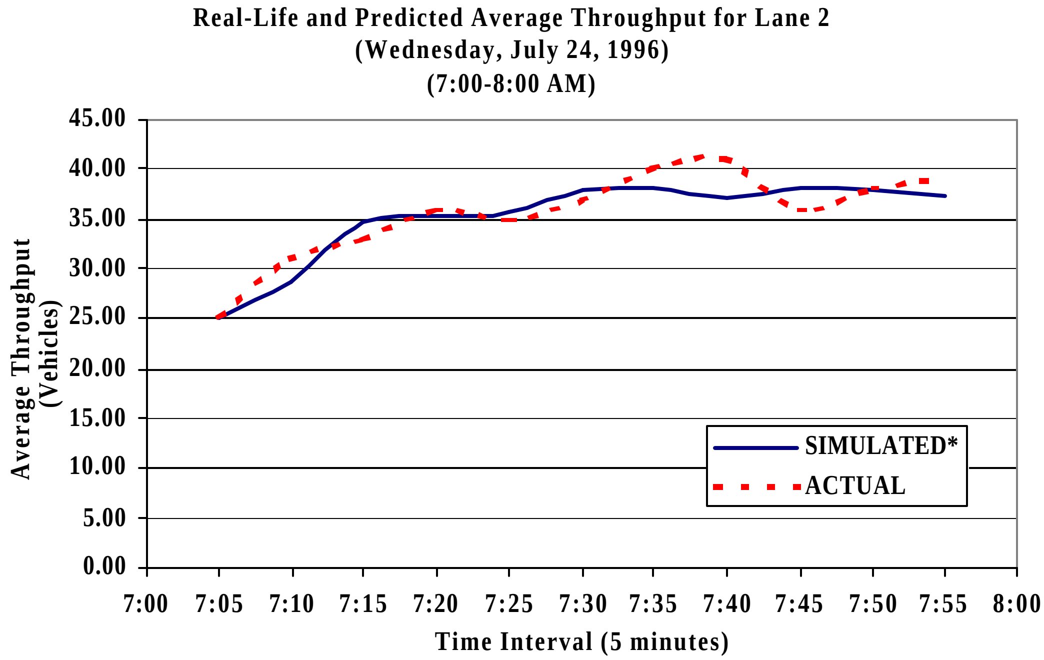
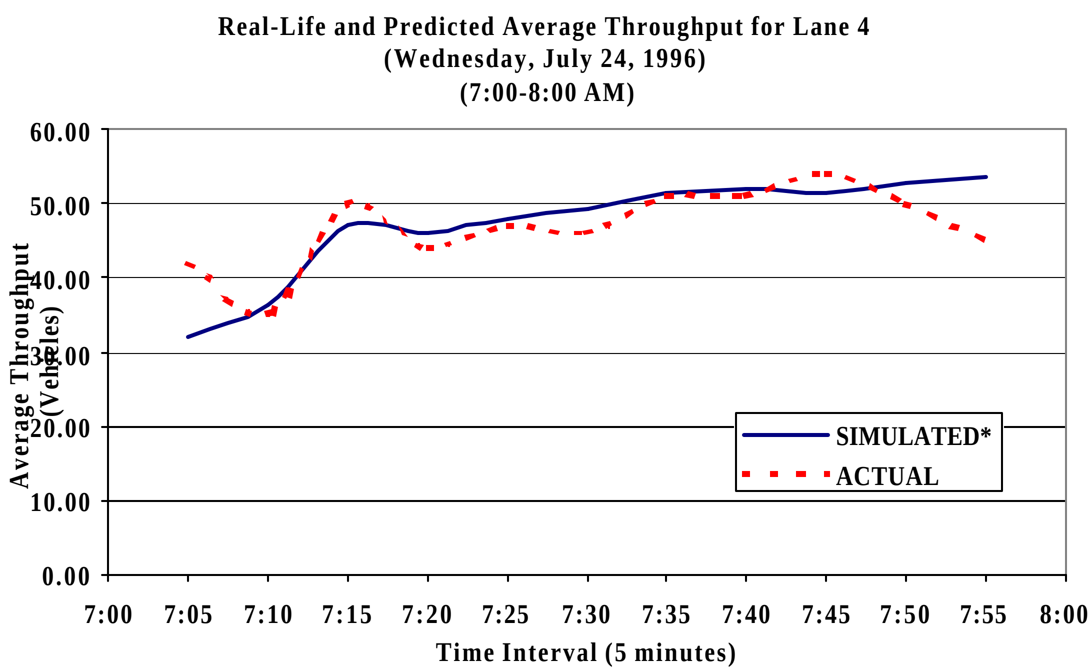
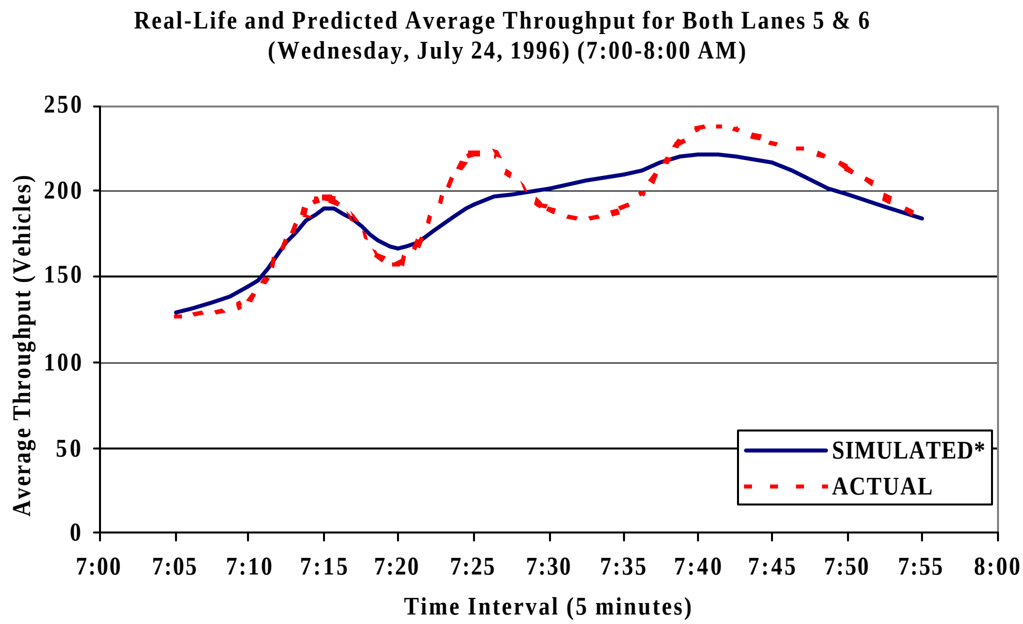
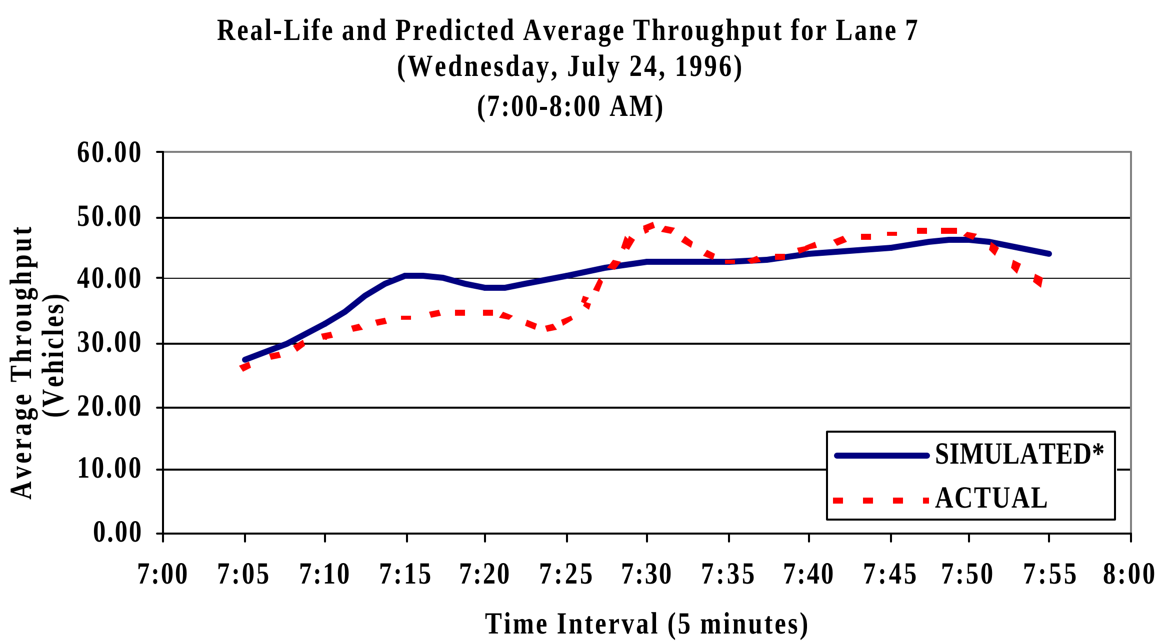




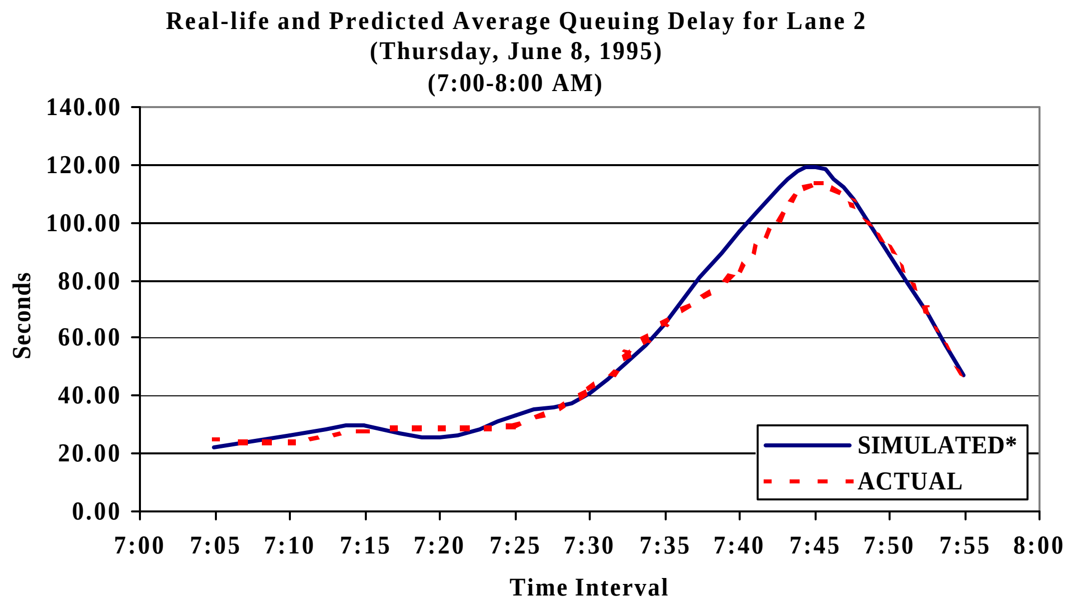
* Based on averages of 10 runs

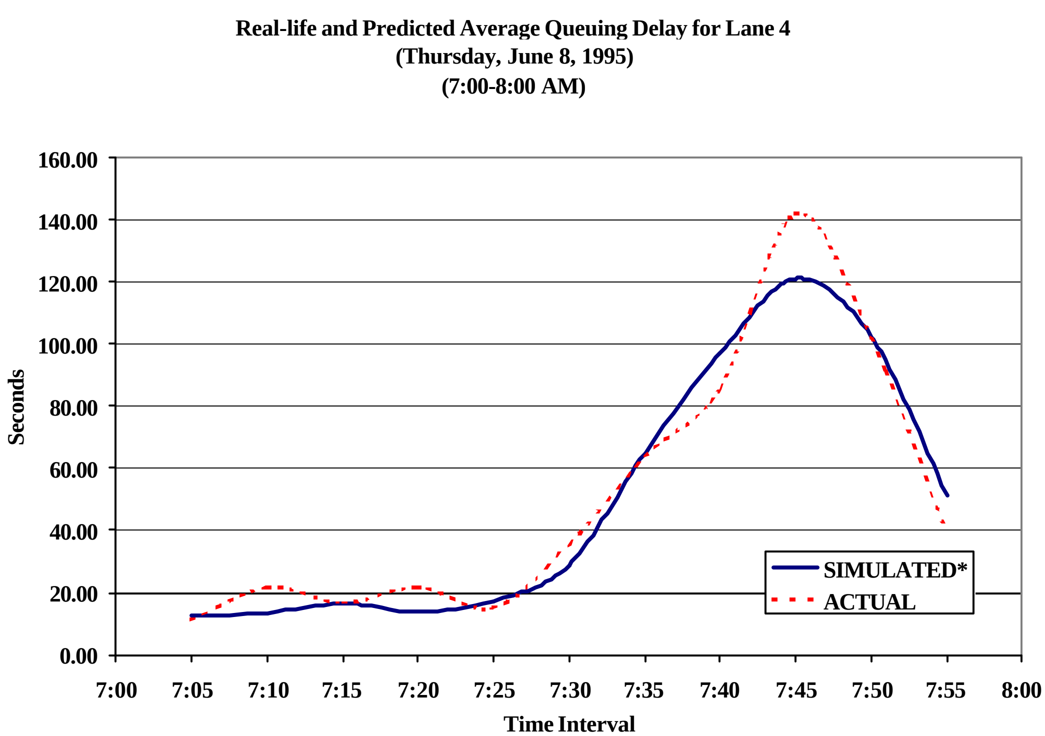




* Based on averages of 10 runs

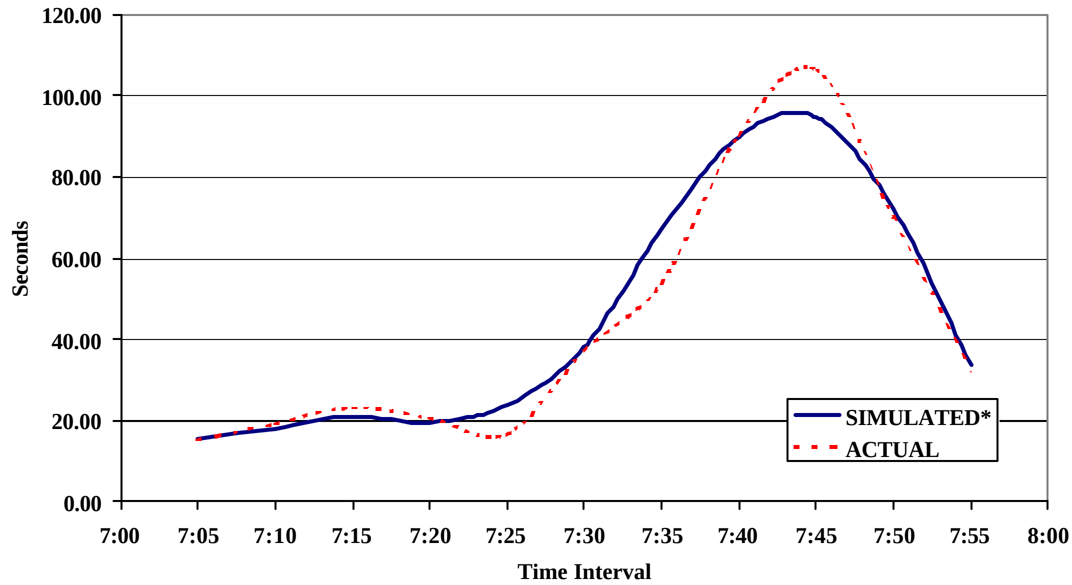
AVERAGE QUEUING DELAY



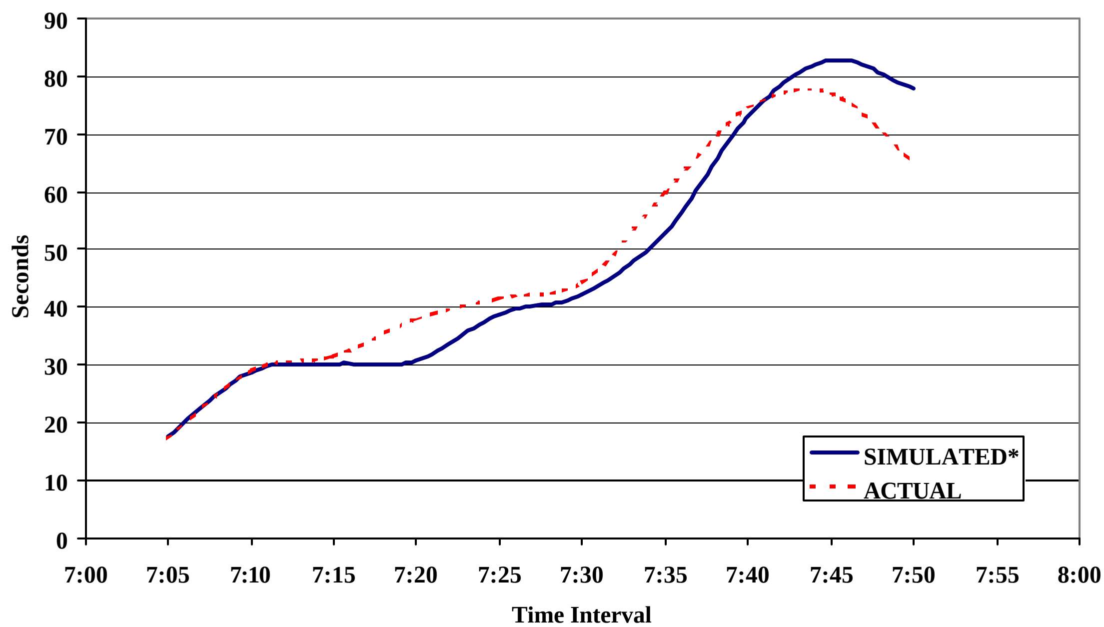


* Based on averages of 10 runs

Real-life and Predicted Average Queuing Delay for Lane 6
(Thursday, June 8, 1995)
(7:00-8:00 AM)

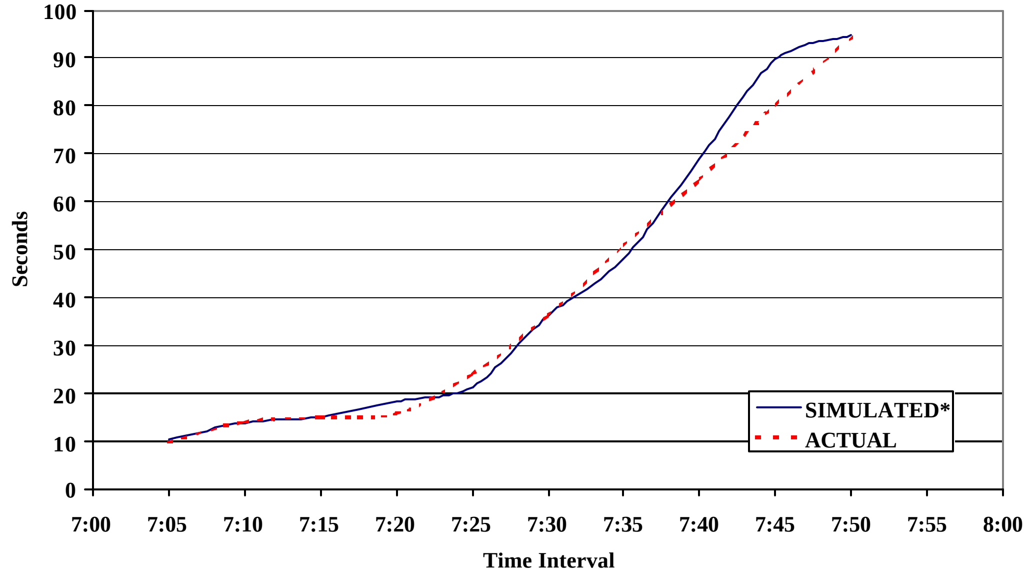


Real-life and Predicted Average Queuing Delay for Lane 2
(Tuesday, July 9, 1996)
(7:00-8:00 AM)



* Based on averages of 10 runs

Real-life and Predicted Average Queuing Delay for Lane 4
(Tuesday, July 9, 1996)
(7:00-8:00 AM)



Real-life and Predicted Average Queuing Delay for Lane 7
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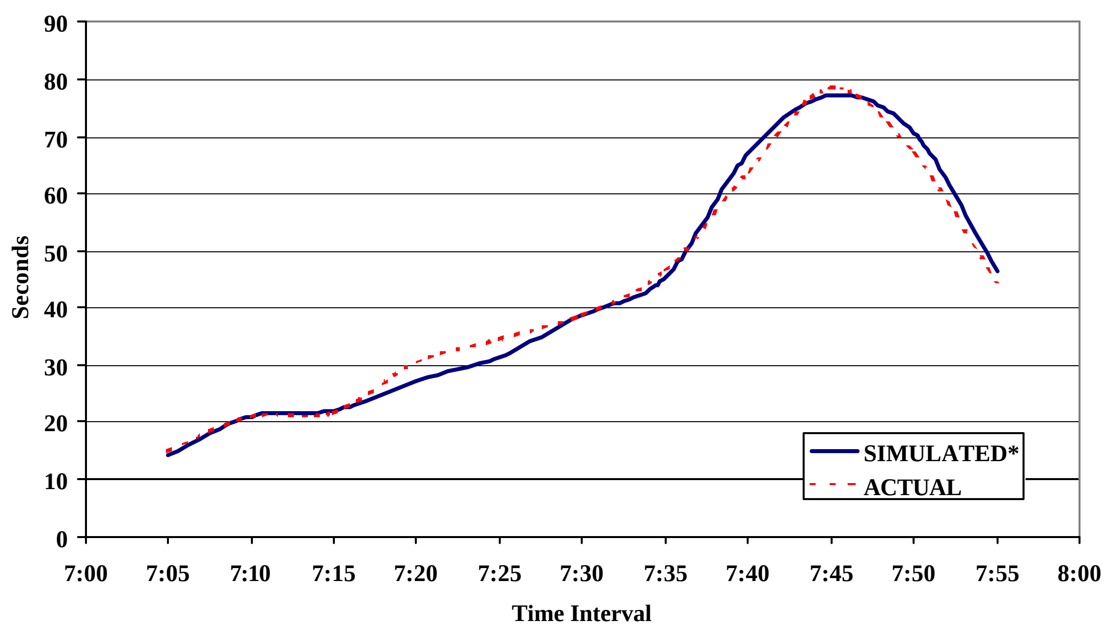
(7:00-8:00 AM)



* Based on averages of 10 runs

Real-life and Predicted Average Queuing Delay for Lane 2
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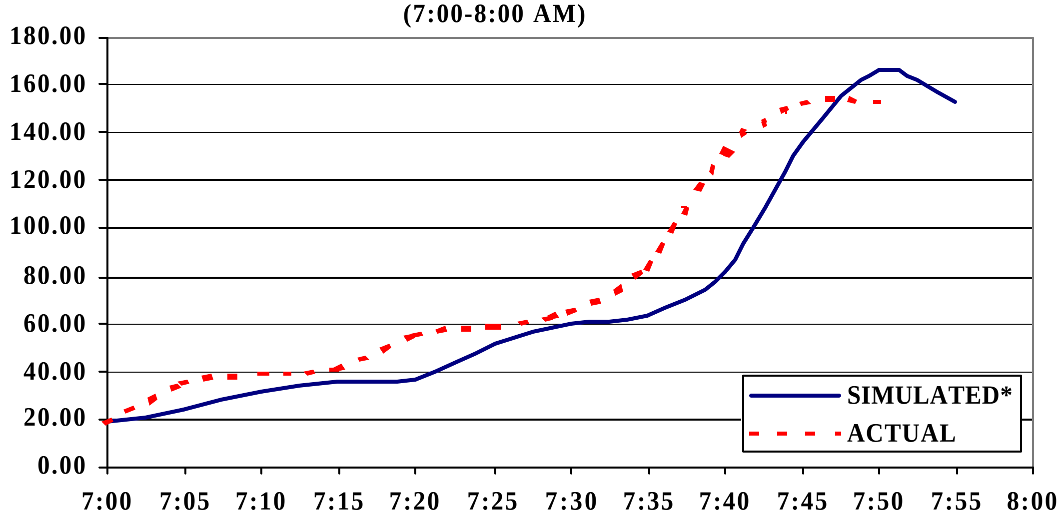
(7:00-8:00 AM)



Real-life and Predicted Average Queuing Delay for Lane 4
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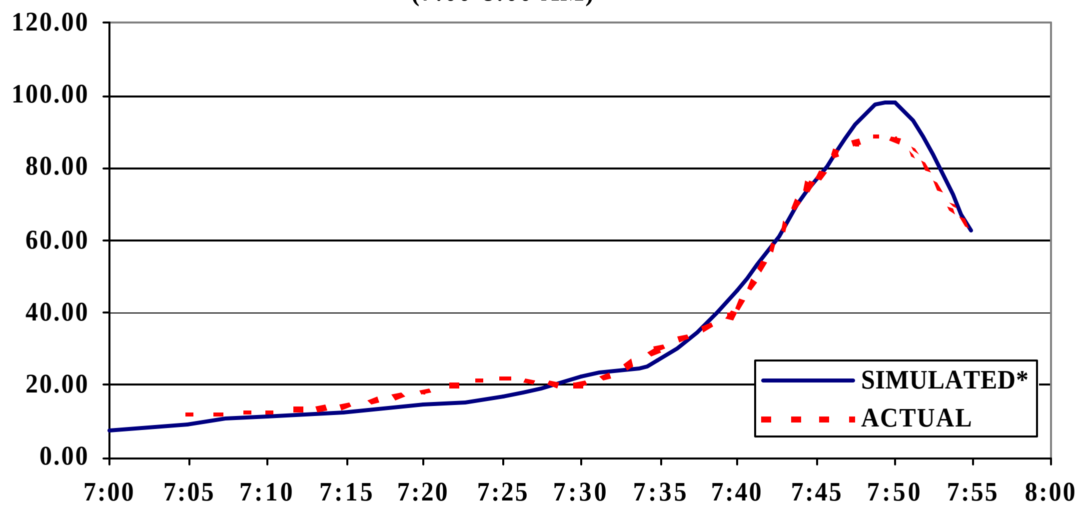
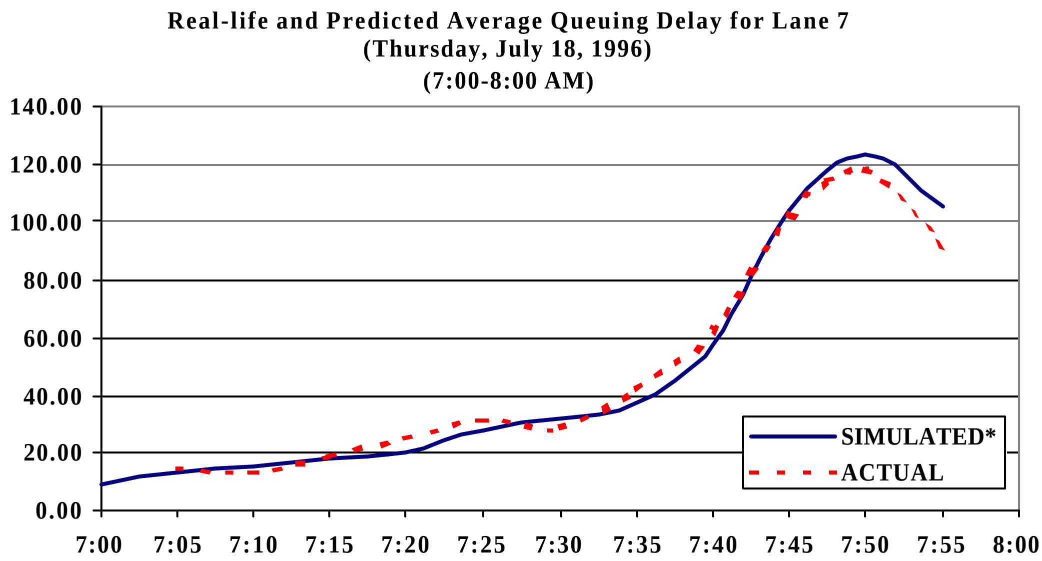
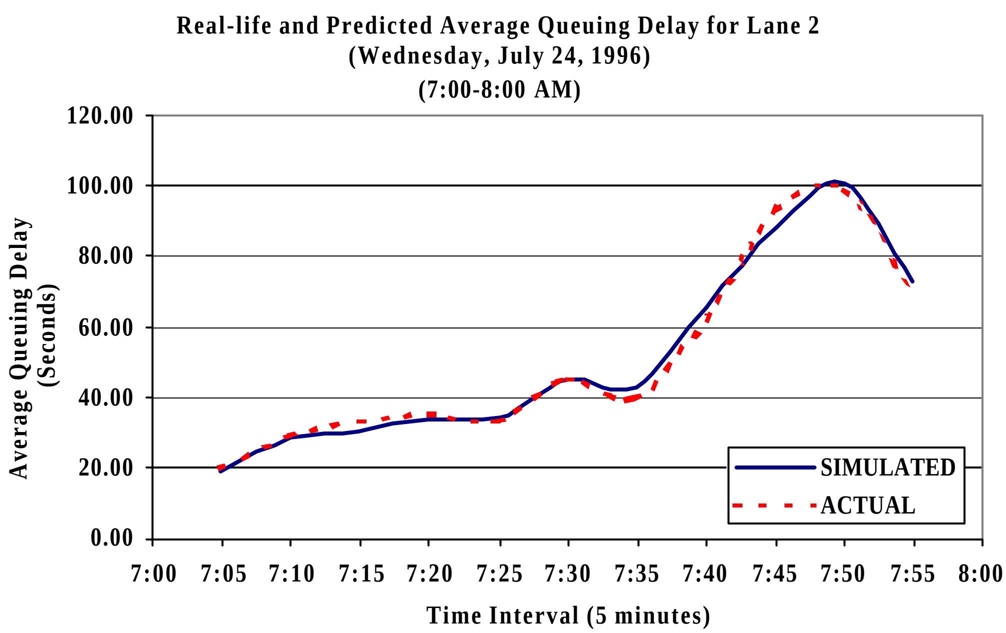
(7:00-8:00 AM)



* Based on averages of 10 runs





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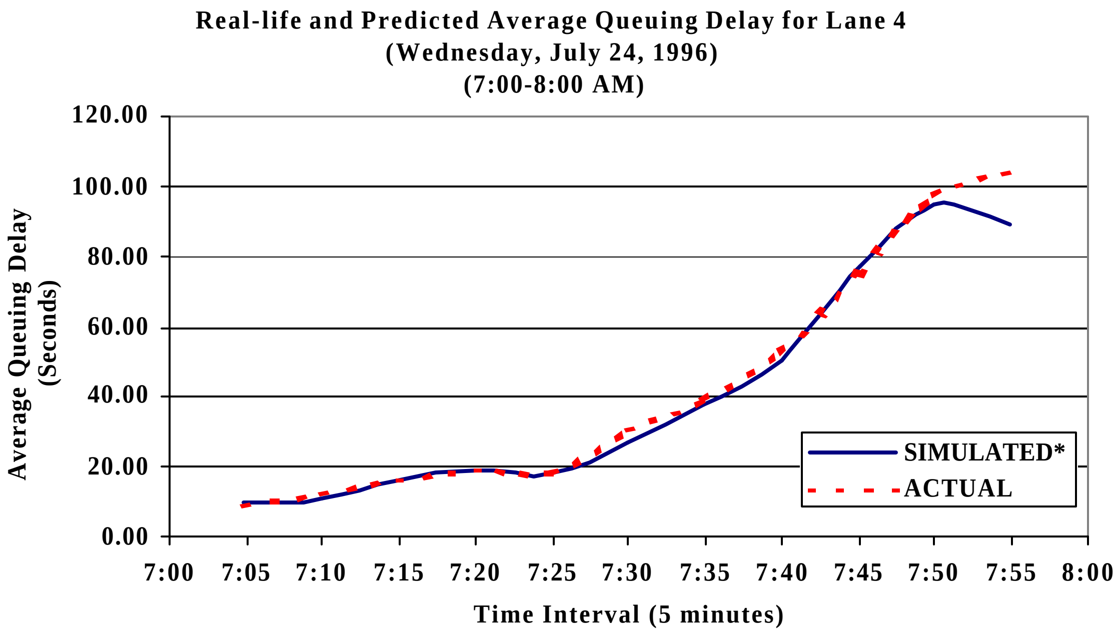
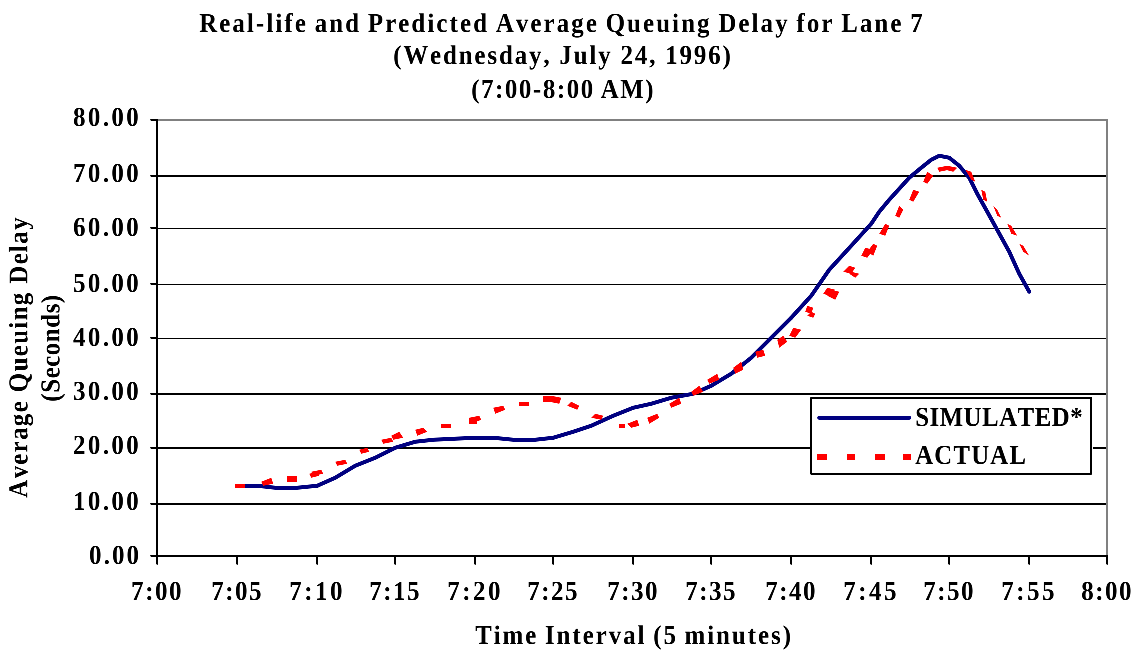
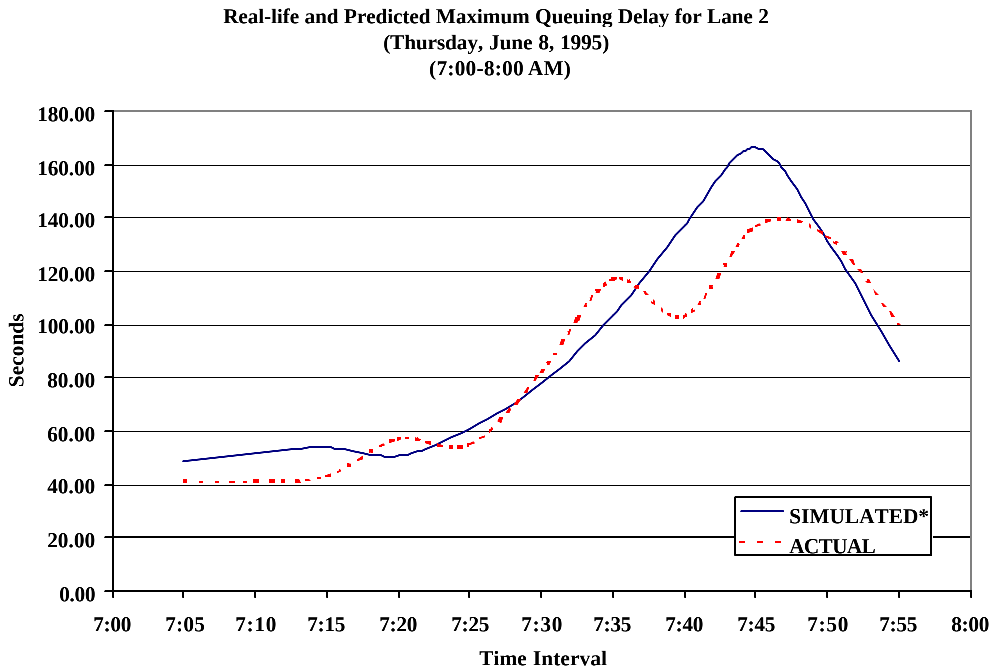
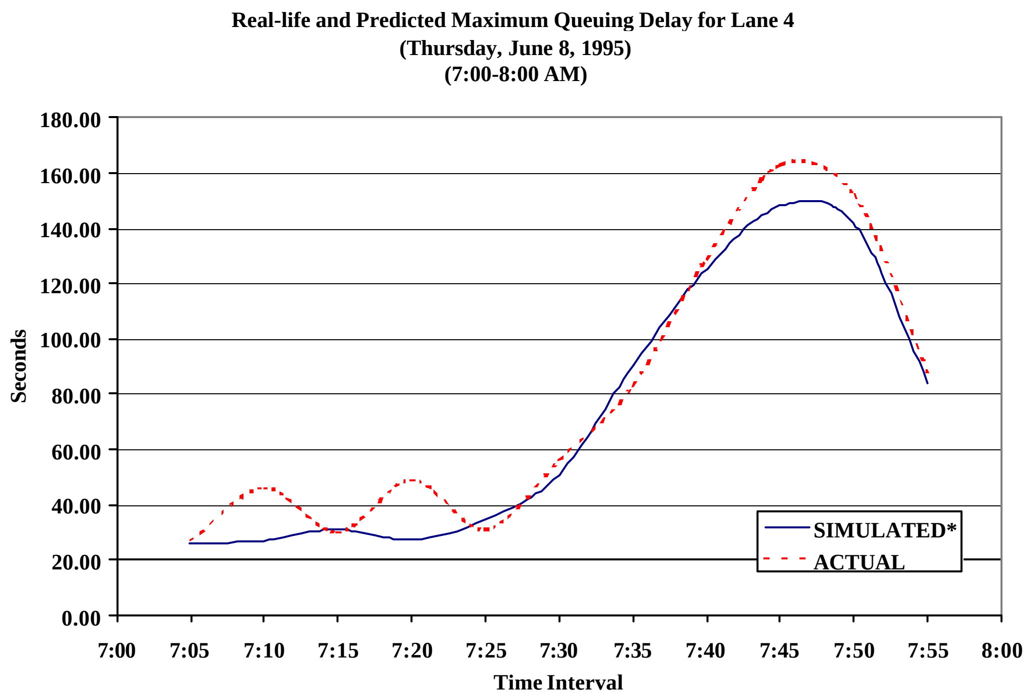




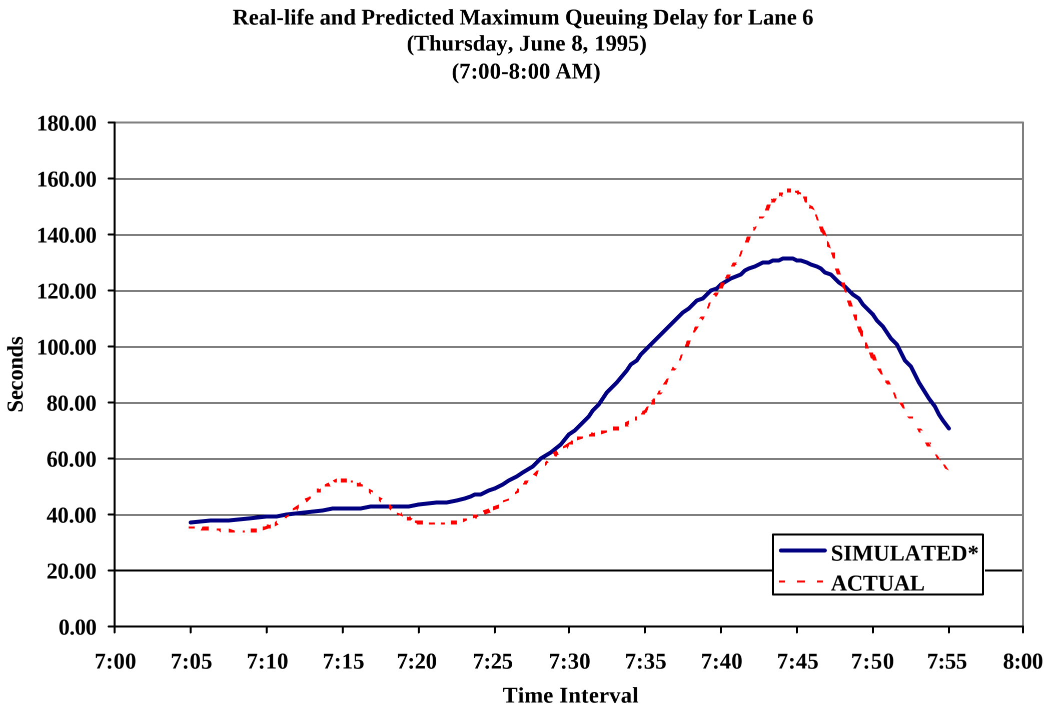
* Based on averages of 10 runs

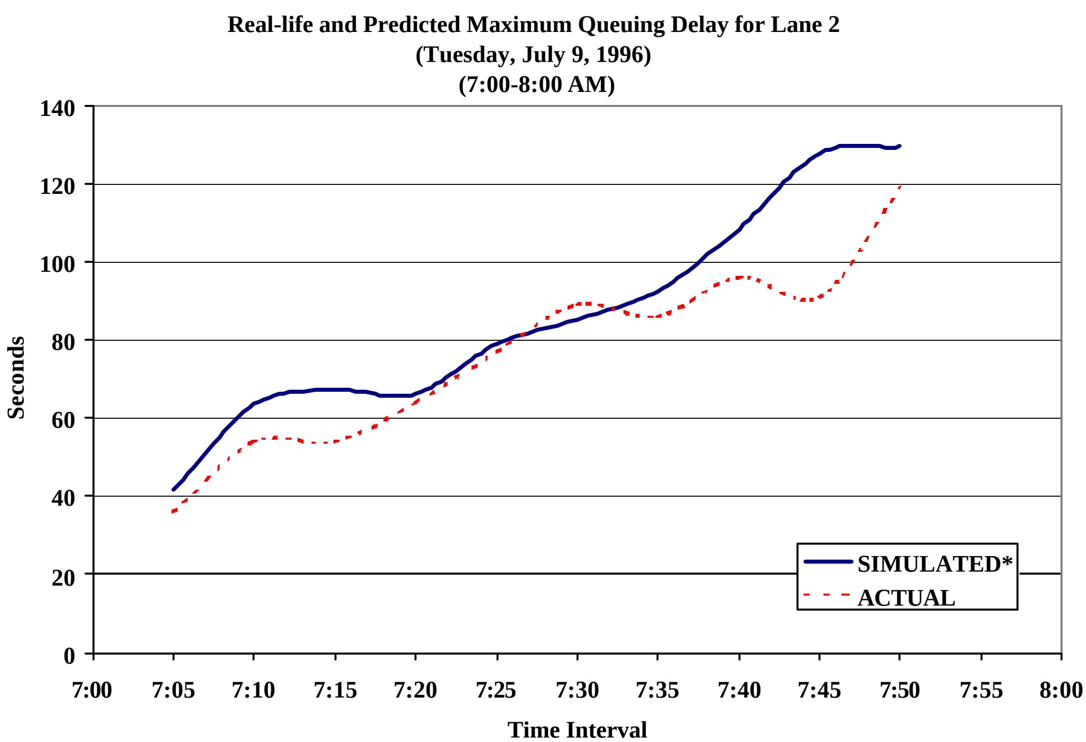
3- MAXIMUM QUEUING DELAY





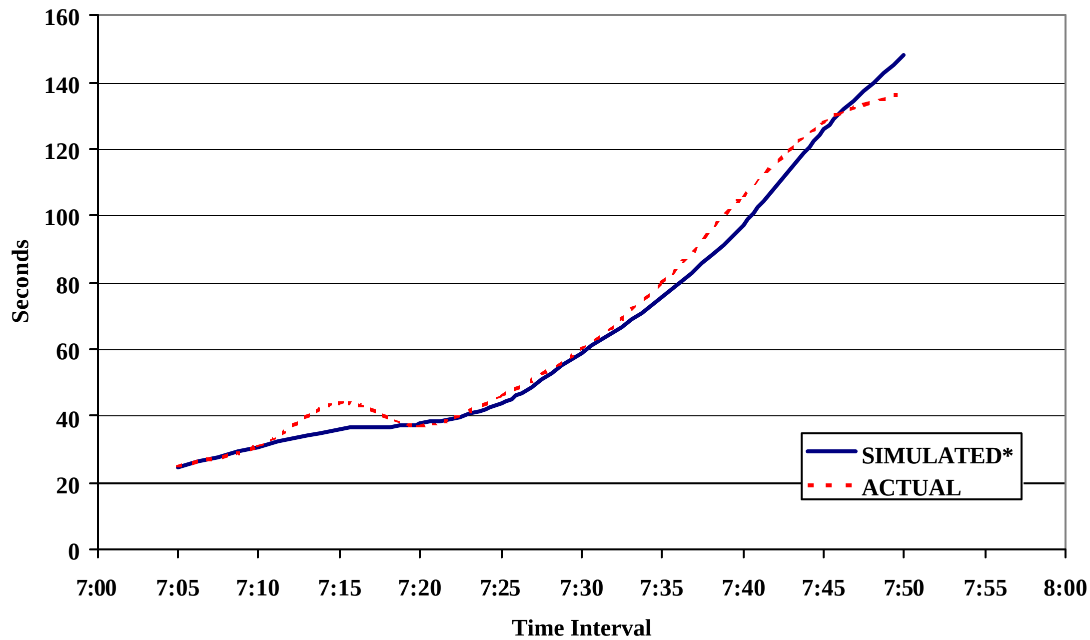
* Based on averages of 10 runs



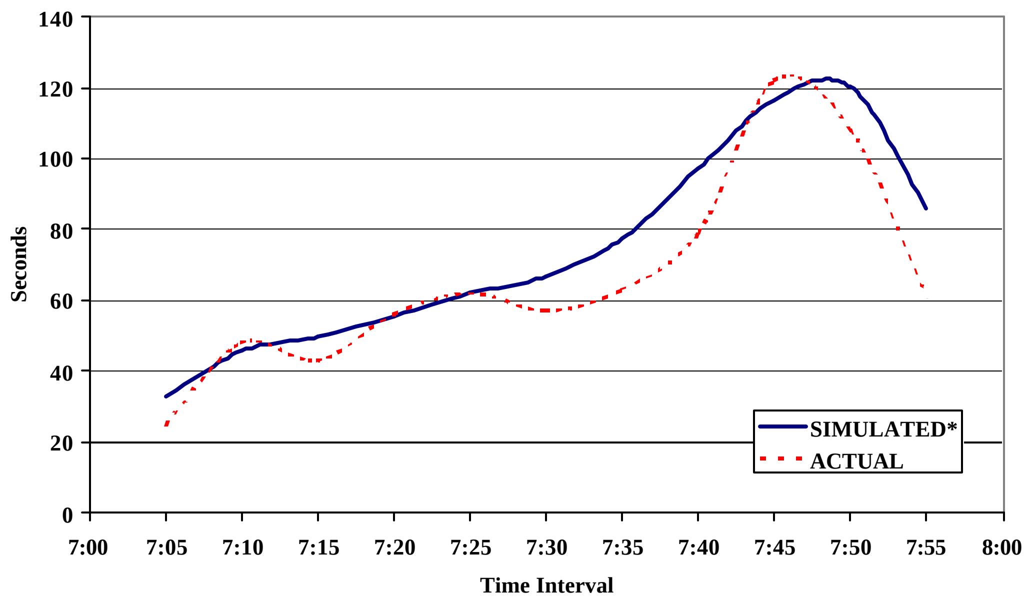


* Based on averages of 10 runs

Real-life and Predicted Maximum Queuing Delay for Lane 4
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

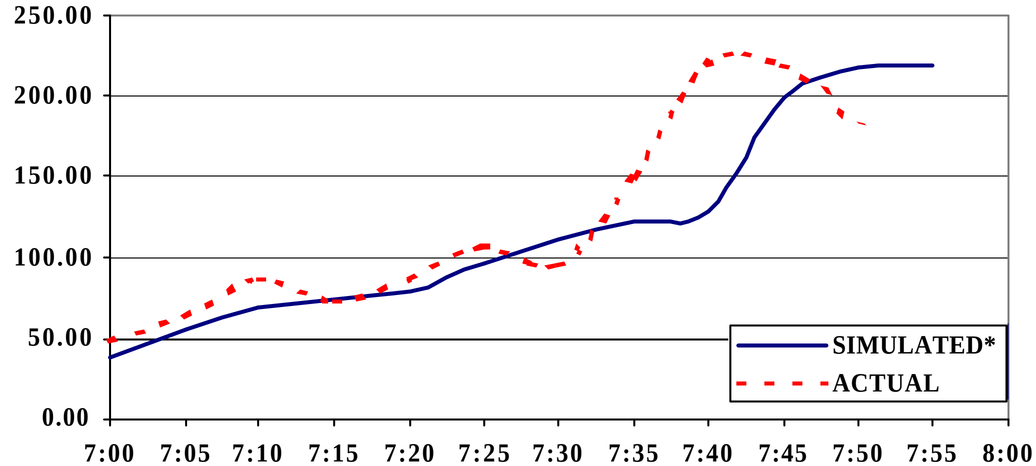


Real-life and Predicted Maximum Queuing Delay for Lane 7
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

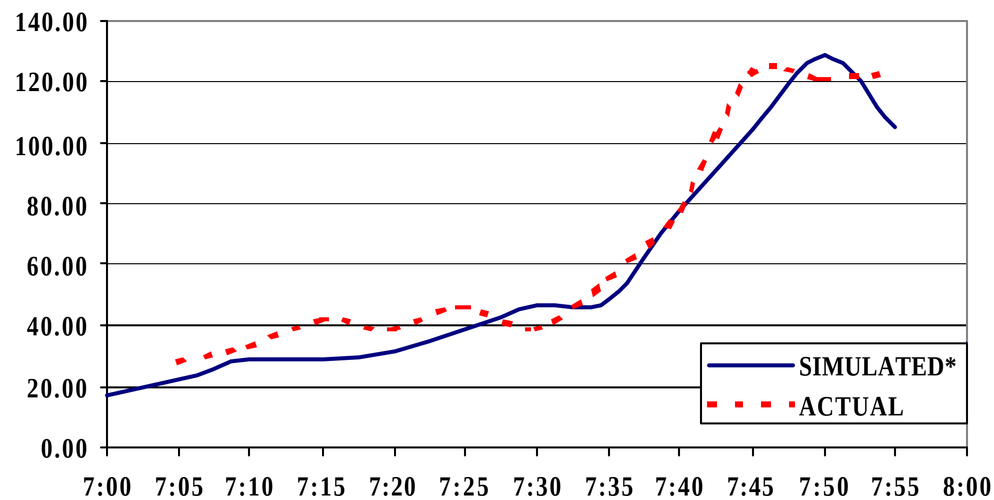


* Based on averages of 10 runs

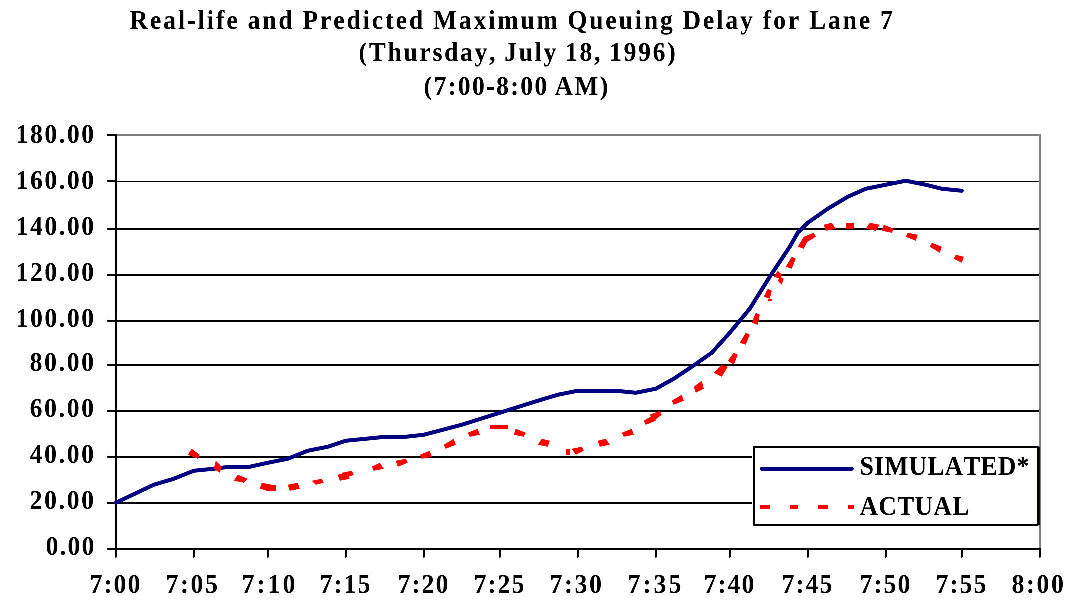
Real-life and Predicted Maximum Queuing Delay for Lane 2
(Thursday, July 18, 1996)
(7:00-8:00 AM)

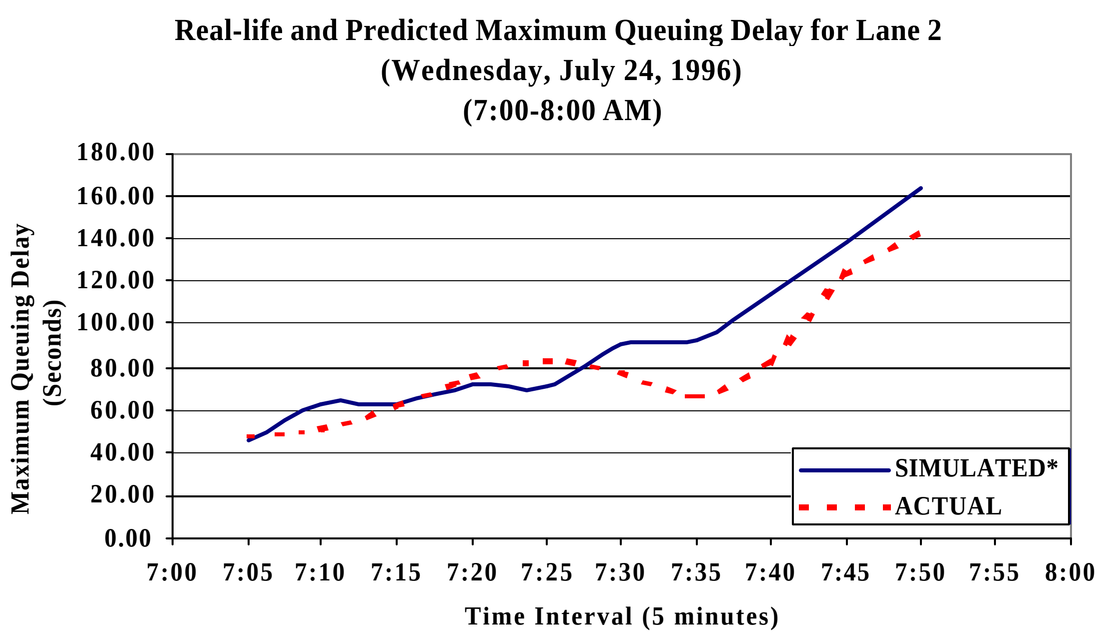


Real-life and Predicted Maximum Queuing Delay for Lane 4
(Thursday, July 18, 1996)
(7:00-8:00 AM)



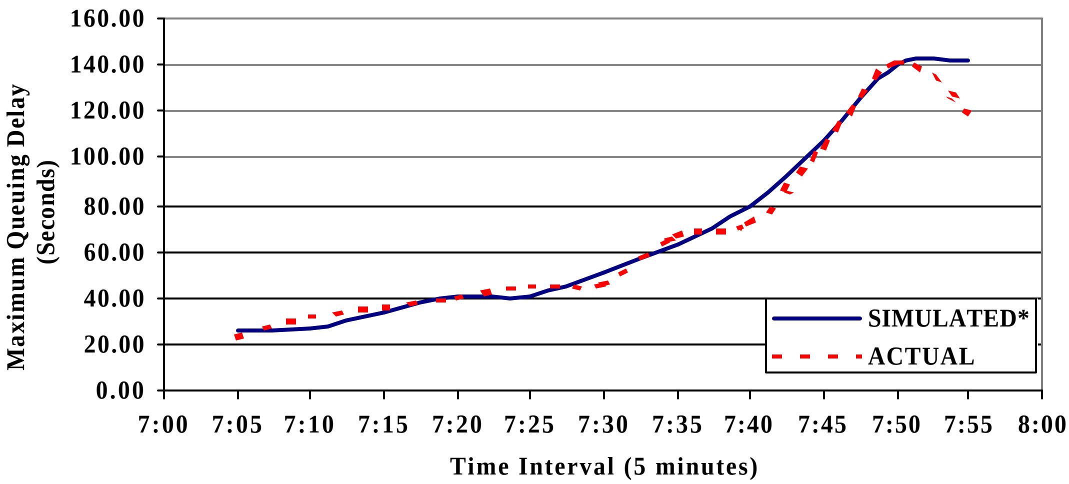
* Based on averages of 10 runs



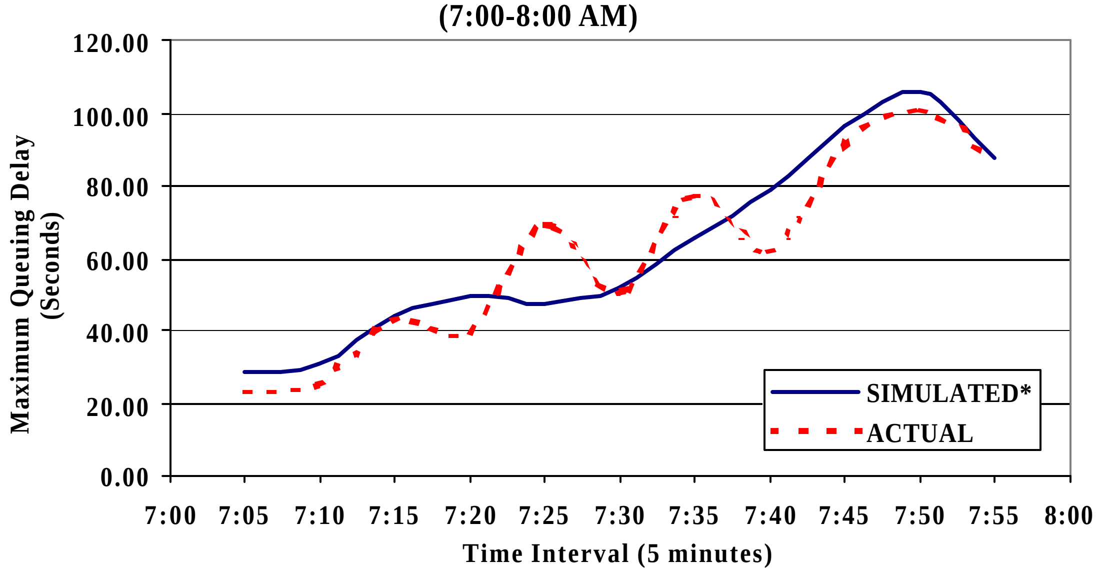


* Based on averages of 10 runs

Real-life and Predicted Maximum Queuing Delay for Lane 4
(Wednesday, July 24, 1996)
(7:00-8:00 AM)

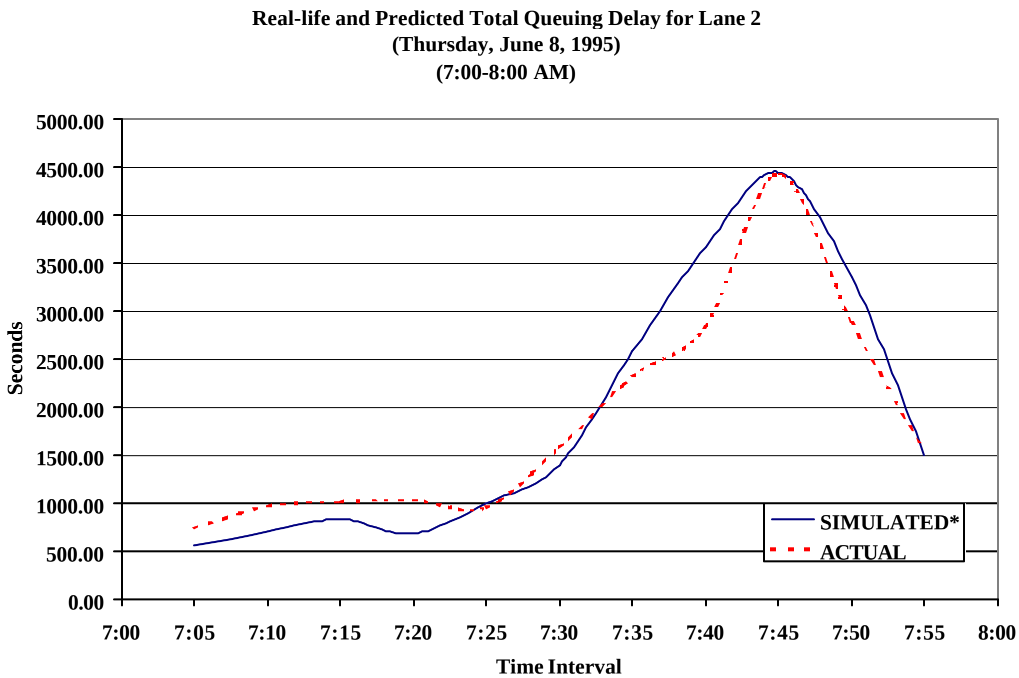


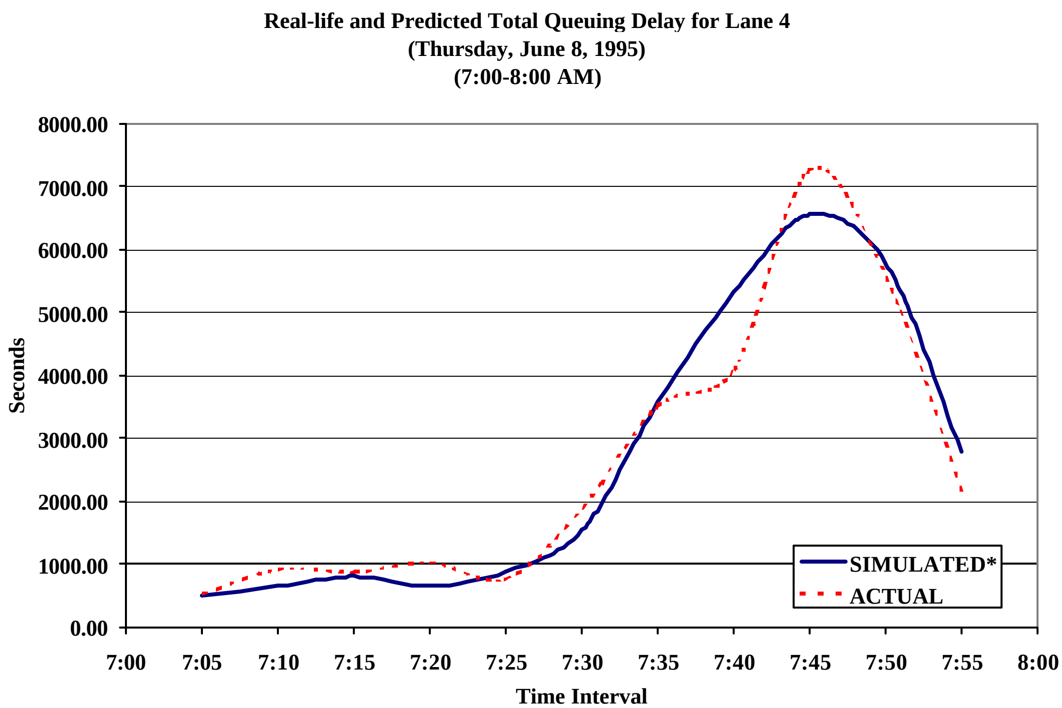
Real-life and Predicted Maximum Queuing Delay for Lane 7
(Wednesday, July 24, 1996)
(7:00-8:00 AM)



* Based on averages of 10 runs

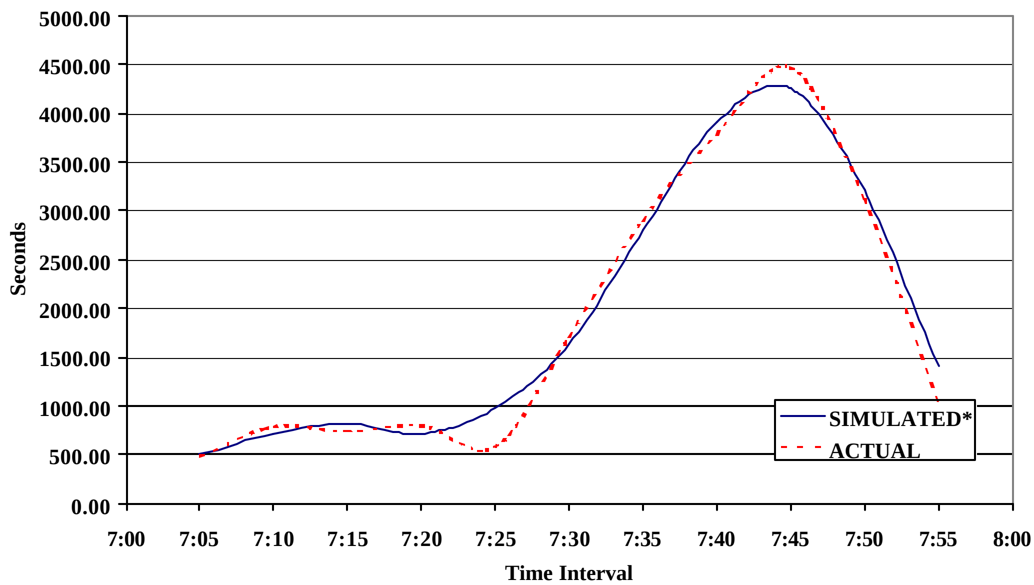
TOTAL QUEUING DELAY



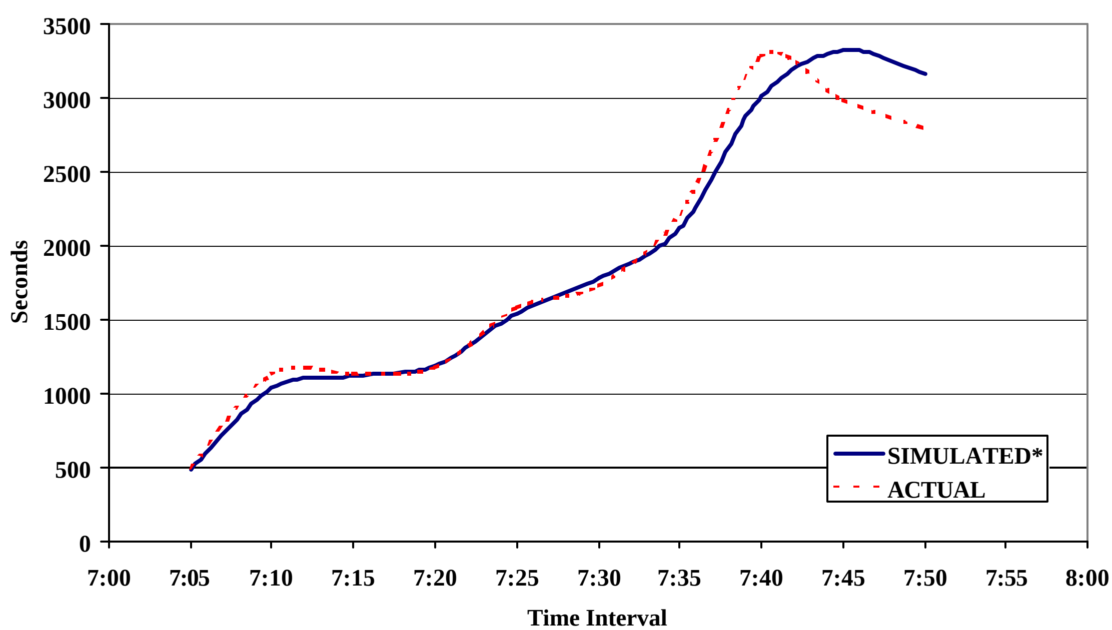


* Based on averages of 10 runs

Real-life and Predicted Total Queuing Delay for Lane 6
(Thursday, June 8, 1995)
(7:00-8:00 AM)

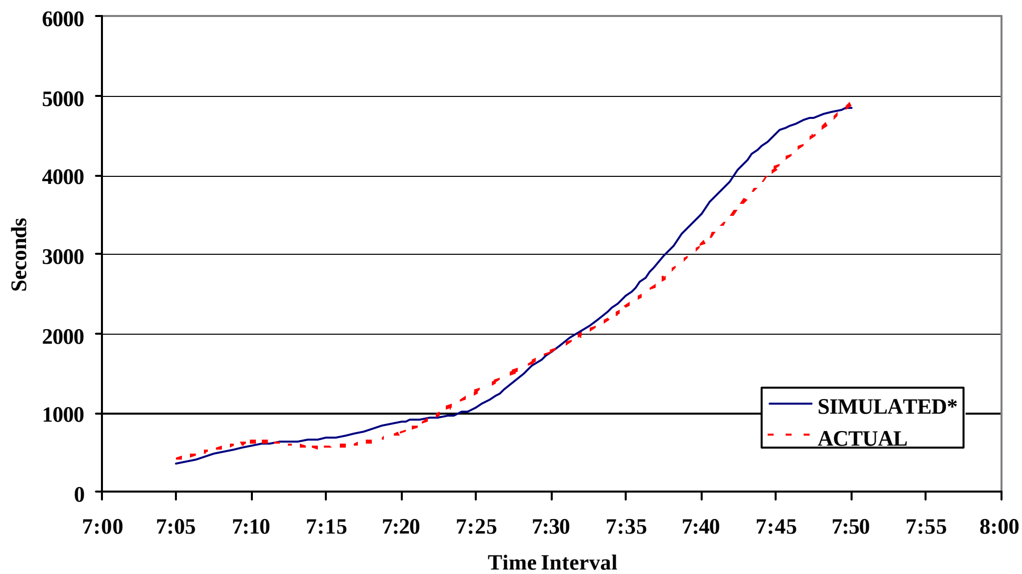


Real-life and Predicted Total Queuing Delay for Lane 2
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

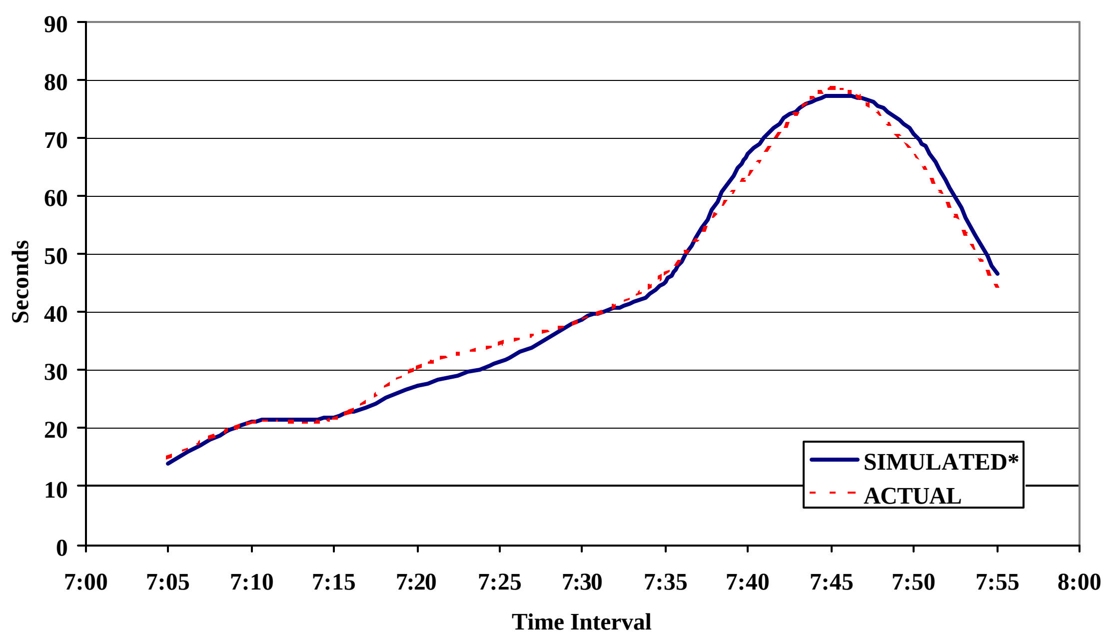


* Based on averages of 10 runs

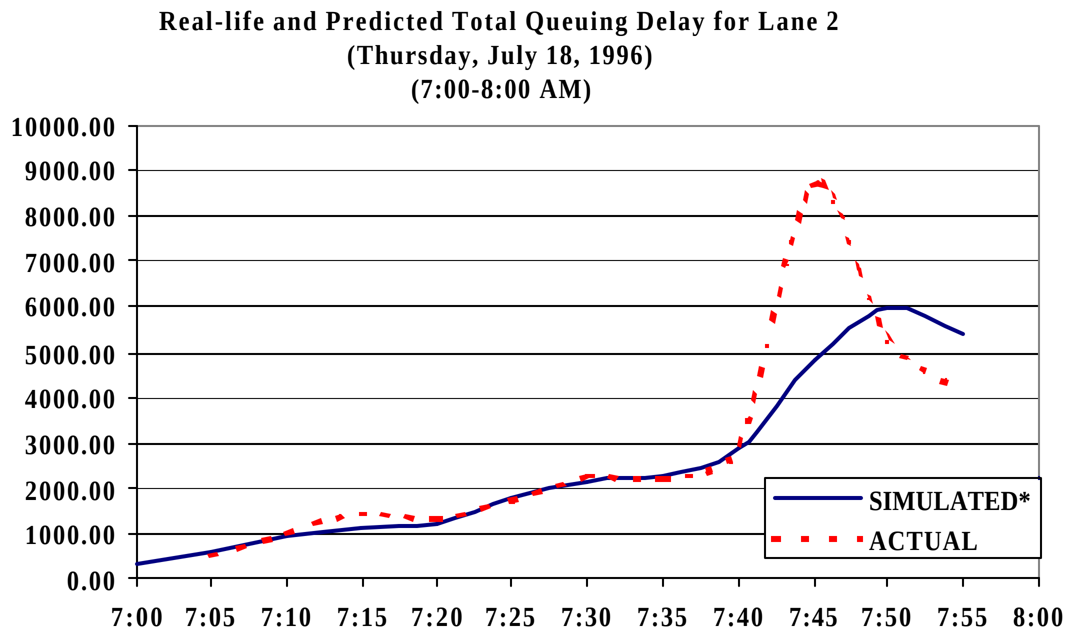
Real-life and Predicted Total Queuing Delay for Lane 4
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

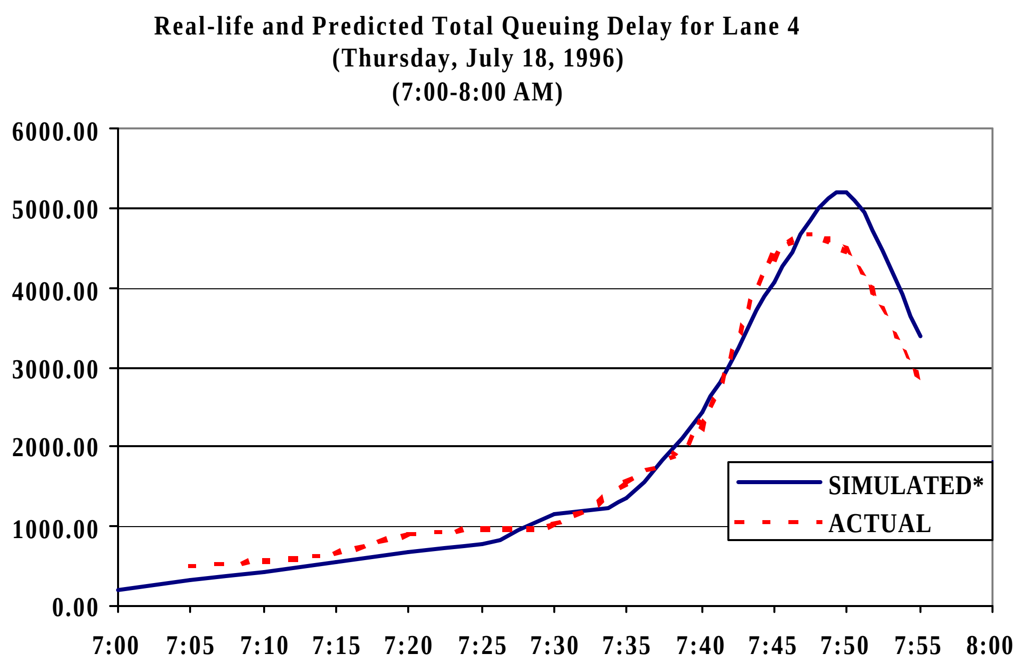


Real-life and Predicted Average Queuing Delay for Lane 7
(Tuesday, July 9, 1996)
(7:00-8:00 AM)

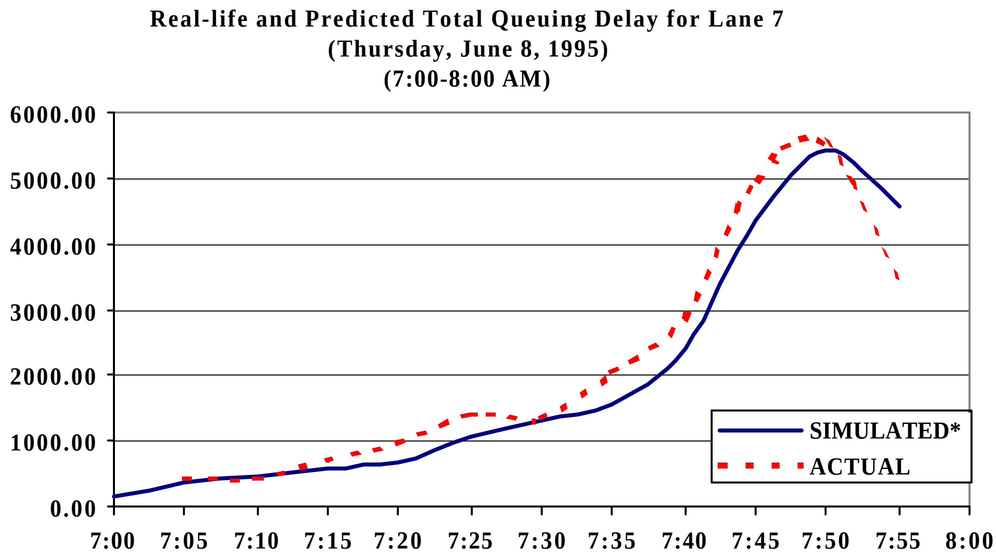


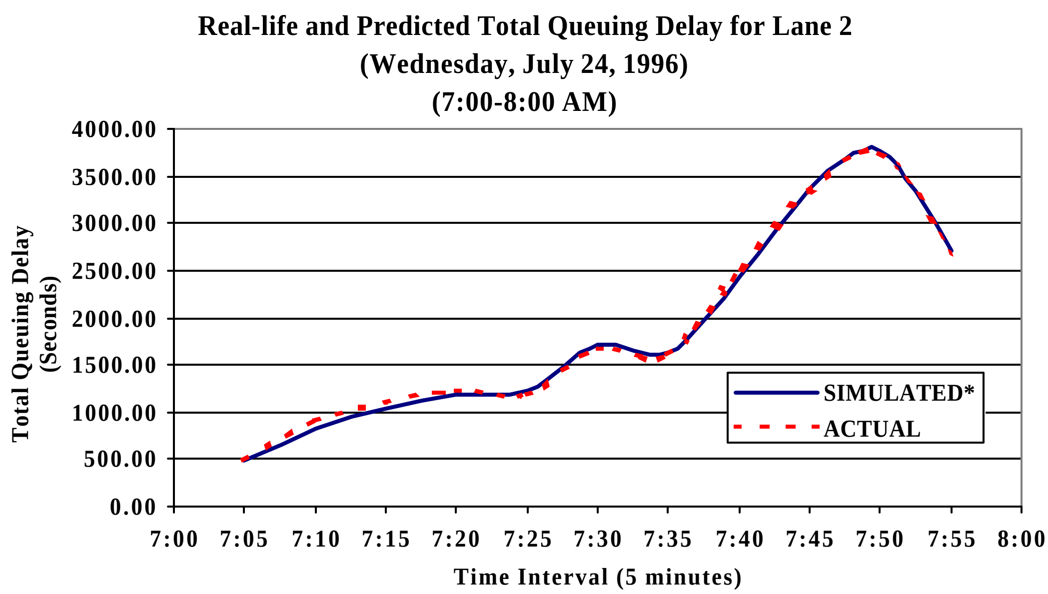
* Based on averages of 10 runs



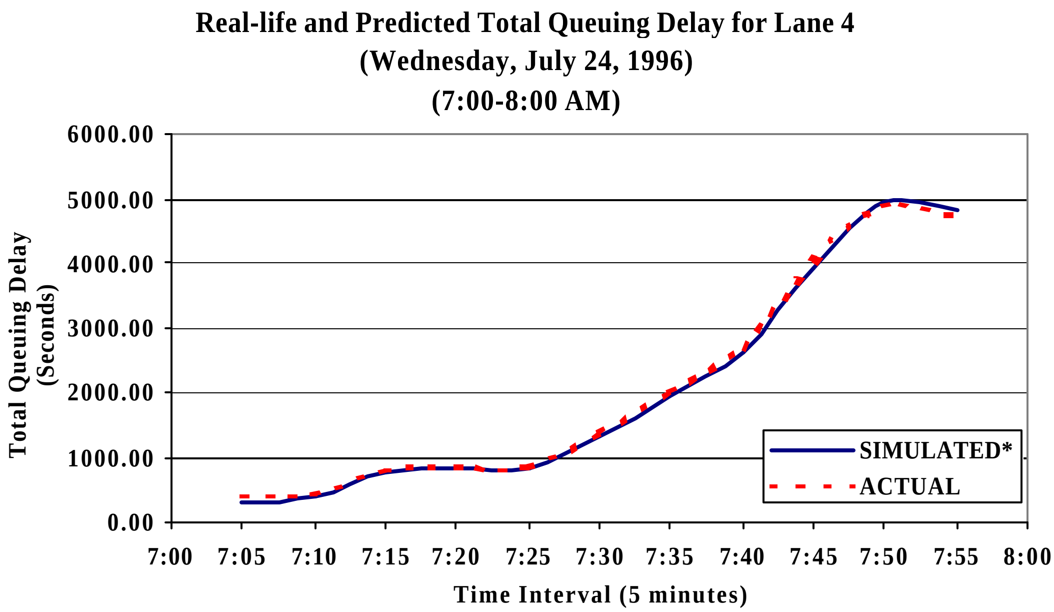


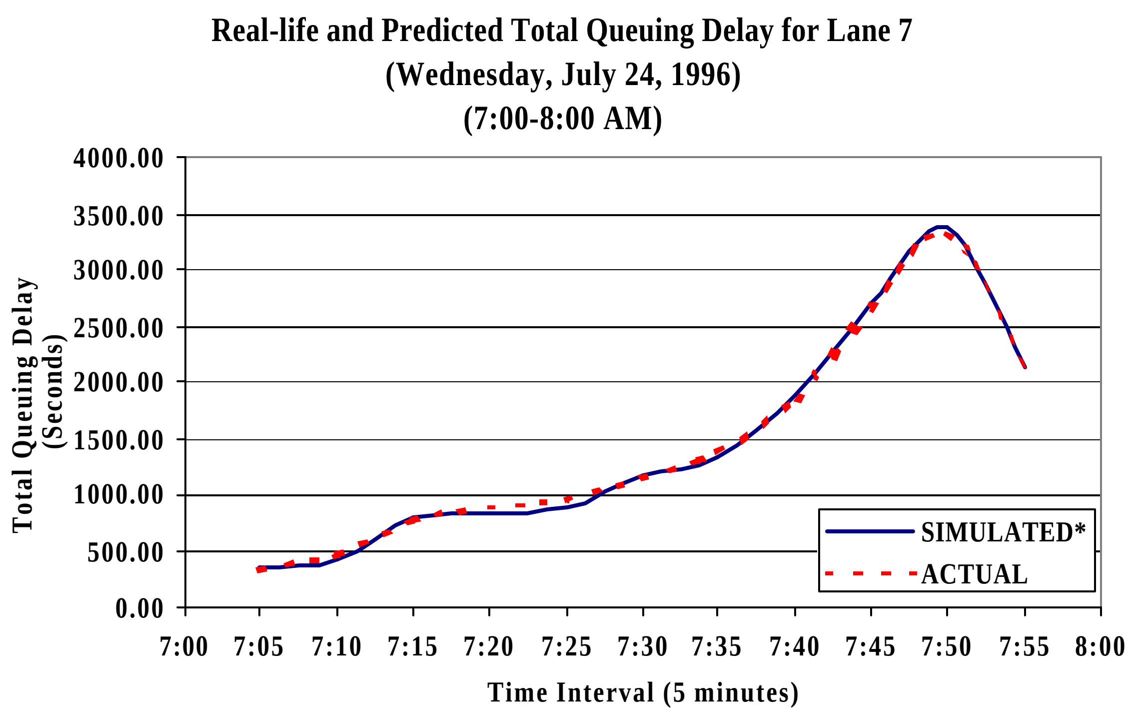
* Based on averages of 10 runs





* Based on averages of 10 runs





* Based on averages of 10 runs

REFERENCES

1. Schaufler A.E., "*NCHRP Synthesis of Highway Practice 240, Toll Plaza Design*", Transportation Research Board, TRB, National Research Council, Washington, D.C. 1997.
2. Al-Deek H. M, Mohamed A. A., and Radwan A. E.; "*Operational benefits of Electronic Toll Collection : Case Study*", ASCE Journal of Transportation Engineering, Vol. 123 No. 6, Nov/Dec 1997, pp. 467-477.
3. Gulewicz V. and Danko J. "*A Simulation Based Approach to Evaluating Optimal Toll Plaza Lane Staffing Requirements*"; Transportation Research Board Conference, Washington DC, 1995.
4. Rao L. and Owen L. E., "A Validation Procedure for Traffic Simulation Models", Presented at the 77th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1998.
5. Orlando-Orange County Expressway Authority (OOCEA), Year 2015 Projection Traffic Volume http://www.expresswayauthority.com/facts/2015.html, Accessed July 6, 1999.
6. Klodzinski J.G., Al-Deek H. M., and Radwan A. E.; "*Evaluation of Vehicle Emissions at an Electronic Toll Collection Plaza*", Presented at the 77th Annual Meeting of the Transportation Research Board, Washington, D.C., January 1998.
7. ASHTO, "*A Policy on Geometric Design of Highways and Streets*"; The American Association of State Highway and Transportation Officials (ASHTO), Washington, D.C., 1990.
8. Mendenhall, W., and Sincich T.: Statistics for Engineering and the Sciences. Prentice Hall,Inc., Englewood Cliffs, New Jersey, 1994