EVALUATION OF THE POTENTIAL BENEFITS TO TRAFFIC OPERATIONS AT A TOLL PLAZA WITH EXPRESS ETC LANES

by

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ABSTRACT

The effectiveness of modifying a conventional toll plaza for implementation of an open road tolling concept with express ETC lanes was evaluated in this thesis. Speed controlled dedicated ETC lanes were replaced with express ETC lanes at the Orlando-Orange County Expressway Authority (OOCEA) University Mainline Toll Plaza. This evaluation was accomplished by utilizing collected field data and simulated scenarios using Toll Plaza SIMulation (TPSIM) software developed by the University of Central Florida. The speed controlled dedicated ETC lanes were located within toll lanes (contained within a toll plaza canopy) with widths ranging between 10 to 14 ft. These types of lanes required all vehicles to reduce their speed from the highway speed to 35 mph. Express ETC lanes (sometimes referenced as open road tolling or non-stop tolling) allow vehicles to pass through the plaza at high speeds. Open road tolling is a concept that employs high speed toll lanes.

A before and after study of the University toll plaza was conducted. Benefits in the form of reduced delays and increased capacities were observed when making the comparison between the before and after studies. Since we expect the capacity of an express ETC lane to be greater than the dedicated ETC lanes (due to an increase in free-flow speed), further analysis using equations and car-following theory proved that if the ETC speed was increased, then the capacity would increase as well. Using equations derived from the Highway Capacity Manual (HCM) and car-following theory, the capacity was increased from 2016 to 2314 vph when the ETC speed increased from 31 mph to 65 mph. This indicated an increase in capacity of 14.8 percent (based on the conversion from dedicated to express ETC lanes).

The field data was also used as input for TPSIM (a computer simulation model) in order to perform a sensitivity analysis of the express ETC lanes by varying the type of ETC lane, number of approach lanes, and plaza configurations (the addition of an ACM lane) between scenarios. Results that were observed during the after study were verified using the TPSIM scenarios. Reductions in delays for the entire plaza were observed using the TPSIM model when making similar improvements to the plaza as in the after study.

The changes made to the University Mainline Toll Plaza after construction was completed resulted in benefits by reducing delays and increasing the capacity of the toll plaza (by converting dedicated ETC lanes to express ETC lanes and adding an additional A/ETC lane per direction). These benefits were measured using field data and confirmed when performing the TPSIM scenarios. A customer's travel time along the toll facility will be reduced by using the express ETC lanes (since they are not required to decelerate at the toll plaza). In addition, weaving maneuvers downstream of the plaza are no longer required by customers using the express ETC lanes due to the location of the downstream travel lanes in relation to the express ETC lanes. These benefits may have led to changes in the number and percentage of ETC users in each of the toll lanes. Changes in ETC usage in the conventional mixed-use lanes directly impacted the throughput and delays for each of these lanes, since ETC equipped vehicles have a service time of zero seconds. In addition to the operational benefits, other possible benefits for express ETC lanes were identified and recommended for further evaluation and research. The re-distribution of customers at the plaza due to the implementation of open road tolling, in the form of express ETC lanes, was a great benefit to the overall traffic operations for the University Mainline Toll Plaza in Orlando, Florida.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A/ETC	Automatic Coin Machine toll lane equipped with ETC capability
ACM	Automatic Coin Machine toll lane
AETC	Automated Electronic Toll Collection
AVI	Automatic Vehicle Identification
ETC	Electronic Toll Collection
ETTM	Electronic Toll collection and Traffic Management
ITS	Intelligent Transportation Systems
M/ETC	Manual toll lane equipped with ETC capability
MOE	Measure of Effectiveness
OOCEA	Orlando Orange County Expressway Authority
ORT	Open Road Tolling

CHAPTER ONE: INTRODUCTION

The City of Orlando and surrounding areas comprise one of the fastest growing regions in the United States and it was estimated that 1.49 million people lived in the Orlando Metropolitan Area in 2001 (Metroplan 2002). The Orlando Metropolitan Area is located in east Orlando and includes Orange, Seminole, and Osceola counties. The overall population in the area (the three-county area) increased from 1,072,748 in 1990 to 1,434,033 in 2000 (which was a 33.7 percent increase) (Caskey 2002). The overall population grew to 1,487,587 in 2001, which indicates an increase of 3.7 percent between 2000 and 2001 (Metroplan 2002).

From 1997 to 2001, the population of the Orlando metropolitan area increased by 15.8 percent. During the same time period, the number of registered vehicles increased by 23.9 percent and the number of vehicle miles traveled (VMT) increased by 37.1 percent. From 1995 to 2000, the traffic congestion in the area increased by 24.7 percent (Metroplan 2002). This population growth resulted in more traffic congestion on central Florida's roadways. New and innovative transportation solutions are necessary to reduce the impact of this congestion to motorists.

Transportation planners and engineers, through the implementation of Intelligent Transportation Systems (ITS), seek to make existing transportation facilities such as toll roads more efficient by increasing capacity and decreasing the delays experienced by drivers. One of the technologies being used is electronic toll collection (ETC) (Al-Deek 1996a, 1996b, 1999, Al-Deek 2001a). ETC utilizes automatic vehicle identification (AVI) technology to identify and confirm vehicles uniquely. This allows these AVI-equipped vehicles to pass through the plaza and automatically pay tolls without being required to stop.

The Orlando-Orange County Expressway Authority (OOCEA) highway network includes eleven mainline toll plazas. The five types of toll plaza lane transactions currently in use on the OOCEA system include the following (Pietrzyk 1994):

- Manual (conventional type with toll attendant)
- Automatic Coin Machine (conventional type)
- Mixed Conventional with ETC
- Dedicated ETC (permits ETC patrons only with a reduced speed limit)
- Express ETC (permits ETC patrons only at higher free-flow speeds)

Conventional toll lanes require all drivers to stop at the plaza and tolls are paid manually to either a machine or toll attendant. Mixed ETC lanes combine ETC capability with either manual or automatic service thus providing additional lane selection for ETC users. Dedicated ETC lanes do not provide service for conventional toll collection and are positioned as the center lanes of the mainline toll plazas. Express ETC lanes can be physically separated (i.e. barrier) from the other types of lanes and allow vehicles to drive at free-flow speeds (55 mph or more).

Prior to May 1994, ETC technology was not in use at any of the OOCEA facilities. By March 1995, all lanes at each of the OOCEA plazas were equipped with the ETC technology, known as E-PASS, in the form of mixed ETC lanes. Gradually, some of these ETC lanes were converted from mixed ETC lanes to dedicated ETC lanes and the timing of conversion was usually based on E-PASS usage levels (OOCEA 2002). The number of E-PASS transponders in use during 1997 was 125,943 (Metroplan 2002). In 2001, the E-PASS usage grew to 309,942, which was an increase of 146.1 percent. Initially, the ETC systems were added to improve accountability for revenue collection, save operating costs and increase capacity but other benefits have been measured and quantified in prior research (Al-Deek 1996a, 1996b, 1999; Worrall 1999). Although gates were originally used at dedicated ETC lanes to reduce and/or eliminate toll violations, it was found that gates have an impact on the capacity of dedicated ETC lanes. Therefore, gates were eliminated on all toll lanes and speed limits were imposed at dedicated ETC lanes (Worrall 1999). In addition, cameras were also employed to help prevent toll violations.

A new E-PASS system compatible with the SunPass (FDOT Turnpike) system was implemented in December 2001 and uses windshield mounted transponders. This enables travel throughout the state using the same transponder (OOCEA 2002). Express E-PASS lanes were first implemented on the OOCEA highway network at the Forrest Lake Mainline toll plaza (Pustelnyk 2000). This plaza is located on State Road 429, which was opened in July of 2000 and provides two express ETC lanes in each direction. E-PASS customers remain on the mainline highway and conventional payment customers exit to the right and use a traditional toll plaza. Then, after paying the toll, the toll patrons return to the mainline highway.

During the next decade, OOCEA has planned to incorporate express ETC lanes at all eleven of the mainline toll plazas (OOCEA 2002). OOCEA has already completed construction at the University Mainline toll plaza to incorporate express ETC lanes and make other improvements near the plaza. A study was initiated to evaluate the improvements that were done at this plaza.

CHAPTER TWO: PROBLEM STATEMENT

Traffic volumes are increasing on roadways and it is becoming very costly to continue adding additional toll lanes to meet increasing traffic demands. Some toll facilities have identified the fact that plaza problems on toll roads cannot be solved simply by constructing more toll lanes (Miller 1995). Some toll plaza authorities are in the process of replacing dedicated ETC lanes with express ETC lanes.

There is an inherent delay associated with dedicated ETC lanes, since vehicles are required to reduce their speed before traveling through the plaza. This reduced speed is a source of travel time delay for each vehicle. The reduced speed is required since these dedicated ETC lanes utilize traditional toll lanes that have lane widths of 10-14 feet. Express ETC lanes will not cause any delay to vehicles since they will be allowed to travel at highway speeds and will not have to reduce speed when traveling through the toll collection points, as is the case with dedicated ETC lanes.

Although prior research has been performed to analyze toll plazas with dedicated ETC lanes, further research is required to analyze the performance of express ETC lanes. In addition, there is a need to perform a sensitivity analysis of the express ETC lanes by isolating factors such as number of freeway approach lanes or number of conventional lanes adjacent to the express lanes.

CHAPTER THREE: RESEARCH OBJECTIVES

The objectives of this research include the following:

1. Conduct a before and after study of a mainline toll plaza (in which dedicated ETC lanes are being replaced by express ETC lanes).
2. Evaluate measures of effectiveness to determine what benefits are realized from implementation of express toll lanes.

In addition, the before study data will be used as input in order to conduct a sensitivity analysis of the express toll lanes using TPSIM, a traffic simulation model. The field data will also be used to verify the results of the TPSIM model. The following factors will be isolated and used to evaluate the performance of the express toll lanes:

1. The number of highway approach lanes.
2. Toll plaza configuration (number of ACM lanes).
3. ETC lane type.

Since construction of additional highway lanes (in both directions) and additional toll lanes (one ACM lane per direction) occurred at the same time as implementation of express ETC lanes at the study site, isolating the above factors in the simulation will be important. Without isolating these factors, the results of the analysis could not be attributed to adding express ETC lanes alone. The purpose of this research is to determine the benefits of using express ETC lanes.

CHAPTER FOUR: LITERATURE REVIEW

In 1981, Foote (Foote 1981) indicated that non-stop toll collection could increase the capacity of a conventional toll lane from 600 vehicles per lane-hr to approximately 1800 vehicles per lane-hr. Non-stop toll collection can decrease construction, maintenance and operating costs of tollbooths and motorists will see benefits in time, fuel and convenience. In addition, noise and air pollution could be reduced. The idea behind non-stop toll collection is to allow drivers to travel through the facility at highway speed. During periods of continuous high-speed operation, the capacity of each AVI lane would approach that of a regular traffic lane.

According to Pietrzyk, the average capacity for the different toll plaza lane types are as follows (Pietrzyk 1994):

- Manned – 350 veh/hr
- Automatic – 500 veh/hr
- Mixed AVI – 700 veh/hr
- Dedicated AVI – 1200 veh/hr
- Express AVI – 1800 veh/hr

These average capacities for non-dedicated AVI lane types were derived from individual capacity data records provided by toll agencies including the Florida Turnpike, New Jersey Turnpike, and the Dallas North Tollway. The estimated average capacities for the dedicated and express AVI lanes were based on average speeds and vehicle spacing (headways).

Benefits of electronic toll collection have been documented in numerous publications including those by Al-Deek et al. (Al-Deek 1996b, 1997a, 1997b). For example, service times, vehicle arrival times, departure times, and vehicle counts were collected before and after installation of a dedicated E-PASS lane at the Holland East Plaza, which is the largest and busiest of all plazas in the OOCEA network (Al-Deek 1997a, 1997b). The following improvements were observed for the dedicated E-Pass lane:

- The measured capacity increased by a factor of three
- Service time decreased by five seconds per vehicle
- Average queuing delay decreased by one minute per vehicle
- Maximum queuing delay decreased by 2.5-3 minutes per vehicle
- Total queuing delay decreased by 8.5-9.5 vehicle-hours per morning peak hour

Although the capacity, headway, and service times of the remaining mixed lanes did not change significantly, the overall traffic operations for the plaza were improved because vehicles shifted from the mixed lanes to the dedicated E-Pass lane.

In December, 1997, a model called the Toll Plaza Model (or TPModel) was used to estimate and predict the operational performance of the Holland East Plaza (Al-Deek 1997c). The simulation model was programmed in Visual Basic 5.0 and was used to analyze traffic operations at the Holland East Plaza during the following stages of E-Pass implementation:

- No E-Pass lanes
- Mixed E-Pass lanes
- One dedicated E-Pass lane
- Two dedicated E-Pass lanes

Performance was compared to the percentage of E-Pass usage and timing of when to implement the different lane configurations. This report recommended further enhancement of the simulation model so that it could be used at the other eleven OOCEA plazas. This simulation model could be used as a convenient decision tool for deciding when to implement additional E-Pass lanes at a toll plaza.

A new model for evaluating traffic operations at plazas with electronic toll collection was introduced in 2000 (Al-Deek 2000a, 2000b; Mohamed 2000). The Transportation Systems Institute at the University of Central Florida, Orlando, developed a Toll Plaza SIMulation model called TPSIM. TPSIM is a stochastic object oriented discrete-event microscopic simulation model that was coded using Microsoft Visual Basic 6.0 and interfaces with Windows98/NT. Toll plazas with up to 5 approach lanes and up to 10 toll lanes in each direction can be modeled using TPSIM. The model contains algorithms for car-following, lane-changing, and toll-lane selection and provides output for measures of effectiveness (MOE) which include throughput, average queuing delay, maximum queuing delay, and total queuing delay.

Simulation and evaluation of the Holland East Plaza was performed using TPSIM and a report was produced in April 2000 (Al-Deek 2000b). Real-life data was collected at the busiest toll plaza in the OOCEA system and was used to validate the simulation model. Statistical tests verified that there was no significant difference at the 95% confidence interval between the measures of effectiveness obtained from the model and those collected in the field. In addition, a sensitivity analysis of market penetration of the E-Pass system was performed.

A similar evaluation using TPSIM was presented in July 2001 in which the transferability of the simulation model was tested on the Dean Mainline Toll Plaza (Al-Deek 2001a, Klodzinski 2002a). Three separate days of data were collected and used to validate the model. Input parameters were identified and the model was calibrated using a specific experimental design. Although the calibration parameters that were developed for the Dean plaza are not directly applicable to any other toll plaza, the calibration results could be used as initial calibration values for a plaza with similar characteristics. Measures of effectiveness were also tested at a 95% confidence level for the model results and results measured in the field. This analysis proved that the TPSIM computer model could be used to model other toll plazas.

Field data that was collected by Zarrillo for a paper submitted during the 79th TRB Annual Meeting presented processing rates for different customer-groups at the Holland East Plaza and Interchange 11A, located on the Massachusetts Turnpike 90 (Zarillo 2000). Eleven customer-groups were identified and below is a summary of the customer-groups (and associated processing rates) that are common to the OOCEA toll facilities:

1. (M) Manual service, can process 8.3±0.8 veh/min (498 ± 48 vph).
2. (ACM) Automatic Coin-Machine Service lanes (no semi-trucks permitted and no gate present), can process 10.3±0.5 veh/min (618 ± 30 vph).
3. (T) Manual service consisting of drivers of semi-Trucks, can process 2.3±1.3 veh/min (138 ± 78 vph).
4. (E15) ETC Service using AVI technology to automatically record the toll amount and drivers are limited to speed limits of 15 mph, can process 15.0±2.0 veh/min (900 ± 120 vph).
5. (E35) ETC with drivers limited to speed limits of 35 mph, can process 23.0±2.0 veh/min (1380 ± 120 vph).
6. (E55) ETC with drivers limited to speed limits of 55 mph, can process 32.0±2.0 veh/min (1920 ± 120 vph).

The Forrest Lake Main Toll Plaza on State Road 429 was opened in July 2000 and was the first toll plaza in Florida to feature open road tolling. Open road tolling will allow E-PASS customers to pass through the toll collection point at highway speed without having to stop at a toll plaza. According to the US DOT website, open road tolling is defined as “Fully automated electronic tolling in an open road environment allowing vehicles to travel at normal speeds when passing through toll collection points”. All of the Expressway Authority’s toll plazas are scheduled to feature open road tolling by 2007 (OOCEA 2002).

CHAPTER FIVE: METHODOLOGY

The following steps for methodology were used while performing research for this project:

- Study Site Selection
- Data Collection
- Before Study
- After Study
- Before and After Studies Comparison
- Analysis of Express ETC lanes
- TPSIM Calibration
- TPSIM Scenarios
- Conclusions

5.1 Study Site Selection

The selected study site is the University Mainline Toll Plaza. This plaza is one of eleven mainline toll plazas that are owned and operated by OOCEA. In 1998, E-Pass usage at the plaza was more than 53% (Pustelnyk 1998). The growth in E-Pass usage during the peak AM hour was recorded from October 2000 through September 2001 and this information was collected by the OOCEA. The transaction data indicated the following for the peak hour E-Pass usage at the University Mainline Toll Plaza (OOCEA 2002):

- 63.9% for 2-Hour peak 2-Way
- 65.0% for 1-Hour peak 2-Way
- 67.8% for 1-Hour peak 1-Way

Data was collected weekly (typically Wednesdays) beginning on October 4, 2000 and ending on October 3, 2001. Information for the average annual weekday traffic (AAWT) was also obtained from OOCEA and below is a summary of the AAWT (OOCEA 2002):

- 1996 – 37,300
- 1997 – 38,730
- 1998 – 44,610
- 1999 – 49,900
- 2000 – 53,240
- 2001 – 55,790

These numbers indicate that the overall growth of traffic volume between 1996 and 2001 was 49.6 percent. More traffic is traveling in the southbound direction during the peak AM time period. The opposite is true during the peak PM time period.

The University Mainline toll plaza is located south of University Boulevard (northeast of downtown Orlando) on the Central Florida Greenway (SR 417). Construction has been completed at this plaza and the purpose of the project was to increase cash lane capacity and add express ETC lanes. Construction occurred during heavy traffic conditions and work was scheduled into five different phases (Pustelnyk 2000). At the end of construction, two express ETC lanes were provided in each direction of travel at the University plaza. The University plaza was the second plaza owned by OOCEA to provide express ETC lanes to E-PASS users. Another facility, the Forrest Lake Mainline Toll Plaza on SR 429, was the first to offer express

ETC lanes on the OOCEA network. The following paragraphs include information regarding the before and after study configurations of the plaza.

The before configuration of the University Mainline Toll Plaza consisted of 4 manual lanes, 2 ACM/E-Pass lanes and 2 dedicated E-Pass lanes. Two highway lanes (both directions) were provided south of the plaza and three highway lanes (both directions) were provided north of the plaza. During morning periods, the peak traffic volume was observed to be traveling southbound, towards downtown Orlando. Two manual lanes, one ACM lane, and two E-Pass lanes were provided in the southbound direction during the AM peak time period. The two middle dedicated E-Pass lanes at the plaza were reversible and could provide service to patrons in either direction, depending on the time of day and direction of peak traffic volume at the plaza. At the same time, during the AM peak time period, two manual lanes and one E-Pass lane were provided for traffic in the northbound direction. During weekday afternoons (the PM peak time period), this configuration is reversed. Table 1 and Figure 1 show the AM configuration during the before study. Table 2 and Figure 2 show the PM configuration during the before study. Note that the number scheme in these figures was the same utilized by OOCEA.

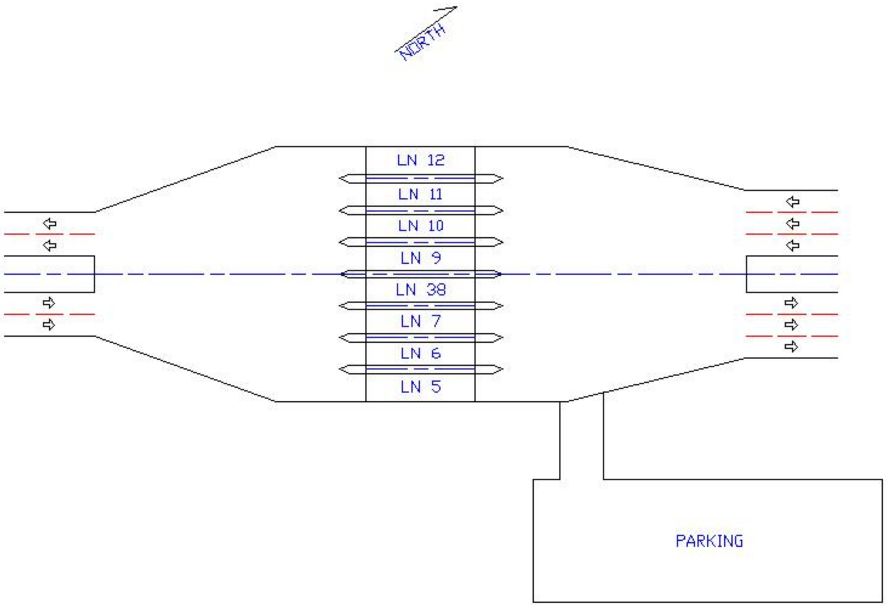

Figure 1 Before Study – AM Configuration

Table 1 Before Study – AM Configuration

Direction	Lane # / Payment Type							
Southbound				38 (E)	9 (E)	10 (A)	11 (M)	12 (M)
Northbound	5 (M)	6 (M)	7 (E)					

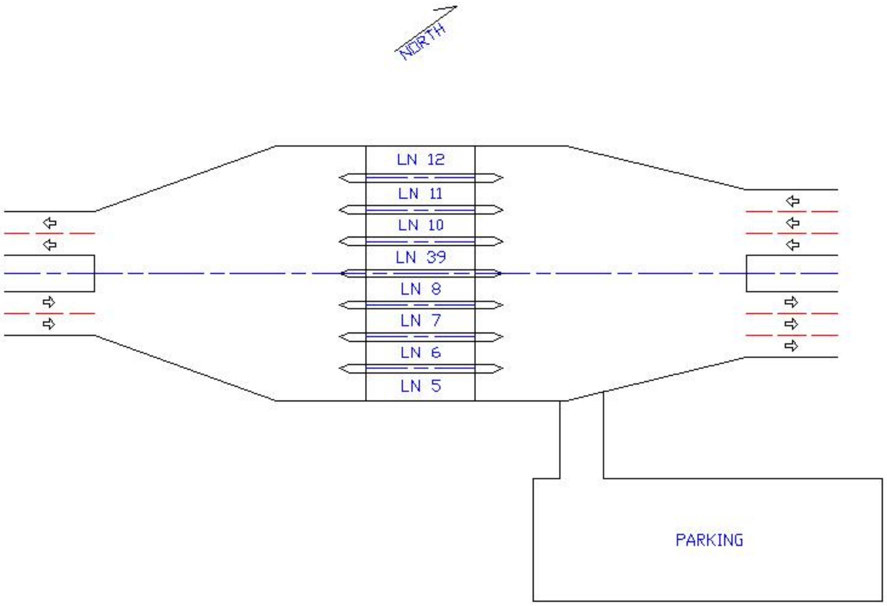

Figure 2 Before Study – PM Configuration

Table 2 Before Study – PM Configuration

Direction	Lane # / Payment Type						
Southbound					10 (E)	11 (M)	12 (M)
Northbound	5 (M)	6 (M)	7 (A)	8 (E)	39 (E)		

Upon completion of construction, two manual lanes, two ACM lanes, and two express ETC lanes were provided in each direction. In addition, the number of approach lanes along the mainline highway was increased. See Figure 3 and Table 3 for the After Study Configuration of the plaza. Three highway lanes (both directions) were provided south of the plaza and four highway lanes (both directions) were provided north of the plaza. Note that the numbering scheme used in this figure was the same as that employed by OOCEA.

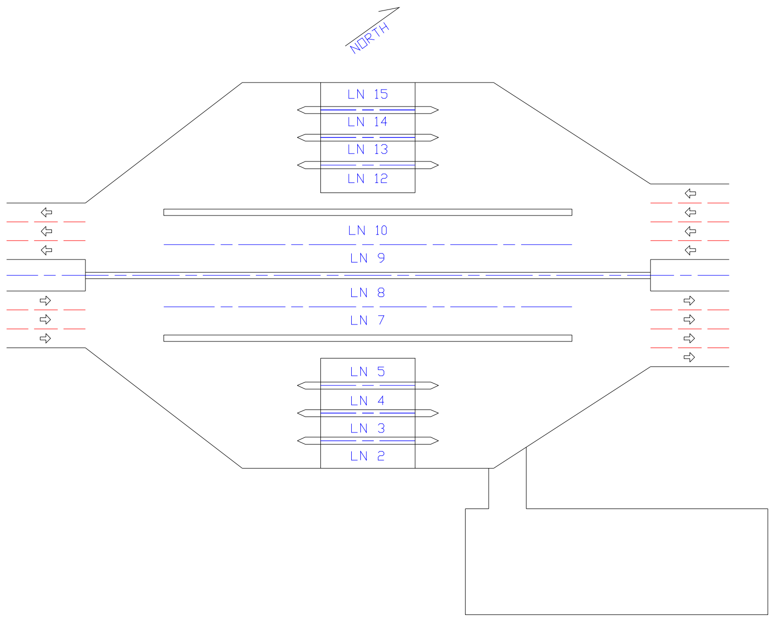

Figure 3 After Study – Configuration

Table 3 After Study – Configuration

Direction	Lane # / Payment Type											
SB							9 (Ex)	10 (Ex)	12 (A)	13 (A)	14 (M)	15 (M)
NB	2 (M)	3 (M)	4 (A)	5 (A)	7 (Ex)	8 (Ex)						

5.2 Data Acquisition

Although field data collection is considered a tedious and time-consuming task, it is unavoidable in order to verify and calibrate the simulation model. Traffic during the AM and PM traffic periods was recorded using video cameras. Two video cameras were synchronized so that times for individual vehicles could be matched. One camera was placed on top of the plaza canopy and faced upstream of the plaza to capture individual vehicle arrivals and verify queue lengths. The other camera was placed downstream of the plaza to record departure times and service times for each vehicle. According to prior research and reports, the service time is the parameter that has the largest impact on queuing delays (Klodzinski 2002b). Every vehicle's arrival and departure from the plaza were individually recorded so that overall arrival counts and throughput could be summarized. Each vehicle was traced individually to ensure the accuracy of the data for the analysis. Data collection for the before study was completed and a list is included in Table 4.

Table 4 Before Study – Video Data Inventory

Data Type	Days Collected	Lane Hours Collected
AM		
Southbound	17	85
Northbound	1	3
Total	18	88
PM		
Southbound	4	14
Northbound	15	75
Total	19	89

Transaction data and vehicle speed data were also collected and utilized as part of the analysis. Transaction data in the form of detailed audits (DAs) were received from OOCEA and specific data was extrapolated and filtered. The extracted data include the ETC lane throughput and speed data, vehicle classification by axel count (which was often used to match vehicles between videos and the DAs), and the ETC percent use in each mixed lane. Vehicle speed data was collected upstream of the plaza. Portable vehicle classifiers were placed at two locations upstream of the plaza in each direction. The speed data was used to investigate the effect of increasing traffic volume and the effect on approach speeds upstream of the plaza.

Vehicle approach speeds, deceleration, and acceleration within the toll plaza vicinity were based on data collected at the Holland East Plaza using Distance Measuring Equipment (DMI). A DMI is a portable device that can determine the instantaneous time, distance, and speed of the vehicle for which the DMI equipment is attached (Klodzinski 1998). Five teams, consisting of a driver and DMI operator, collected this data at each lane type. Beginning and ending points of the data collection were chosen carefully to allow the vehicles to reach acceptable cruising speeds both upstream and downstream of the plaza. Platoon speed profiles were captured for the different lane types and a total of five runs were completed during the morning peak hour for seven days. This resulted in a total of 35 runs which were then used to compute the approach speeds, deceleration, and acceleration of the vehicles. The acceleration and deceleration data were used as a starting point for the TPSIM calibration model.

5.3 Data Analysis

The field data was recorded manually and databases were created so that this information could either be used as input for the simulation model or used to verify the results of the simulation. Upstream and downstream video recordings during the peak hours were viewed and a total of 20 lane-hours of traffic data were analyzed. Over 15,000 vehicles were individually traced through the plaza. Table 5 is an inventory of the data analysis. This table includes the number of lane-hours analyzed and vehicles processed for each hour. The number of vehicles processed is equal to the total number of departures that were counted during the hour.

Table 5 Before Study – Data Analysis Inventory

Data Set	Vehicles Processed	Lane-Hours Analyzed
Feb 6th, 2002 AM Peak (Southbound)	3917	5
February 12th, 2002 PM Peak (Northbound)	3580	5
Feb 20th, 2002 AM Peak (Southbound)	3978	5
Feb 20th, 2002 PM Peak (Northbound)	3846	5
Total	15321	20

The upstream videos provided individual arrival times for each non-ETC vehicle. The downstream videos were used to determine the individual departures and service times of each non-ETC vehicle. Certain vehicles types (large trucks, easily identifiable vehicles, etc.) were used to ensure accurate vehicle matches between the arrival and departure vehicles. The times were recorded to the nearest second.

Not all collected video data was analyzed. Each set of video data chosen for analysis was selected carefully. It was important to ensure that the data was not affected by activities such as traffic accidents and special events that generated additional traffic. Weather conditions such as rain or heavy fog were also considered during the selection, since inclement weather conditions can alter traffic patterns. Other criteria that were considered when analyzing the video data included obtaining a matching set of AM and PM peak hours for a given day, having collected a comprehensive peak hour (both directions collected), and ensuring that collection was done during a peak hour when there was no influence from a special traffic generator. Using the data collected in the field, the following were computed:

- 1-min arrivals for each lane
- Percent of each lane type (Man vs. ACM vs. ETC)
- 1-min throughput for each lane
- 5-min throughput
- 5-min Average Queuing Delay (AQD)
- 5-min Maximum Queuing Delay (MQD)
- 5-min Total Queuing Delay (TQD)
- Service time distributions (for cash lanes)

5.4 Before Study

The before study includes analysis of the four measures of effectiveness (MOE) as well as other evaluated parameters. The four measures of effectiveness are throughput, average delay, maximum delay, and total delay. Other analysis were conducted for the before study and include the inter-vehicle time, arrival rate, and percentage of ETC vehicles per lane. The graphs are separated into AM and PM peak hours.

The throughput is the volume of traffic departing from the toll plaza for each lane of the direction analyzed. See Table 6 for results for each day by lane. The manual transaction lanes show lower hourly throughput compared to the A/E lane. The dedicated ETC lane adjacent to the conventional toll lanes had a higher volume compared to the other dedicated ETC lane. This can be attributed to drivers being unwilling to make excess weaving/merging movements when approaching and departing the plaza. Figures 4 and 5 graphically display the throughput.

Table 6 Before Study - Throughput

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Throughput (vph)	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Throughput (vph)
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	937	Lane 5 (M/E)	409
Lane 9 (E)	1800	Lane 6 (M/E)	407
Lane 10 (A/E)	492	Lane 7 (A/E)	498
Lane 11 (M/E)	364	Lane 8 (E)	1664
Lane 12 (M/E)	324	Lane 39 (E)	767
Total Plaza	3917	Total Plaza	3745
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	924	Lane 5 (M/E)	372
Lane 9 (E)	1825	Lane 6 (M/E)	392
Lane 10 (A/E)	496	Lane 7 (A/E)	469
Lane 11 (M/E)	404	Lane 8 (E)	1512
Lane 12 (M/E)	319	Lane 39 (E)	640
Total Plaza	3968	Total Plaza	3385
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	1006	Lane 5 (M/E)	381
Lane 9 (E)	1737	Lane 6 (M/E)	416
Lane 10 (A/E)	516	Lane 7 (A/E)	545
Lane 11 (M/E)	359	Lane 8 (E)	1710
Lane 12 (M/E)	360	Lane 39 (E)	794
Total Plaza	3978	Total Plaza	3846

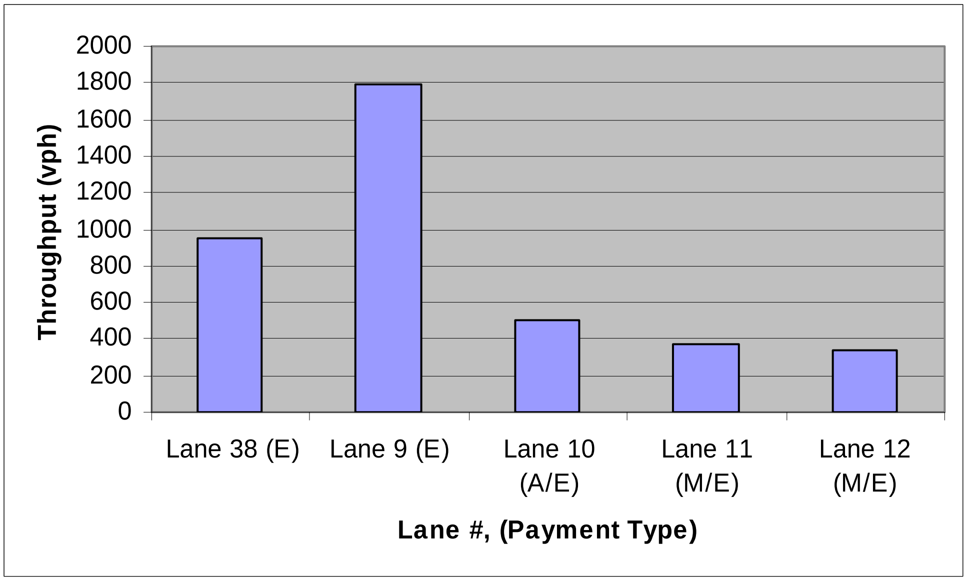

Figure 4 Before Study - Throughput (AM Southbound)

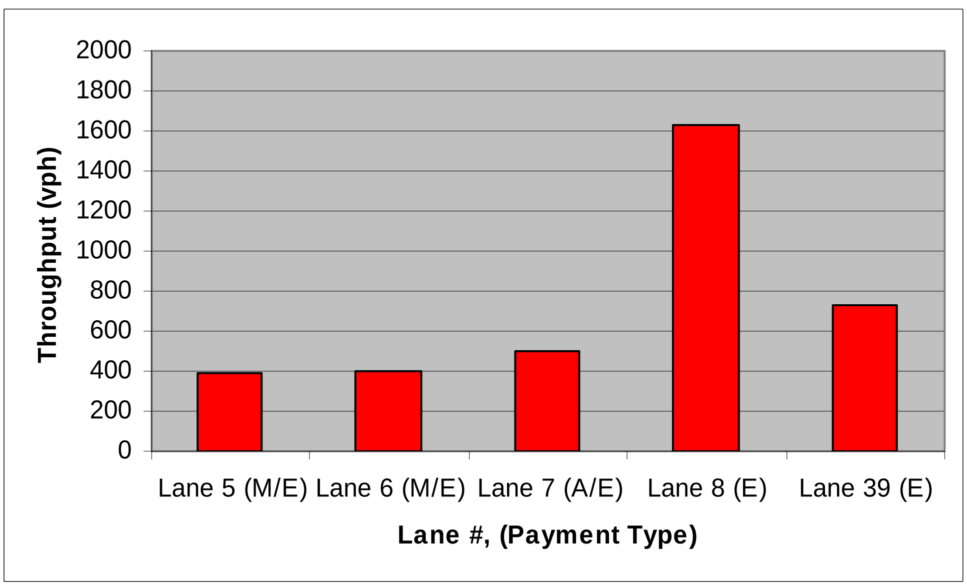

Figure 5 Before Study – Throughput (PM Northbound)

See Table 7 and Figures 6 and 7 for the percentage of ETC users in each lane. Although the percentages of ETC vehicles in the A/E are generally high, the number of arrivals and throughput is also high, which increases congestion and causes greater delays. Normally, if the ETC percentage is higher in a particular lane, we would expect the delays to be less. But there are other factors that need to be considered including number of arrivals, inter-vehicle times, throughput, and service times.

Table 7 Before Study – Percent ETC

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	% ETC	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	% ETC
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	100.00%	Lane 5 (M/E)	10.61%
Lane 9 (E)	100.00%	Lane 6 (M/E)	6.03%
Lane 10 (A/E)	18.73%	Lane 7 (A/E)	10.98%
Lane 11 (M/E)	4.28%	Lane 8 (E)	100.00%
Lane 12 (M/E)	8.10%	Lane 39 (E)	100.00%
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	100.00%	Lane 5 (M/E)	9.09%
Lane 9 (E)	100.00%	Lane 6 (M/E)	3.95%
Lane 10 (A/E)	21.67%	Lane 7 (A/E)	9.88%
Lane 11 (M/E)	2.97%	Lane 8 (E)	100.00%
Lane 12 (M/E)	5.00%	Lane 39 (E)	100.00%
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	100.00%	Lane 5 (M/E)	3.23%
Lane 9 (E)	100.00%	Lane 6 (M/E)	3.97%
Lane 10 (A/E)	19.60%	Lane 7 (A/E)	10.62%
Lane 11 (M/E)	4.66%	Lane 8 (E)	100.00%
Lane 12 (M/E)	8.70%	Lane 39 (E)	100.00%

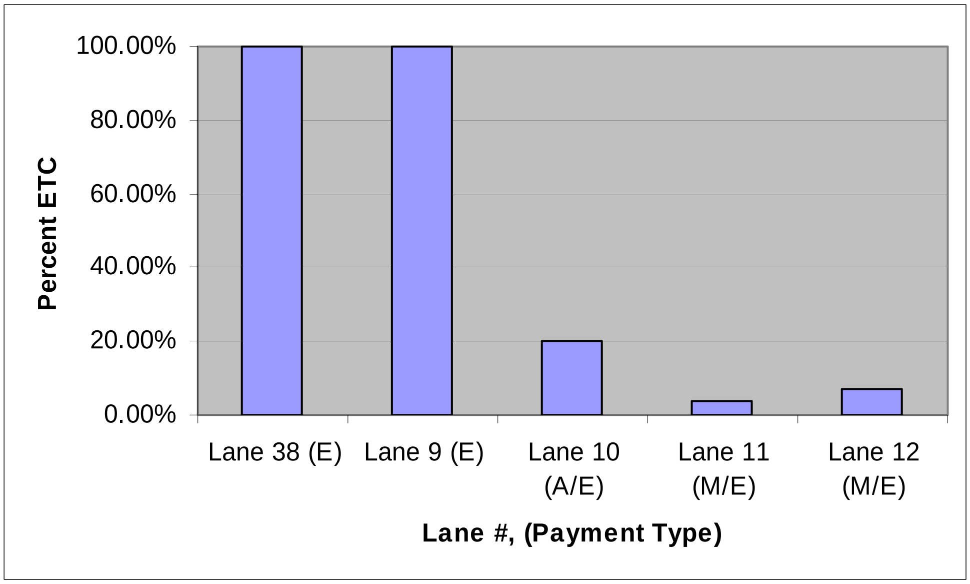

Figure 6 Before Study – Percent ETC (AM Southbound)

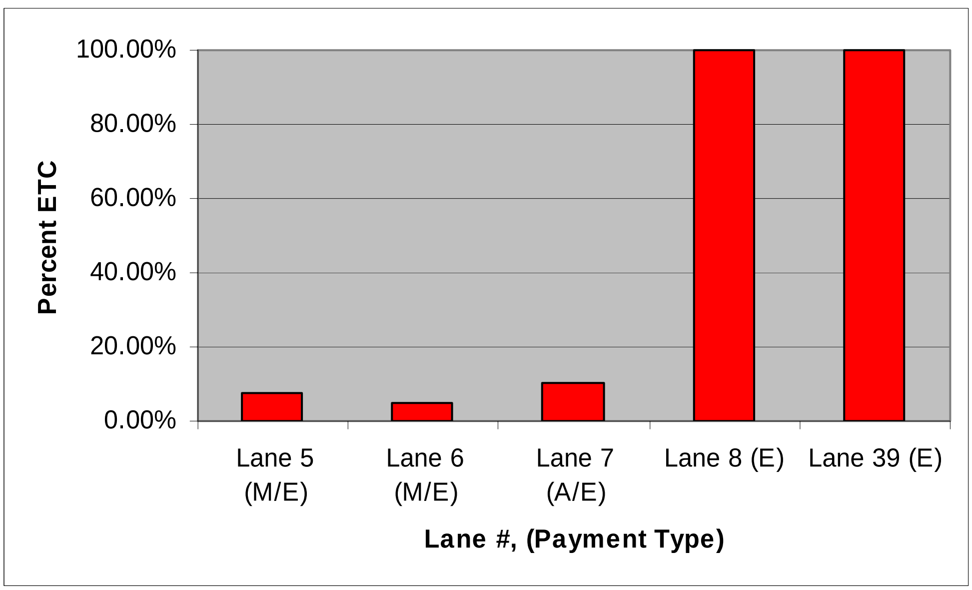

Figure 7 Before Study – Percent ETC (PM Northbound)

The average delay for each non-dedicated ETC lane (currently all mixed lanes at University Plaza) was calculated from the individual vehicular delays for each lane of each peak hour. Table 8 and Figures 8 and 9 show the results for average delay. These individual delays were equal to the difference between a specific vehicle's arrival and departure time. Delay includes any queuing delay, the vehicle service time and headway. The headway was observed to be approximately 2 seconds and is the time it takes for a following vehicle to pull up for service at a toll booth. There is no delay recorded for the dedicated ETC lanes.

Table 8 Before Study - Average Delay

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Avg. Delay	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Avg. Delay
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	0:00:18
Lane 9 (E)	--	Lane 6 (M/E)	0:00:19
Lane 10 (A/E)	0:00:11	Lane 7 (A/E)	0:00:18
Lane 11 (M/E)	0:00:19	Lane 8 (E)	--
Lane 12 (M/E)	0:00:19	Lane 39 (E)	--
Overall Average	0:00:16	Overall Average	0:00:18
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	0:00:12
Lane 9 (E)	--	Lane 6 (M/E)	0:00:13
Lane 10 (A/E)	0:00:09	Lane 7 (A/E)	0:00:12
Lane 11 (M/E)	0:00:12	Lane 8 (E)	--
Lane 12 (M/E)	0:00:19	Lane 39 (E)	--
Overall Average	0:00:13	Overall Average	0:00:12
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	0:00:13
Lane 9 (E)	--	Lane 6 (M/E)	0:00:12
Lane 10 (A/E)	0:00:11	Lane 7 (A/E)	0:00:13
Lane 11 (M/E)	0:00:16	Lane 8 (E)	--
Lane 12 (M/E)	0:00:14	Lane 39 (E)	--
Overall Average	0:00:14	Overall Average	0:00:12

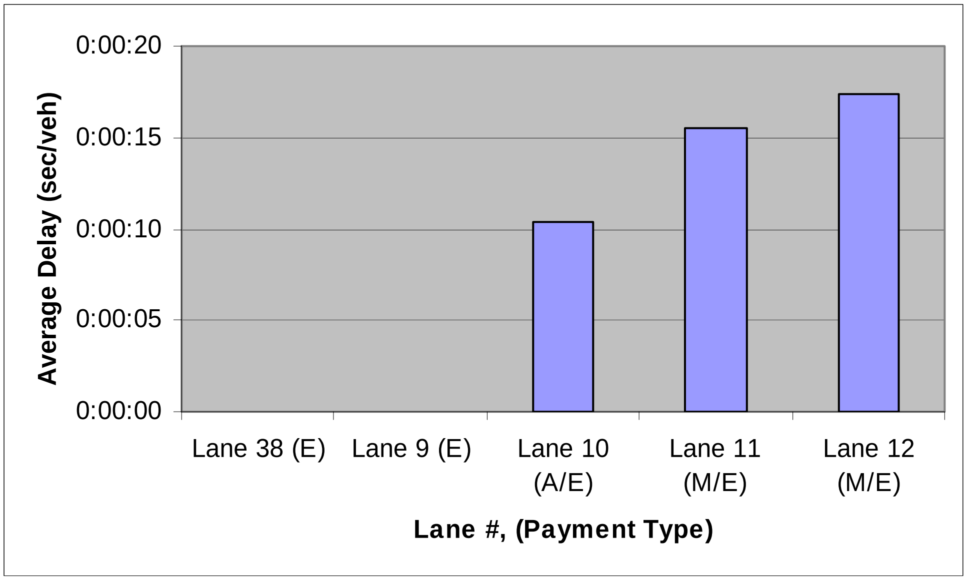

Figure 8 Before Study - Average Delay (AM Southbound)

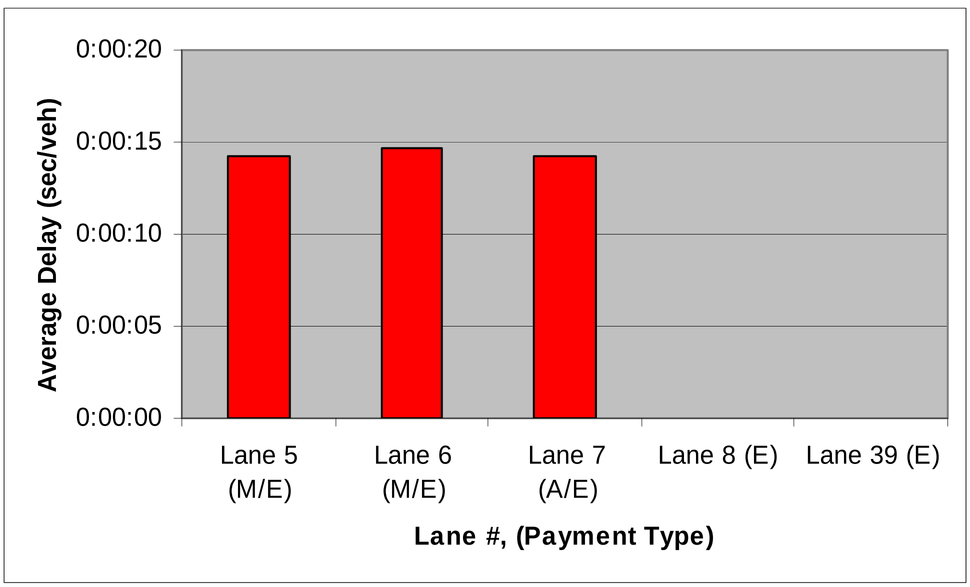

Figure 9 Before Study - Average Delay (PM Northbound)

Maximum delay is the highest recorded delay of any one individual vehicle during the peak hour of analysis. This provides information on the maximum time that a vehicle could expect to wait for the specified lane or lane type. It was observed that the A/E lane in the PM peak hour for the northbound direction has a higher maximum delay compared to the AM peak hour southbound. This was attributed to the higher volume (throughput) for the PM peak hour for this lane, see Table 5. The maximum delays in the before study were typically greater for Lane 7 (A/E) than Lane 5 (M/E). The throughput and number of arrivals for Lane 5 was less than Lane 7 but the percentage of ETC users was nearly the same. This could account for the difference in observed maximum delay between these two lanes in the PM peak hour. Table 9 and Figures 10 and 11 show the results of the maximum delay analysis.

Table 9 Before Study - Maximum Delay

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Max. Delay	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Max. Delay
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	0:01:04
Lane 9 (E)	--	Lane 6 (M/E)	0:01:22
Lane 10 (A/E)	0:00:40	Lane 7 (A/E)	0:01:09
Lane 11 (M/E)	0:01:00	Lane 8 (E)	--
Lane 12 (M/E)	0:01:09	Lane 39 (E)	--
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	0:00:35
Lane 9 (E)	--	Lane 6 (M/E)	0:00:55
Lane 10 (A/E)	0:00:41	Lane 7 (A/E)	0:00:57
Lane 11 (M/E)	0:00:40	Lane 8 (E)	--
Lane 12 (M/E)	0:01:22	Lane 39 (E)	--
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	0:00:48
Lane 9 (E)	--	Lane 6 (M/E)	0:01:20
Lane 10 (A/E)	0:00:53	Lane 7 (A/E)	0:01:23
Lane 11 (M/E)	0:01:19	Lane 8 (E)	--
Lane 12 (M/E)	0:01:03	Lane 39 (E)	--

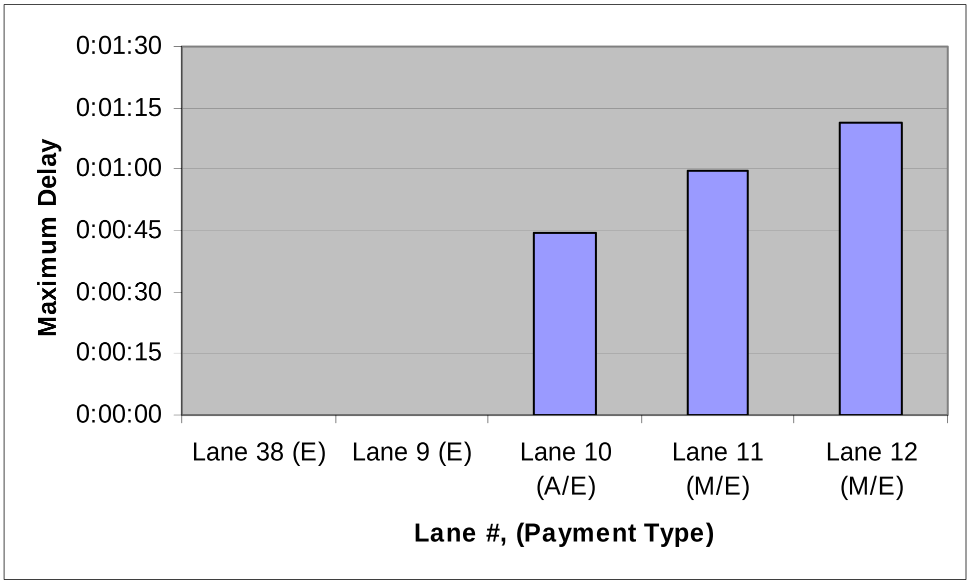

Figure 10 Before Study - Maximum Delay (AM Southbound)

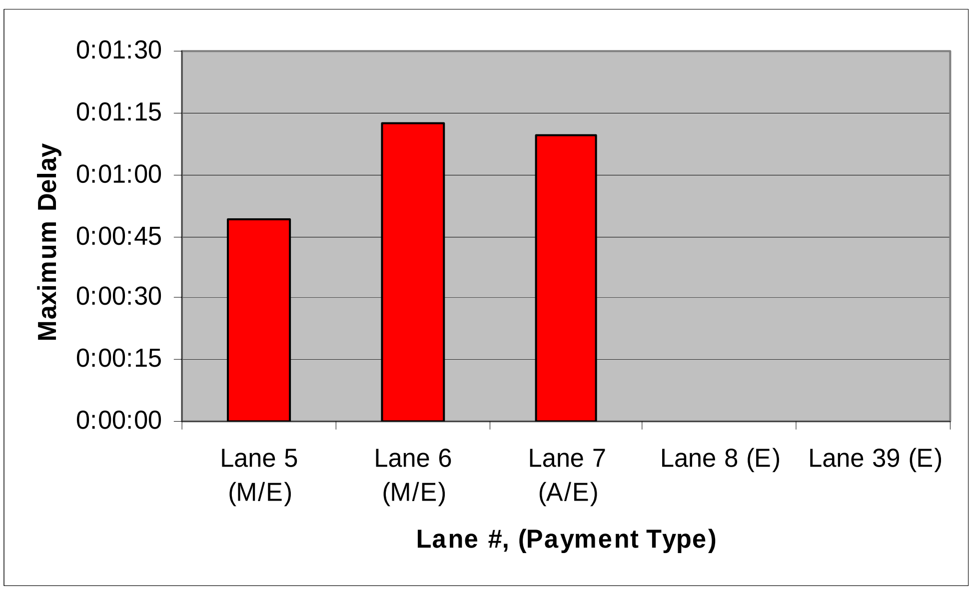

Figure 11 Before Study - Maximum Delay (PM Southbound)

Total delay is the sum of all individual vehicular delays for a given lane during one peak hour for one direction. This includes ETC equipped vehicles in the non-dedicated ETC lanes. Similar to the maximum delays during the PM peak hour, the total delays are higher for Lane 7

(A/E) than Lane 5 (M/E). This is due to the fact that the throughput and arrival rates are greater while the percentage of ETC vehicles is approximately the same. Therefore, delays are greater in Lane 7, even though the service times for A/E lanes are usually less than for M/E lanes. Table 10 and Figures 12 and 13 show the results of the total delay analysis. This is a good representation of how the current plaza handles (or cannot handle) significant demand.

Table 10 Before Study - Total Delay

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Total Delay	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Total Delay
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	2:04:32
Lane 9 (E)	--	Lane 6 (M/E)	2:10:15
Lane 10 (A/E)	1:28:29	Lane 7 (A/E)	2:32:53
Lane 11 (M/E)	1:54:29	Lane 8 (E)	--
Lane 12 (M/E)	1:45:11	Lane 39 (E)	--
Overall Total	5:08:09	Overall Total	6:47:40
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	1:15:48
Lane 9 (E)	--	Lane 6 (M/E)	1:22:18
Lane 10 (A/E)	1:12:36	Lane 7 (A/E)	1:30:15
Lane 11 (M/E)	1:20:00	Lane 8 (E)	--
Lane 12 (M/E)	1:38:26	Lane 39 (E)	--
Overall Total	4:11:02	Overall Total	4:08:21
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	--	Lane 5 (M/E)	1:21:35
Lane 9 (E)	--	Lane 6 (M/E)	1:25:41
Lane 10 (A/E)	1:36:36	Lane 7 (A/E)	1:54:44
Lane 11 (M/E)	1:33:44	Lane 8 (E)	--
Lane 12 (M/E)	1:22:50	Lane 39 (E)	--
Overall Total	4:33:10	Overall Total	4:42:00

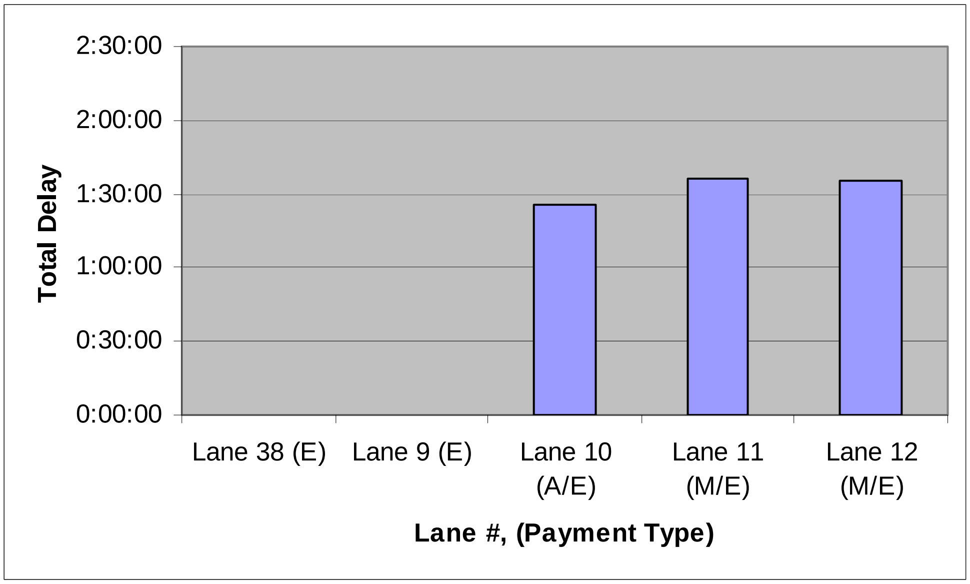

Figure 12 Before Study - Total Delay (AM Southbound)

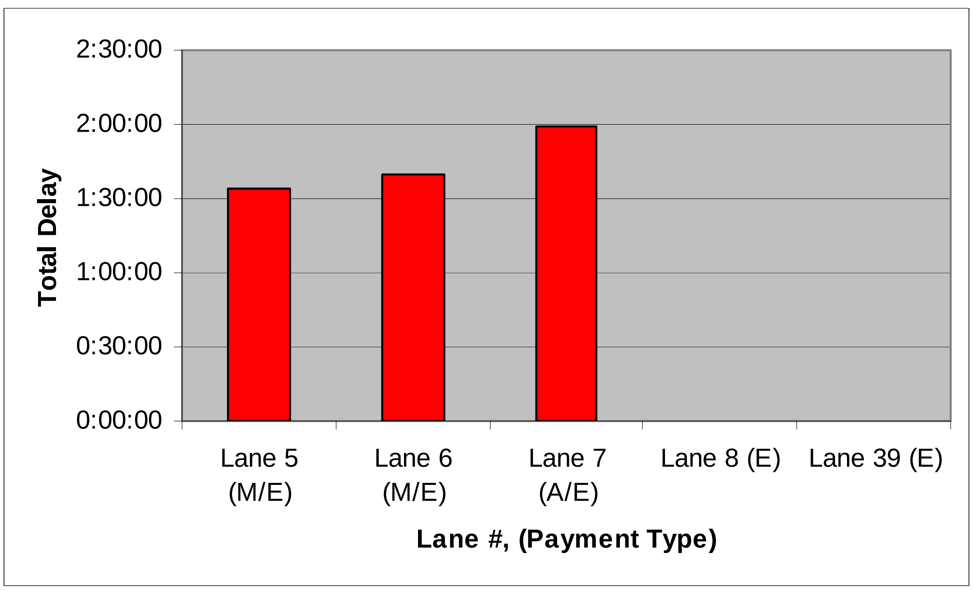

Figure 13 Before Study - Total Delay (PM Northbound)

Inter-vehicle time is the difference between departure times for two consecutive vehicles at the toll plaza for each lane. The individual recorded times for each lane were averaged to obtain an overall inter-vehicle lane average. The overall inter-vehicle lane average was rounded to the nearest second. Typically, lower volumes should produce higher average inter-vehicle times. The inter-vehicle times for the A/E lanes are lower than the M/E lanes. This indicates that the A/E lanes have smaller average headways. Based on the throughput analysis, the A/E lanes had higher throughput than the M/E lanes. Typically, lower volumes should produce higher average inter-vehicle times. This was generally the case for the ETC lanes. Unlike the A/E and M/E lanes, the ETC lanes do not experience any variations in the individual service times (they each have a service time of zero seconds). This was useful for calculating an estimate of a toll lane's capacity and performance in processing vehicles. Table 11 and Figures 14 and 15 show the results for the inter-vehicle time analysis.

Table 11 Before Study – Average Inter-vehicle Time

AM Peak Hour (7-8 AM)		PM Peak Hour (5-6 PM)	
Southbound		Northbound	
Lane # (Type)	Avg. IntVeh (hour)	Lane # (Type)	Avg. IntVeh (hour)
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	0:00:04	Lane 5 (M/E)	0:00:09
Lane 9 (E)	0:00:02	Lane 6 (M/E)	0:00:09
Lane 10 (A/E)	0:00:07	Lane 7 (A/E)	0:00:07
Lane 11 (M/E)	0:00:10	Lane 8 (E)	0:00:02
Lane 12 (M/E)	0:00:11	Lane 39 (E)	0:00:06
Overall Average	0:00:07	Overall Average	0:00:07
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	0:00:04	Lane 5 (M/E)	0:00:10
Lane 9 (E)	0:00:02	Lane 6 (M/E)	0:00:09
Lane 10 (A/E)	0:00:07	Lane 7 (A/E)	0:00:08
Lane 11 (M/E)	0:00:09	Lane 8 (E)	0:00:02
Lane 12 (M/E)	0:00:11	Lane 39 (E)	0:00:06
Overall Average	0:00:07	Overall Average	0:00:07
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	0:00:04	Lane 5 (M/E)	0:00:09
Lane 9 (E)	0:00:02	Lane 6 (M/E)	0:00:09
Lane 10 (A/E)	0:00:07	Lane 7 (A/E)	0:00:07
Lane 11 (M/E)	0:00:10	Lane 8 (E)	0:00:02
Lane 12 (M/E)	0:00:10	Lane 39 (E)	0:00:05
Overall Average	0:00:07	Overall Average	0:00:06

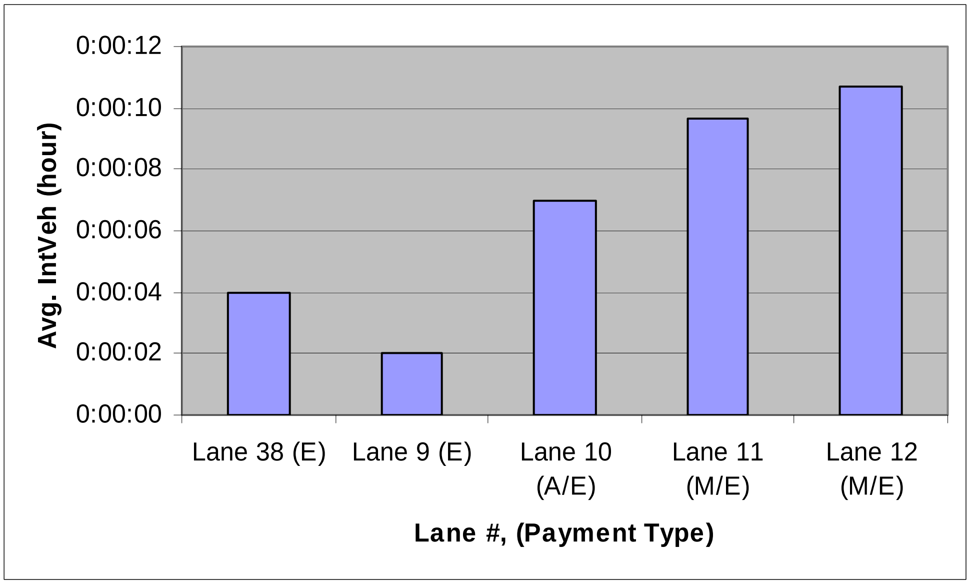

Figure 14 Before Study – Avg. IntVeh (AM Southbound)

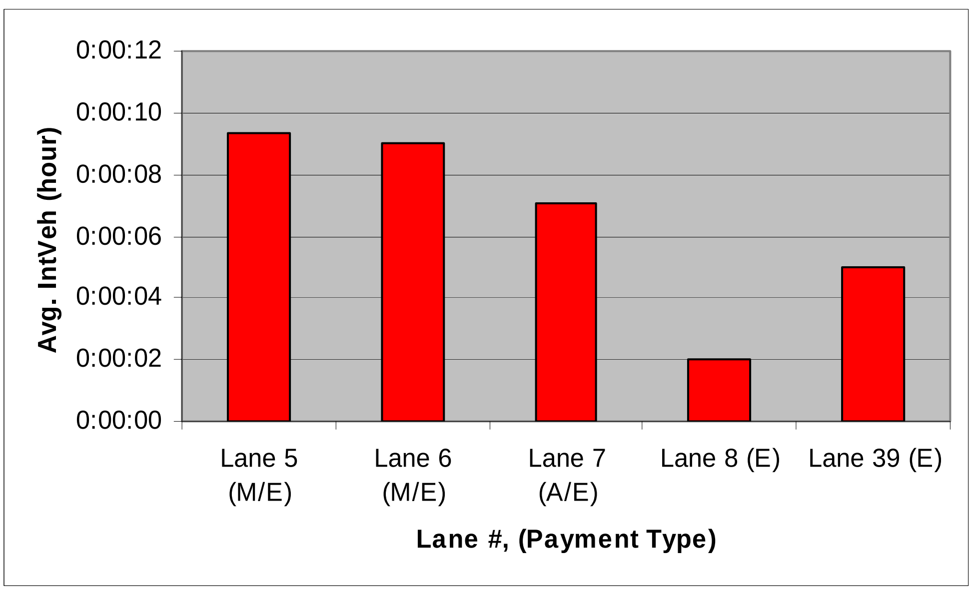

Figure 15 Before Study – Avg. IntVeh (PM Northbound)

The arrival rate is the number of vehicle arrivals each minute recorded from the peak hour for each lane. For the non-dedicated ETC lanes, the vehicle is considered to arrive at a specific toll lane either when joining an existing queue or when pulling up to the toll booth for service (when no queue exists for the lane). The individual arrival times were recorded using the upstream video data. Since vehicles are not required to stop in the dedicated ETC lanes, the number of arrivals is equal to the number of departures. Table 12 and Figures 16 and 17 show the results for the average arrival rates by lane.

Table 12 Before Study – Arrival Rate

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Arrival Rate (vpm)	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Arrival Rate (vpm)
Feb 06, 2002 AM		Feb 12, 2002 PM	
Lane 38 (E)	15	Lane 5 (M/E)	7
Lane 9 (E)	30	Lane 6 (M/E)	7
Lane 10 (A/E)	8	Lane 7 (A/E)	8
Lane 11 (M/E)	6	Lane 8 (E)	28
Lane 12 (M/E)	5	Lane 39 (E)	10
Overall Average	13	Overall Average	12
Feb 19, 2002 AM		Feb 19, 2002 PM	
Lane 38 (E)	16	Lane 5 (M/E)	6
Lane 9 (E)	31	Lane 6 (M/E)	7
Lane 10 (A/E)	8	Lane 7 (A/E)	8
Lane 11 (M/E)	7	Lane 8 (E)	30
Lane 12 (M/E)	5	Lane 39 (E)	13
Overall Average	13	Overall Average	13
Feb 20, 2002 AM		Feb 20, 2002 PM	
Lane 38 (E)	17	Lane 5 (M/E)	6
Lane 9 (E)	29	Lane 6 (M/E)	7
Lane 10 (A/E)	9	Lane 7 (A/E)	9
Lane 11 (M/E)	6	Lane 8 (E)	29
Lane 12 (M/E)	6	Lane 39 (E)	13
Overall Average	13	Overall Average	13

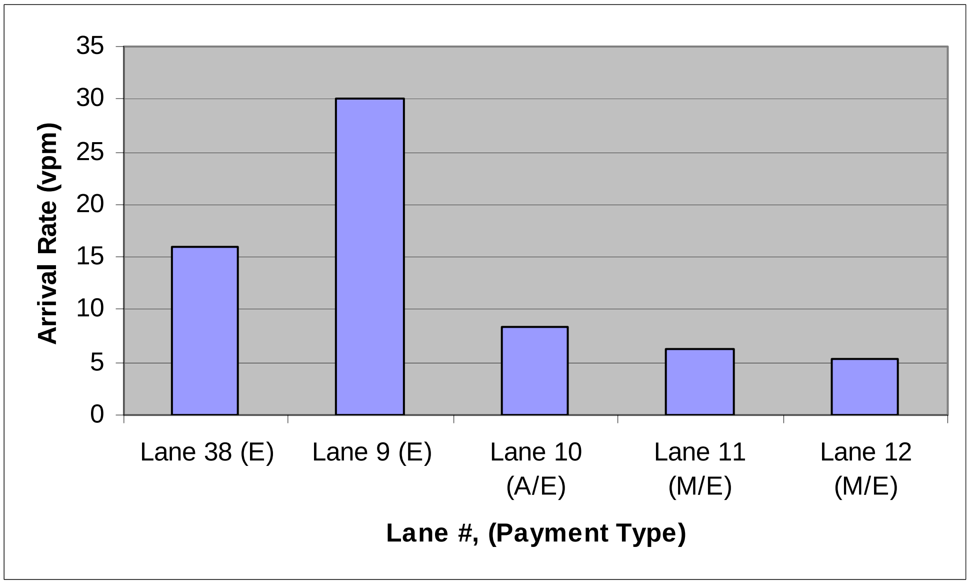

Figure 16 Before Study – Arrival Rate (AM Southbound)

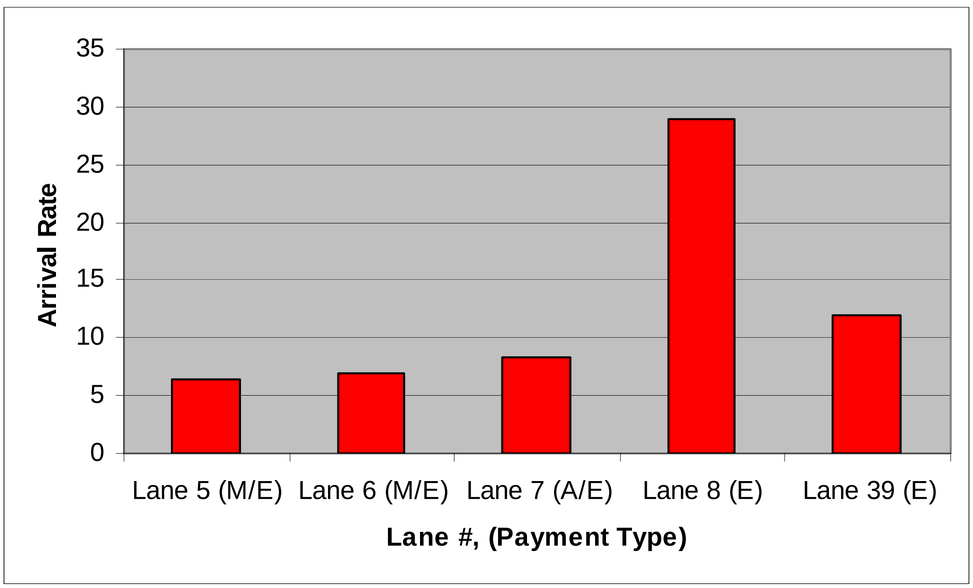

Figure 17 Before Study – Arrival Rate (PM Northbound)

5.5 After Study

The after study analysis includes field results of the four measures of effectiveness (MOE) for selected days after construction was completed at the University mainline toll plaza. The after study is different from the before study in a few ways. Prior to June 2002, the southbound direction of travel had three highway lanes approaching the plaza. The northbound direction of travel had only two highway lanes approaching the plaza between the SR 50 (Colonial Dr.) on-ramp and the plaza. In the after study, an additional approach lane was added for each direction. Therefore, the southbound direction of travel had four highway lanes and the northbound direction of travel had three highway lanes in the after study. One additional Automatic (A/E) toll lane was also added in each direction. In the northbound direction, due to the close proximity of the University Boulevard exit, a high percentage of ETC users were using the conventional lanes to exit rather than the high-speed express ETC lanes in the center of the plaza. This accounts for the higher throughput in the cash lanes for the PM Peak Hour (northbound). At the same time, the throughput in the express lanes remained the same between the southbound and northbound directions for different times of the day; in other words, there were still large numbers of ETC vehicles using the express lanes, despite the high percentage also using the conventional lanes.

The throughput is the volume of traffic departing from the toll plaza for each lane for the direction analyzed. See Table 13 and Figures 18 and 19 for results of the throughput analysis. The graphs are separated into AM or PM peak hours.

Table 13 After Study – Throughput

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Throughput (vph)	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Throughput (vph)
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	1643	Lane 2 (M/E)	363
Lane 10 (Ex)	1161	Lane 3 (M/E)	393
Lane 12 (A/E)	211	Lane 4 (A/E)	418
Lane 13 (A/E)	276	Lane 5 (A/E)	350
Lane 14 (M/E)	311	Lane 7 (Ex)	1128
Lane 15 (M/E)	256	Lane 8 (Ex)	1627
Total Plaza	3858	Total Plaza	4279
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	1684	Lane 2 (M/E)	343
Lane 10 (Ex)	1176	Lane 3 (M/E)	369
Lane 12 (A/E)	205	Lane 4 (A/E)	415
Lane 13 (A/E)	266	Lane 5 (A/E)	398
Lane 14 (M/E)	307	Lane 7 (Ex)	1160
Lane 15 (M/E)	257	Lane 8 (Ex)	1660
Total Plaza	3895	Total Plaza	4345

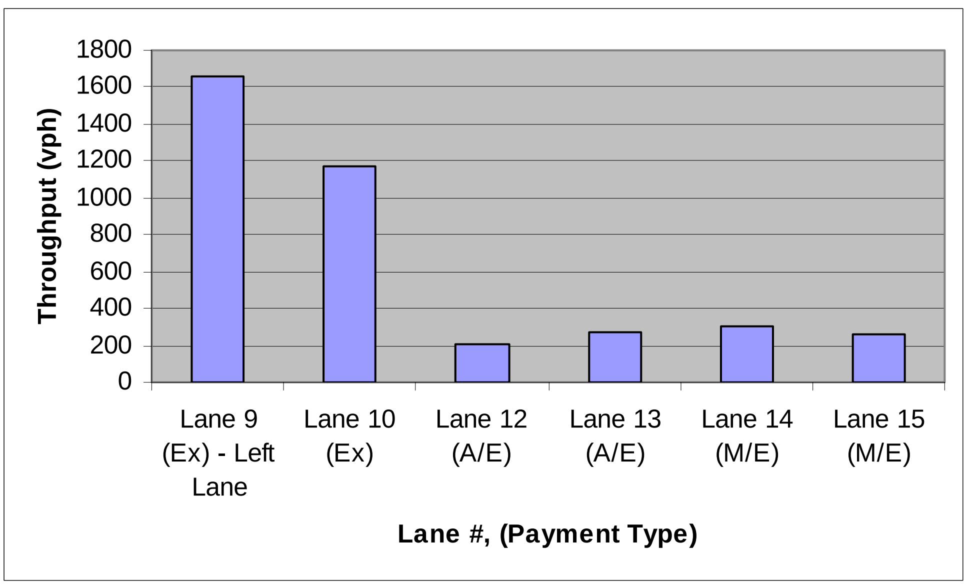

Figure 18 After Study - Throughput (AM Southbound)

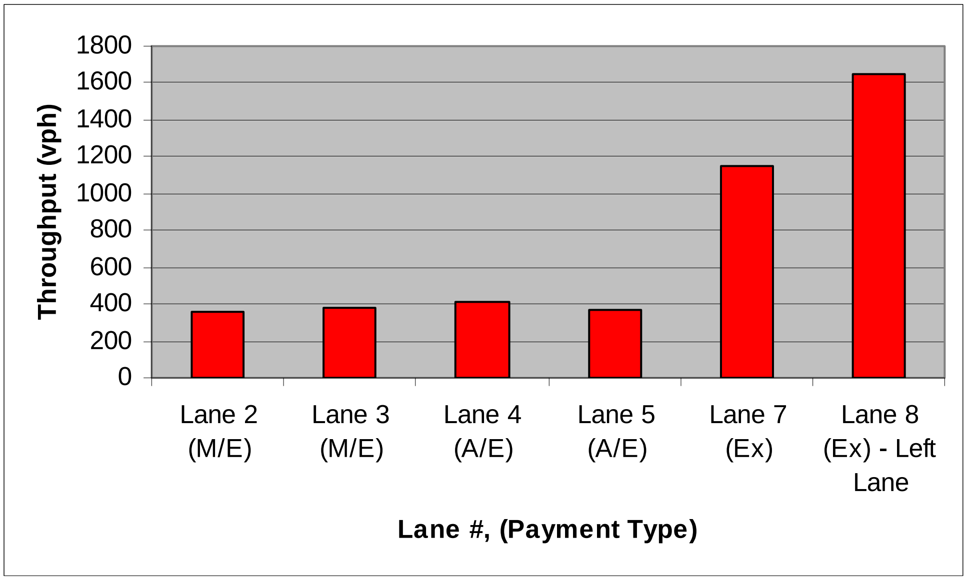

Figure 19 After Study - Throughput (PM Northbound)

Table 14 and Figures 20 and 21 show results for the percent of ETC vehicles in the after study. The figures show the average values for percent of ETC vehicles for each lane. Note the high percentages of ETC vehicles that use the conventional cash lanes during the PM peak hour. This was attributed to the close proximity of the University Boulevard exit where patrons used the right toll lanes to exit, rather than using the express ETC lanes and having to weave downstream of the plaza in order to exit.

Table 14 After Study – Percent ETC

AM Peak Hour (7-8 AM) Southbound		PM Peak Hour (5-6 PM) Northbound	
Lane # (Type)	% ETC	Lane # (Type)	% ETC
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	100.0%	Lane 2 (M/E)	15.4%
Lane 10 (Ex)	100.0%	Lane 3 (M/E)	3.6%
Lane 12 (A/E)	5.1%	Lane 4 (A/E)	23.2%
Lane 13 (A/E)	1.1%	Lane 5 (A/E)	54.4%
Lane 14 (M/E)	0.6%	Lane 7 (Ex)	100.0%
Lane 15 (M/E)	1.6%	Lane 8 (Ex)	100.0%
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	100.0%	Lane 2 (M/E)	11.5%
Lane 10 (Ex)	100.0%	Lane 3 (M/E)	2.5%
Lane 12 (A/E)	7.4%	Lane 4 (A/E)	21.3%
Lane 13 (A/E)	1.8%	Lane 5 (A/E)	43.7%
Lane 14 (M/E)	0.6%	Lane 7 (Ex)	100.0%
Lane 15 (M/E)	1.9%	Lane 8 (Ex)	100.0%

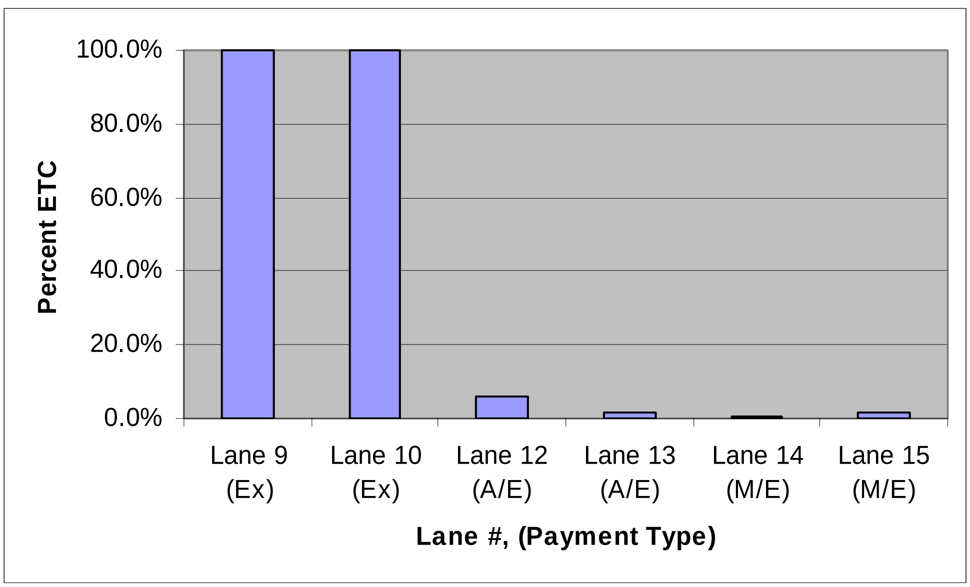

Figure 20 After Study – Avg. Percent ETC (AM Southbound)

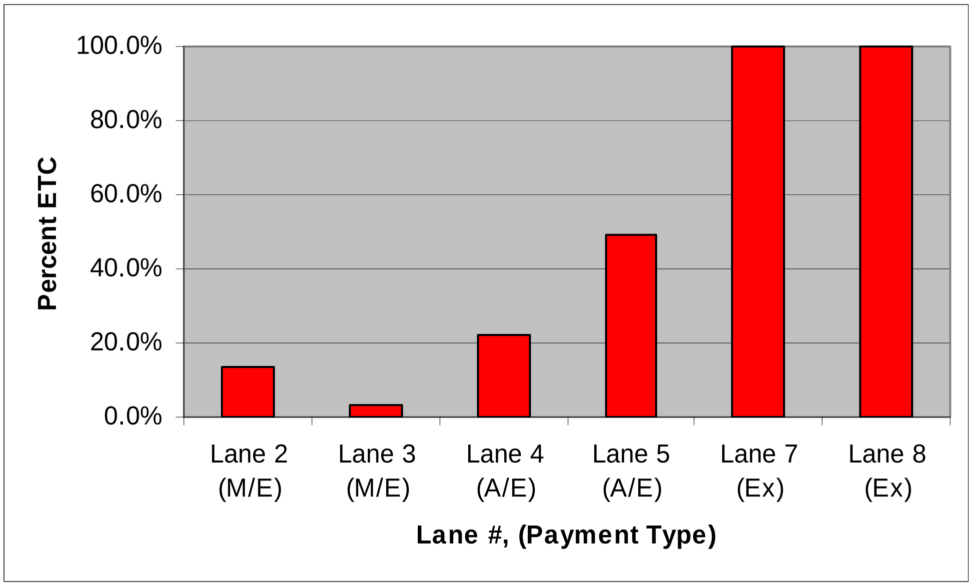

Figure 21 After Study – Avg. Percent ETC (PM Northbound)

The average delay for each non-dedicated ETC lane (currently all mixed lanes at University Plaza) was calculated from the individual vehicular delays for each lane of each peak hour. See Table 15 and Figures 22 and 23 for results of the average delay analysis.

Table 15 After Study - Average Delay

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Avg. Delay	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Avg. Delay
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	--	Lane 2 (M/E)	0:00:06
Lane 10 (Ex)	--	Lane 3 (M/E)	0:00:06
Lane 12 (A/E)	0:00:06	Lane 4 (A/E)	0:00:03
Lane 13 (A/E)	0:00:04	Lane 5 (A/E)	0:00:04
Lane 14 (M/E)	0:00:05	Lane 7 (Ex)	--
Lane 15 (M/E)	0:00:05	Lane 8 (Ex)	--
Overall Average	0:00:05	Overall Average	0:00:05
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	--	Lane 2 (M/E)	0:00:04
Lane 10 (Ex)	--	Lane 3 (M/E)	0:00:07
Lane 12 (A/E)	0:00:10	Lane 4 (A/E)	0:00:04
Lane 13 (A/E)	0:00:10	Lane 5 (A/E)	0:00:03
Lane 14 (M/E)	0:00:12	Lane 7 (Ex)	--
Lane 15 (M/E)	0:00:17	Lane 8 (Ex)	--
Overall Average	0:00:12	Overall Average	0:00:05

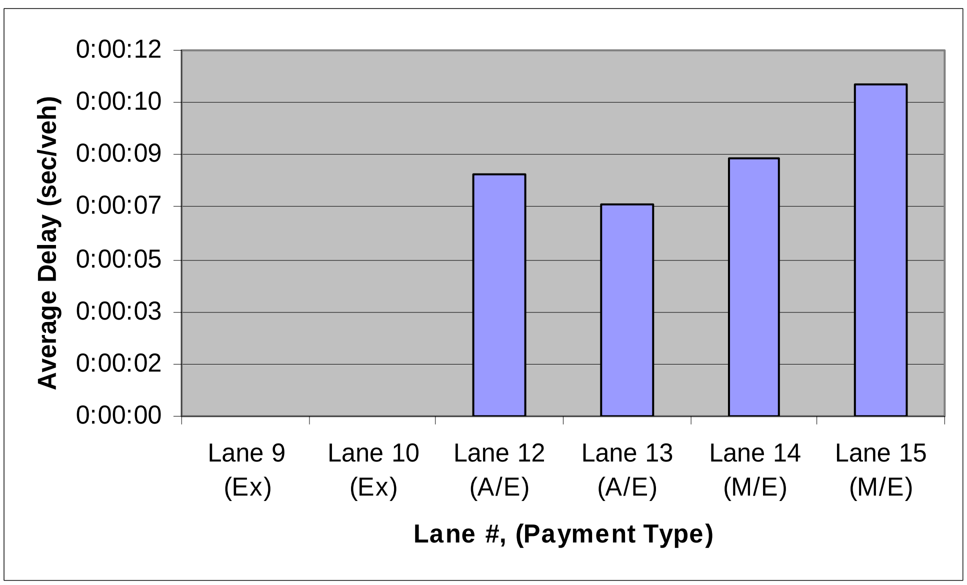

Figure 22 After Study - Average Delay (AM Southbound)

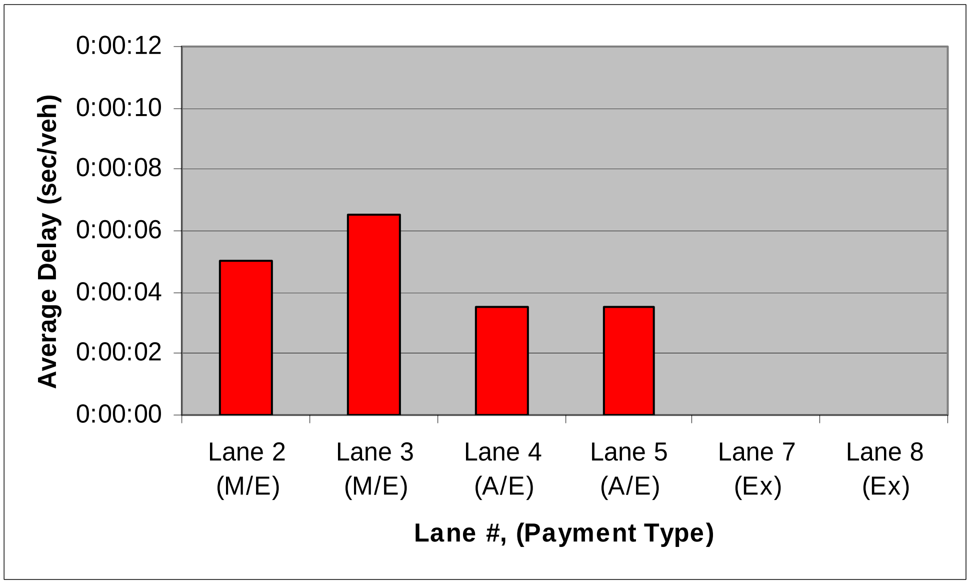

Figure 23 After Study - Average Delay (PM Northbound)

Maximum delay is the highest recorded delay of any one individual vehicle during the peak hour of analysis. See Table 16 and Figures 24 and 25 for results of the maximum delay analysis.

Table 16 After Study – Maximum Delay

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Max. Delay	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Max. Delay
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	--	Lane 2 (M/E)	0:01:27
Lane 10 (Ex)	--	Lane 3 (M/E)	0:00:40
Lane 12 (A/E)	0:01:17	Lane 4 (A/E)	0:00:33
Lane 13 (A/E)	0:00:20	Lane 5 (A/E)	0:00:57
Lane 14 (M/E)	0:00:28	Lane 7 (Ex)	--
Lane 15 (M/E)	0:00:33	Lane 8 (Ex)	--
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	--	Lane 2 (M/E)	0:01:07
Lane 10 (Ex)	--	Lane 3 (M/E)	0:00:48
Lane 12 (A/E)	0:00:50	Lane 4 (A/E)	0:00:27
Lane 13 (A/E)	0:01:11	Lane 5 (A/E)	0:00:25
Lane 14 (M/E)	0:00:42	Lane 7 (Ex)	--
Lane 15 (M/E)	0:01:25	Lane 8 (Ex)	--

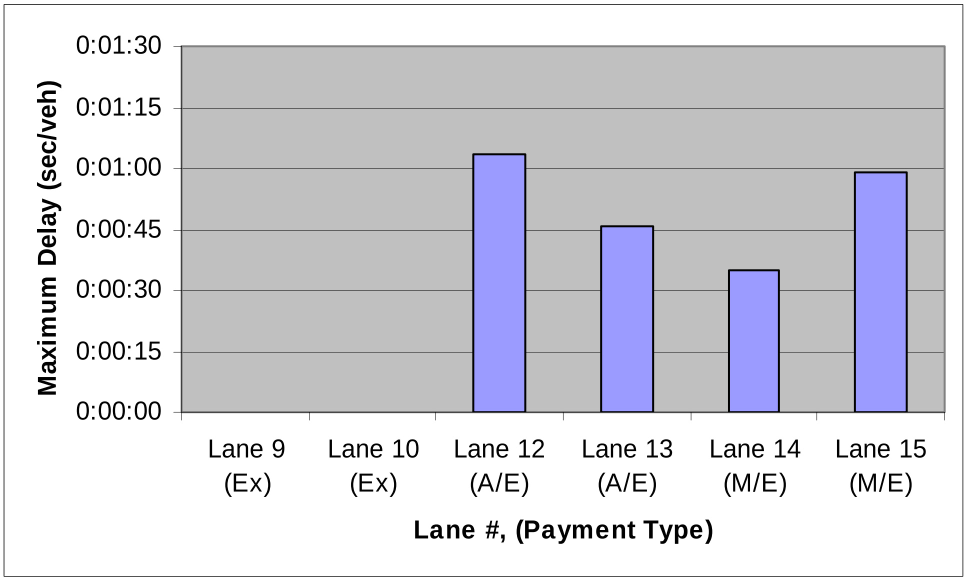

Figure 24 After Study – Maximum Delay (AM Southbound)

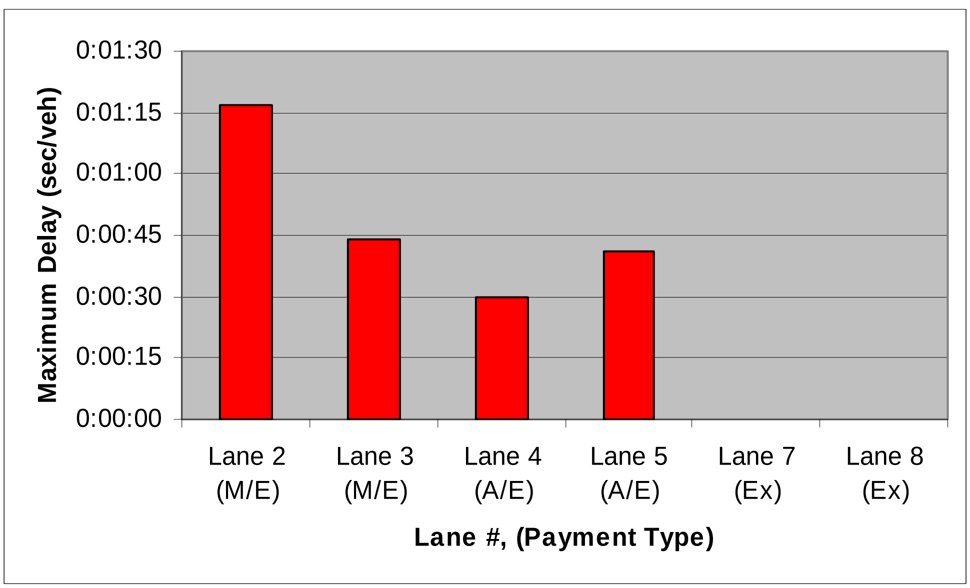

Figure 25 After Study – Maximum Delay (PM Northbound)

Total delay is the sum of all individual vehicular delays for one lane during one peak hour per direction. Table 17 and Figures 26 and 27 show the results of the total delay analysis.

Table 17 After Study - Total Delay

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Total Delay	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Total Delay
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	--	Lane 2 (M/E)	0:35:34
Lane 10 (Ex)	--	Lane 3 (M/E)	0:41:17
Lane 12 (A/E)	0:22:49	Lane 4 (A/E)	0:23:27
Lane 13 (A/E)	0:16:29	Lane 5 (A/E)	0:25:03
Lane 14 (M/E)	0:24:00	Lane 7 (Ex)	--
Lane 15 (M/E)	0:19:28	Lane 8 (Ex)	--
Overall Total	1:22:46	Overall Total	2:05:21
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	--	Lane 2 (M/E)	0:24:33
Lane 10 (Ex)	--	Lane 3 (M/E)	0:42:32
Lane 12 (A/E)	0:34:53	Lane 4 (A/E)	0:27:10
Lane 13 (A/E)	0:42:28	Lane 5 (A/E)	0:18:28
Lane 14 (M/E)	1:02:08	Lane 7 (Ex)	--
Lane 15 (M/E)	1:10:44	Lane 8 (Ex)	--
Overall Total	3:30:13	Overall Total	1:52:43

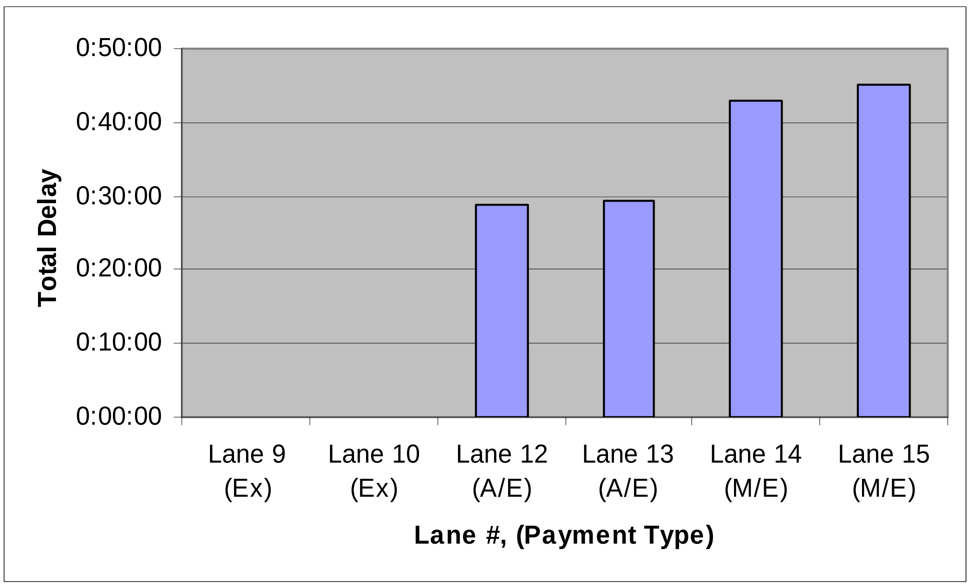

Figure 26 After Study - Total Delay (AM Southbound)

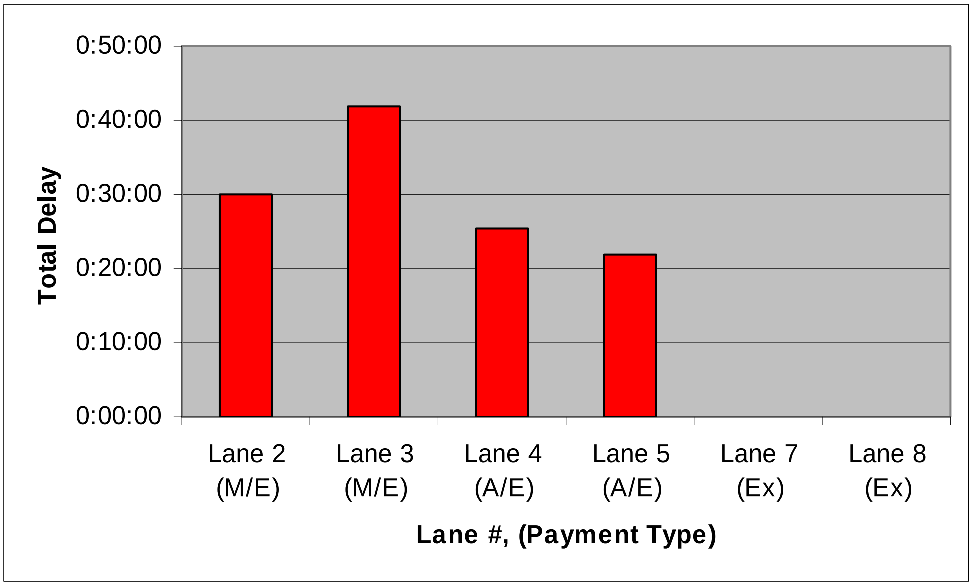

Figure 27 After Study - Total Delay (PM Northbound)

Inter-vehicle time is the difference between departure times for two consecutive vehicles at the toll plaza for each lane. The individual recorded times for each lane were averaged to obtain an overall inter-vehicle lane average. The overall inter-vehicle lane averages were rounded to the nearest second. Typically, lower volumes should produce higher average inter-vehicle times. This was generally the case for the ETC lanes. Unlike the A/E and M/E lanes, the ETC lanes do not experience any variations in the individual service times (they each have a service time of zero seconds). This was useful for calculating an estimate of a toll lane's capacity and performance in processing vehicles. Table 18 and Figures 28 and 29 show the results for the inter-vehicle time analysis.

Table 18 After Study – Average Inter-vehicle Time

AM Peak Hour (7-8 AM) Southbound		PM Peak Hour (5-6 PM) Northbound	
Lane # (Type)	Avg. IntVeh (hour)	Lane # (Type)	Avg. IntVeh (hour)
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	0:00:02	Lane 2 (M/E)	0:00:10
Lane 10 (Ex)	0:00:03	Lane 3 (M/E)	0:00:09
Lane 12 (A/E)	0:00:17	Lane 4 (A/E)	0:00:09
Lane 13 (A/E)	0:00:13	Lane 5 (A/E)	0:00:10
Lane 14 (M/E)	0:00:12	Lane 7 (Ex)	0:00:03
Lane 15 (M/E)	0:00:15	Lane 8 (Ex)	0:00:02
Overall Average	0:00:10	Overall Average	0:00:07
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	0:00:02	Lane 2 (M/E)	0:00:10
Lane 10 (Ex)	0:00:03	Lane 3 (M/E)	0:00:10
Lane 12 (A/E)	0:00:18	Lane 4 (A/E)	0:00:09
Lane 13 (A/E)	0:00:14	Lane 5 (A/E)	0:00:09
Lane 14 (M/E)	0:00:12	Lane 7 (Ex)	0:00:03
Lane 15 (M/E)	0:00:14	Lane 8 (Ex)	0:00:02
Overall Average	0:00:11	Overall Average	0:00:07

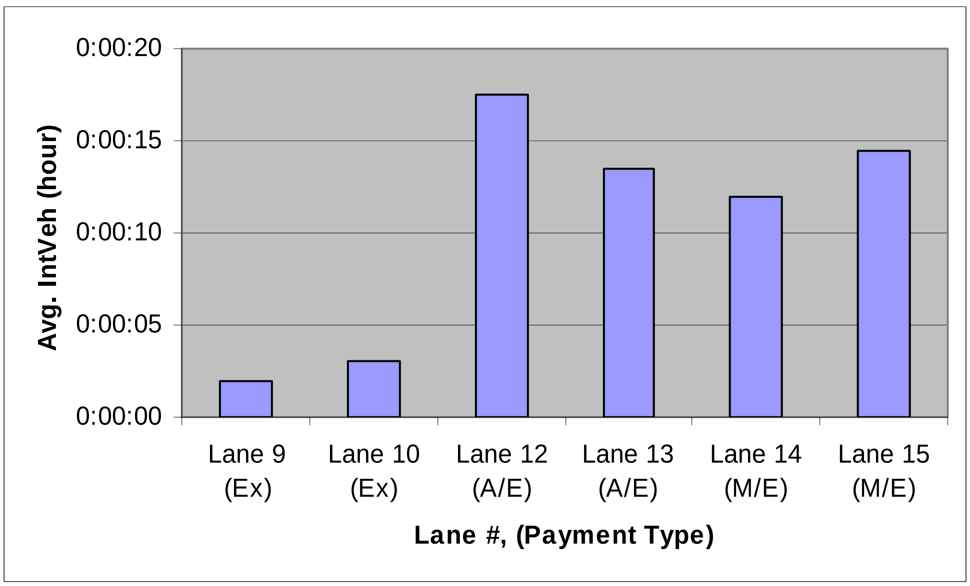

Figure 28 After Study – Avg. IntVeh (AM Southbound)

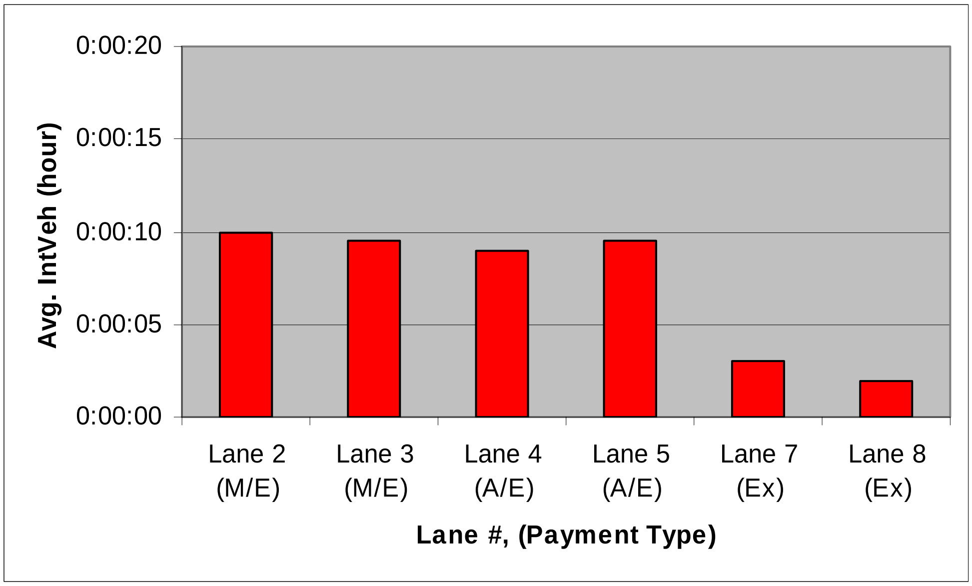

Figure 29 After Study – Avg. IntVeh (PM Northbound)

The arrival rate is the number of vehicle arrivals each minute recorded from the peak hour for each lane. For the non-dedicated ETC lanes, the vehicle is considered to arrive at a specific toll lane either when joining an existing queue or when pulling up to the toll booth for service (when no queue exists for the lane). The individual arrival times were recorded using the upstream video data. Since vehicles are not required to stop in the dedicated ETC lanes, the number of arrivals is equal to the number of departures. Table 19 and Figures 30 and 31 show the results for the average arrival rates by lane.

Table 19 After Study – Arrival Rate

AM Peak Hour (7-8 AM) Southbound Lane # (Type)	Arrival Rate (vpm)	PM Peak Hour (5-6 PM) Northbound Lane # (Type)	Arrival Rate (vpm)
Jun 10, 2003 AM		Jun 24, 2003 PM	
Lane 9 (Ex)	27	Lane 2 (M/E)	6
Lane 10 (Ex)	19	Lane 3 (M/E)	7
Lane 12 (A/E)	5	Lane 4 (A/E)	7
Lane 13 (A/E)	5	Lane 5 (A/E)	6
Lane 14 (M/E)	5	Lane 7 (Ex)	19
Lane 15 (M/E)	4	Lane 8 (Ex)	27
Overall Average	11	Overall Average	12
Jun 11, 2003 AM		Jun 26, 2003 PM	
Lane 9 (Ex)	28	Lane 2 (M/E)	6
Lane 10 (Ex)	20	Lane 3 (M/E)	6
Lane 12 (A/E)	3	Lane 4 (A/E)	7
Lane 13 (A/E)	4	Lane 5 (A/E)	6
Lane 14 (M/E)	5	Lane 7 (Ex)	19
Lane 15 (M/E)	4	Lane 8 (Ex)	28
Overall Average	11	Overall Average	12

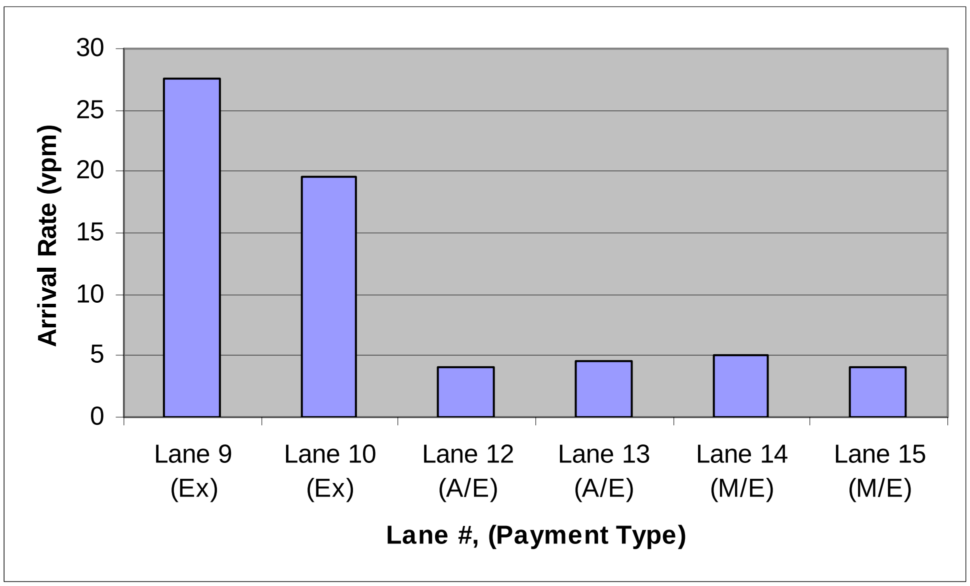

Figure 30 After Study – Arrival Rate (AM Southbound)

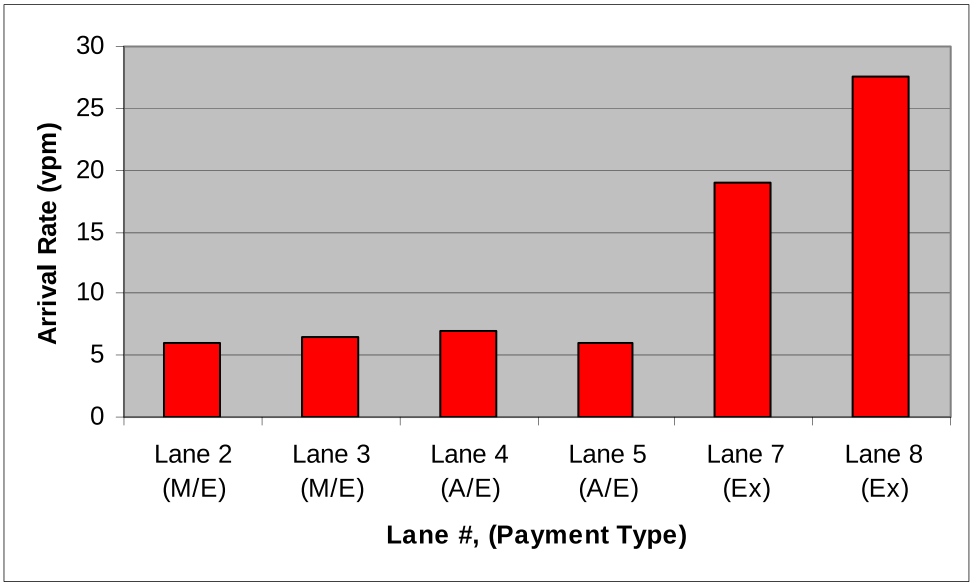

Figure 31 After Study – Arrival Rate (PM Northbound)

5.6 Comparison of Before and After Studies

The following is a comparison between the before and after study data that was collected. Table 20 is a summary of the results by lane. Table 21 is a summary of the results by lane type. Table 22 shows the percent change between the before and after study lane types. Negative percentages indicate that there was a decrease in the after study data compared with the before study. All four measures of effectiveness (throughput, average delay, maximum delay, and total delay) were included as part of the comparison. Other analyses were conducted for the comparison and included the inter-vehicle time, arrival rate, and percentage of ETC vehicles per lane.

Overall, the throughput was observed to increase at the plaza during the after study. Except during the PM peak for the A/E lane, the throughput in each of the conventional toll lanes was observed to decrease. At the same time, small increases were observed in the ETC lanes.

During the PM peak for the A/E lane, the throughput increased due to a high increase in the number of ETC vehicles (the ETC percent in the A/E lanes increased by 239.9%). The large increase in ETC vehicles using these lanes was attributed to the close proximity of the University exit. These ETC equipped vehicles desired to use the mixed lanes so they could exit at University Boulevard. The average inter-vehicle times decreased and the arrival rates were observed to increase for the ETC lanes in the after study. The opposite was true for the conventional toll lanes. The introduction of express ETC lanes was accompanied by the changes in ETC percentages in the conventional lanes, as well as changes in throughput, delays, arrival rates, and inter-vehicle times in each lane at the plaza. Delays were observed to decrease in each of the conventional toll lanes in the after study as well.

Table 20 Comparison – Summary of Results by Lane

	Throughput	Average Delay	Maximum Delay	Total Delay	Avg. IntVeh (hour)	Arrival Rate (vpm)	Percent ETC
Before Study							
AM Peak Hour (SB)							
Lane 38 (E)	956	--	--	--	0:00:04	16	100.00%
Lane 9 (E)	1787	--	--	--	0:00:02	30	100.00%
Lane 10 (A/E)	501	0:00:10	0:00:45	1:25:54	0:00:07	8	20.00%
Lane 11 (M/E)	376	0:00:16	0:01:00	1:36:04	0:00:10	6	3.97%
Lane 12 (M/E)	334	0:00:17	0:01:11	1:35:29	0:00:11	5	7.27%
PM Peak Hour (NB)							
Lane 39 (E)	734	--	--	--	0:00:06	12	100.00%
Lane 8 (E)	1629	--	--	--	0:00:02	29	100.00%
Lane 7 (A/E)	504	0:00:14	0:01:10	1:59:17	0:00:07	8	10.49%
Lane 6 (M/E)	405	0:00:15	0:01:12	1:39:25	0:00:09	7	4.65%
Lane 5 (M/E)	387	0:00:14	0:00:49	1:33:58	0:00:09	6	7.64%
After Study							
AM Peak Hour (SB)							
Lane 9 (Ex) - Left Lane	1664	--	--	--	0:00:02	28	100.0%
Lane 10 (Ex)	1169	--	--	--	0:00:03	20	100.0%
Lane 12 (A/E)	208	0:00:08	0:01:03	0:28:51	0:00:18	4	6.2%
Lane 13 (A/E)	271	0:00:07	0:00:46	0:29:29	0:00:14	5	1.4%
Lane 14 (M/E)	309	0:00:09	0:00:35	0:43:04	0:00:12	5	0.6%
Lane 15 (M/E)	257	0:00:11	0:00:59	0:45:06	0:00:15	4	1.7%
PM Peak Hour (NB)							
Lane 8 (Ex) - Left Lane	1644	--	--	--	0:00:02	28	100.0%
Lane 7 (Ex)	1144	--	--	--	0:00:03	19	100.0%
Lane 5 (A/E)	374	0:00:04	0:00:41	0:21:46	0:00:10	6	49.1%
Lane 4 (A/E)	417	0:00:04	0:00:30	0:25:18	0:00:09	7	22.3%
Lane 3 (M/E)	381	0:00:07	0:00:44	0:41:54	0:00:10	7	3.0%
Lane 2 (M/E)	353	0:00:05	0:01:17	0:30:04	0:00:10	6	13.5%

Table 21 Comparison – Summary of Results by Lane Type

	Throughput	Average Delay	Maximum Delay	Total Delay	Avg. IntVeh (hour)	Arrival Rate (vpm)	Percent ETC
Before Study							
AM Peak Hour (SB)							
ETC lanes	2743	--	--	--	0:00:03	23	100.00%
ACM lanes	501	0:00:10	0:00:45	1:25:54	0:00:07	8	20.00%
Manual lanes	710	0:00:16	0:01:05	3:11:33	0:00:10	6	5.62%
Total	3954						
PM Peak Hour (NB)							
ETC lanes	2362	--	--	--	0:00:03	21	100.00%
ACM lanes	504	0:00:14	0:01:10	1:59:17	0:00:07	8	10.49%
Manual lanes	792	0:00:14	0:01:01	3:13:23	0:00:09	7	6.15%
Total	3659						
After Study							
AM Peak Hour (SB)							
ETC lanes	2832	--	--	--	0:00:02	24	100.0%
ACM lanes	479	0:00:08	0:00:54	0:58:20	0:00:16	4	3.8%
Manual lanes	566	0:00:10	0:00:47	1:28:10	0:00:13	5	1.2%
Total	3877						
PM Peak Hour (NB)							
ETC lanes	2788	--	--	--	0:00:02	23	100.0%
ACM lanes	791	0:00:04	0:00:36	0:47:04	0:00:09	7	35.7%
Manual lanes	734	0:00:06	0:01:00	1:11:58	0:00:10	6	8.2%
Total	4312						

Table 22 Comparison – Summary of Results by Lane Type (Before Study vs. After Study)

Percent Change

AM Peak Hour (SB)	Throughput	Average Delay	Maximum Delay	Total Delay	Avg. IntVeh (hour)	Arrival Rate (vpm)	Percent ETC
ETC lanes	3.2%				-16.7%	4.3%	0.0%
ACM lanes	-4.5%	-27.5%	22.0%	-32.1%	121.4%	-49.0%	-80.8%
Manual lanes	-20.4%	-40.8%	-28.2%	-54.0%	30.3%	-22.9%	-79.0%
Total	-2.0%						
PM Peak Hour (NB)							
ETC lanes	18.0%				-28.6%	9.5%	0.0%
ACM lanes	56.8%	-75.5%	-49.0%	-60.5%	30.8%	-22.0%	239.9%
Manual lanes	-7.4%	-60.2%	-0.3%	-62.8%	6.4%	-6.2%	34.1%
Total	17.9%						

Figures 32 through 45 were included as graphical representations of the results between the before study and the after study. The throughput is the volume of traffic departing from the toll plaza for each lane for the direction analyzed. The throughput shown in the tables was the total number of vehicles processed at the plaza for each transaction type. The ETC volume (throughput) increased in the after study for the AM and PM peak hours by an average of 3.2 and 18.0%, respectively. In the AM peak hour (southbound), the throughput in the ACM and manual lanes decreased by 4.5% and 20.4%, respectively. A small decrease in throughput was observed for the manual lanes during the PM peak hour (this was accompanied by a small decrease in the arrival rate for this lane type), but this was not true for the ACM lanes. There was a large increase in the throughput for the ACM lanes due to the close proximity of the University Boulevard exit. During the after study, many ETC equipped vehicles used the ACM lanes to reach the University Boulevard exit, which was easier to access from the conventional lanes.

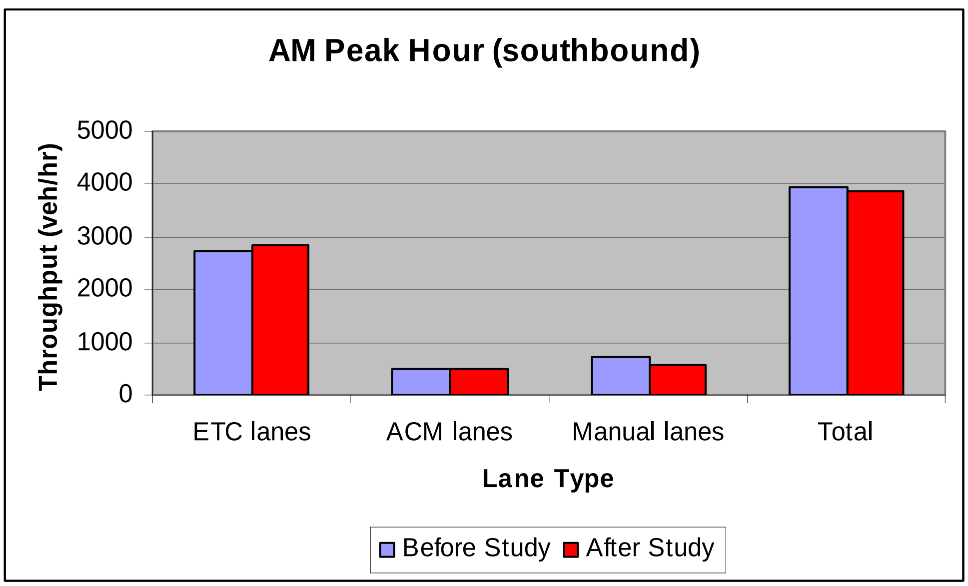

Figure 32 Comparison - Throughput (AM Southbound)

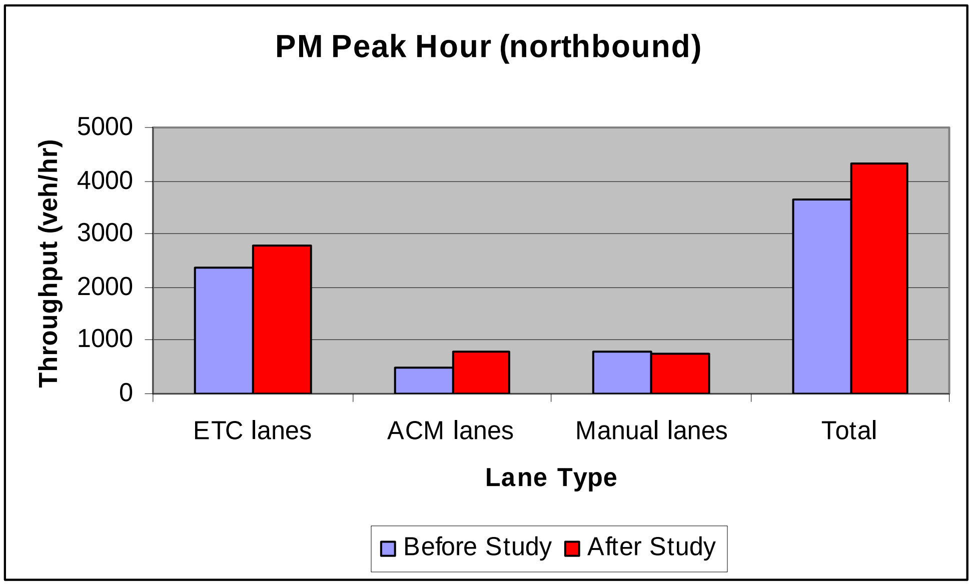

Figure 33 Comparison - Throughput (PM Northbound)

The results for the percentage of ETC vehicles in each lane provided interesting conclusions. The percentages for the ACM and manual lanes decrease in the after study for the southbound direction. This could be a direct result of separating the express ETC lanes and splitting the plaza. In the before study, some ETC vehicles desired to use the adjacent toll lanes so that they would not have to weave upstream and downstream of the plaza in order to access the dedicated ETC lanes. This accompanied the low volume observed in the left dedicated ETC lane, because more weaving was necessary to use this lane. The percent of ETC vehicles in both the ACM and manual lanes actually increased in the after study for the vehicles in the northbound direction (PM peak hour), which is opposite of the results observed for the AM peak hour. This is due to the close proximity of the University Boulevard exit in the northbound direction. Many ETC vehicles used the conventional toll lanes in order to exit at University Boulevard since the percentage of ETC vehicles in these lanes was high.

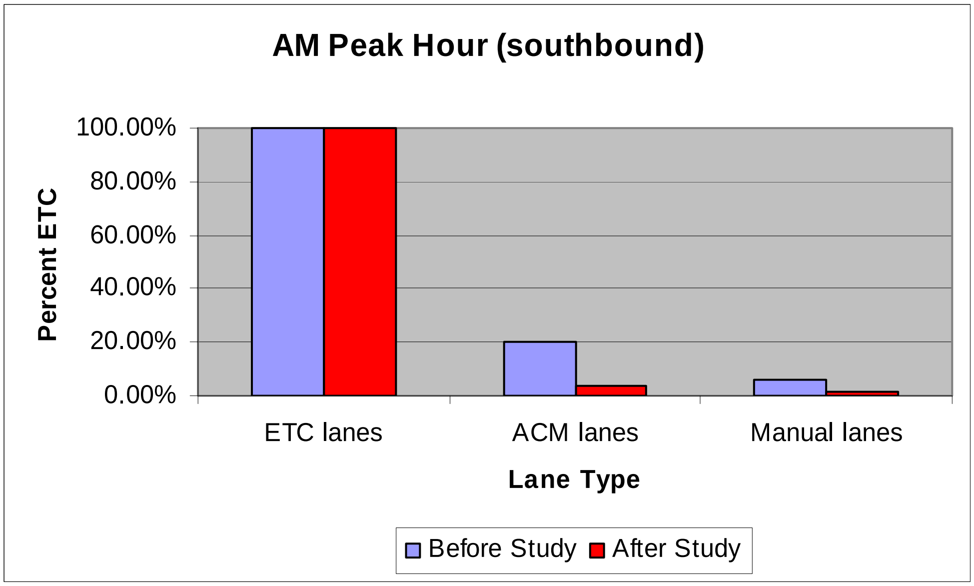

Figure 34 Comparison – Percent ETC (AM Southbound)

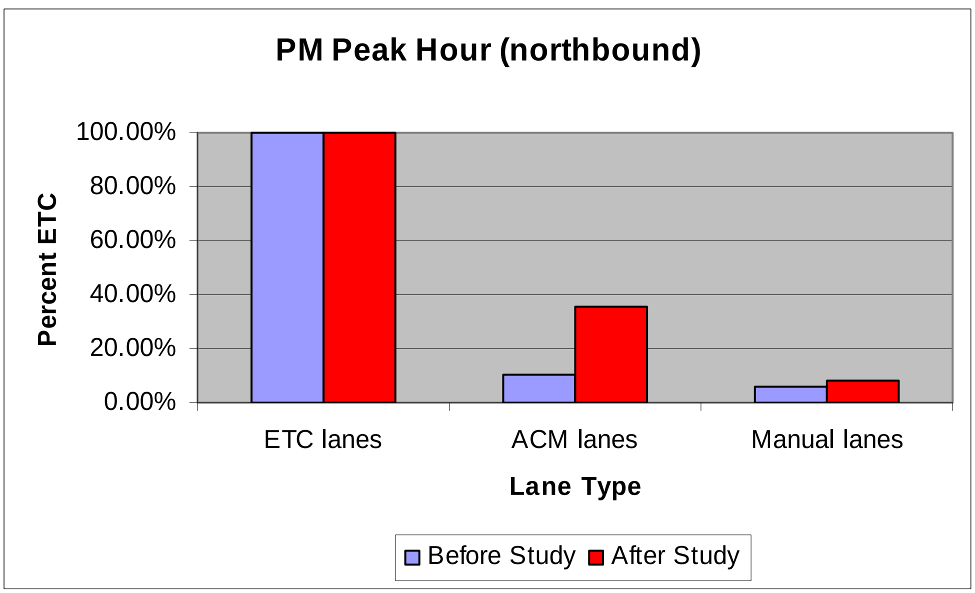

Figure 35 Comparison – Percent ETC (PM Northbound)

The average delay for each non-dedicated ETC lane (currently all mixed lanes at University Plaza) was calculated from the individual vehicular delays for each lane of each peak hour. For average delay, a decrease was observed for the ACM and manual lanes in the after study and was of an even greater magnitude for the northbound direction (PM peak hour). The decrease in average delay for the AM peak hour in the M/E and A/E lanes could be attributed to the reduction in percent ETC use for these lanes, as well as a reduction in the arrival rates for these lane types. Also, in the after study, a second A/E lane was provided to handle the demand for this lane type. On average, vehicles using the non-dedicated ETC lanes experienced less delay in the after study.

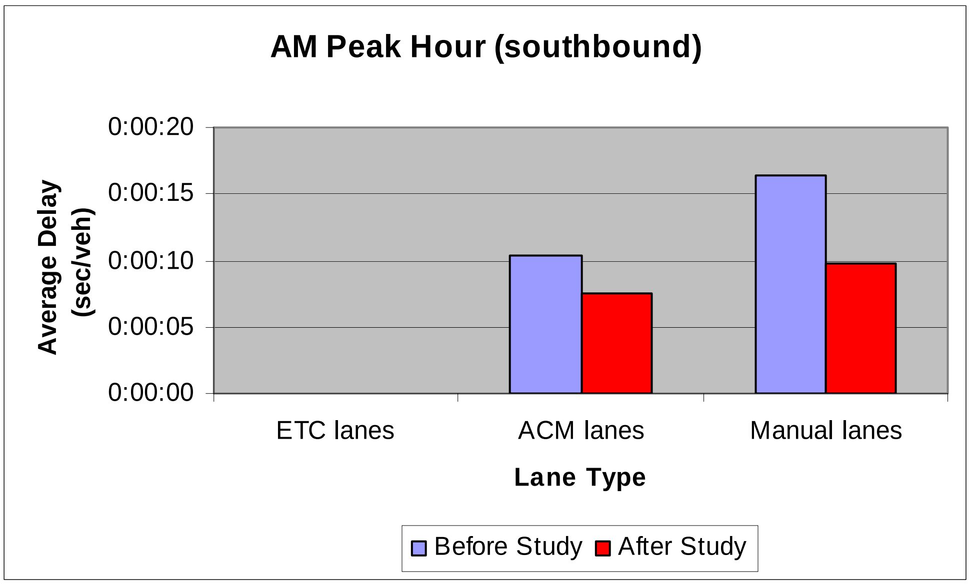

Figure 36 Comparison - Average Delay (AM Southbound)

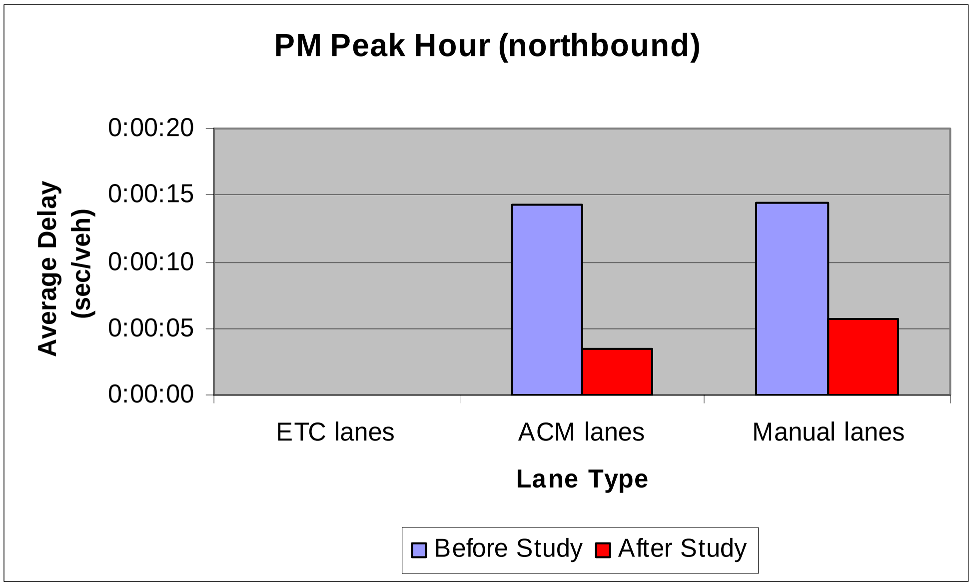

Figure 37 Comparison - Average Delay (PM Northbound)

Maximum delay is the highest recorded delay of any one individual vehicle during the peak hour of analysis. No consistent trends were observed for the maximum delay. During the AM peak hour, the maximum delay for the ACM lanes increased while the maximum delay for the manual lanes decreased. During the PM peak hour, there was a decrease in maximum delay for the ACM lanes but no change for the manual lanes.

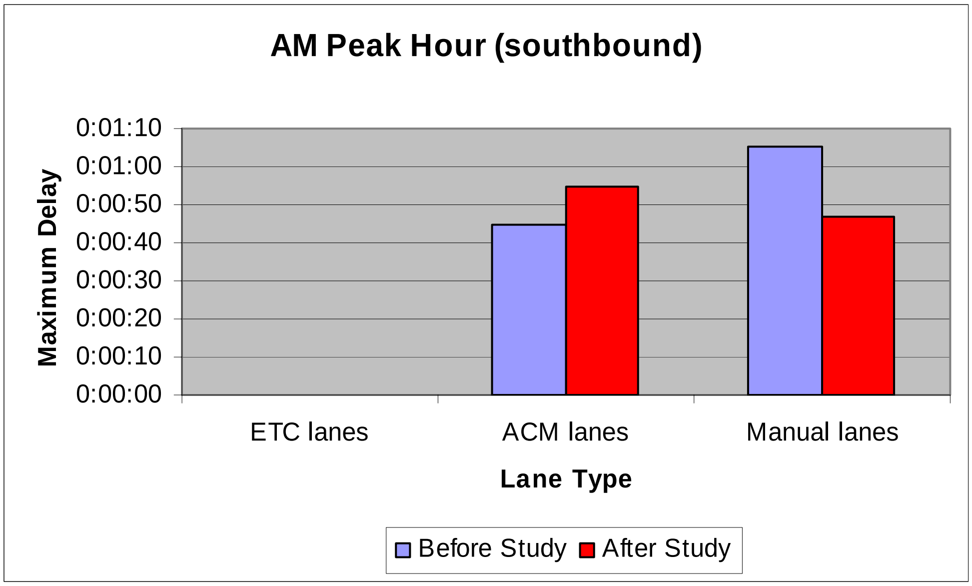

Figure 38 Comparison – Maximum Delay (AM Southbound)

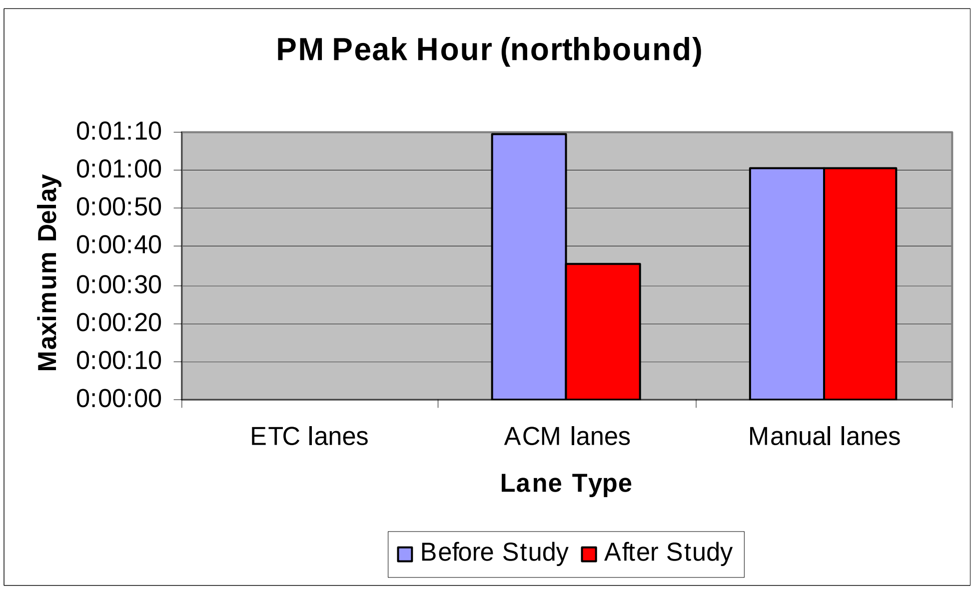

Figure 39 Comparison – Maximum Delay (PM Northbound)

Total delay is the sum of all individual vehicular delays for one lane during one peak hour per direction. This includes ETC vehicles that used the mixed conventional toll lanes. Similar to the average delay, the total delay in the after study decreased for both the ACM lanes and manual lanes for both peak hours. The reduction in total delay was 32 percent or more for all lane types. This represents an average savings in delay of 8 seconds per vehicle using the mixed conventional lanes in the after study.

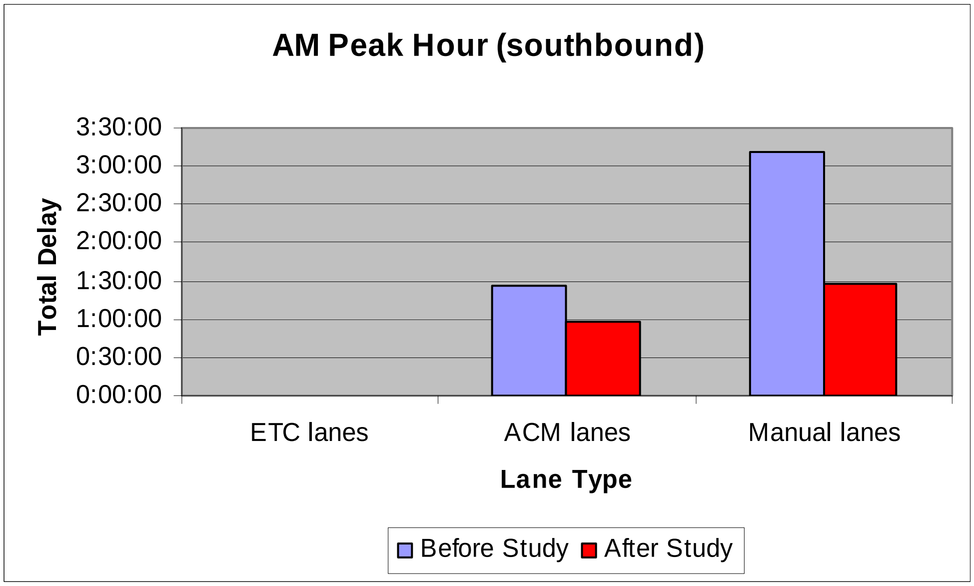

Figure 40 Comparison - Total Delay (AM Southbound)

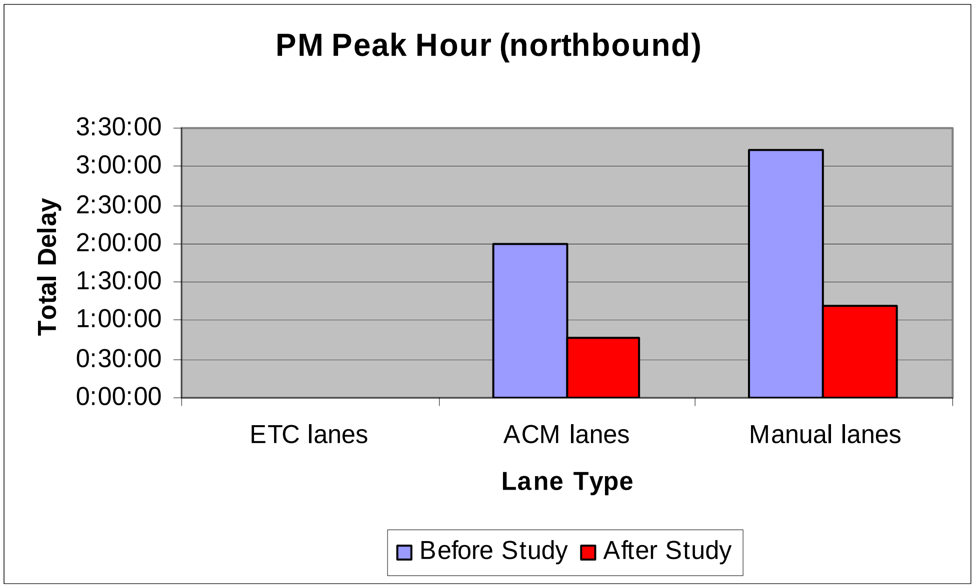

Figure 41 Comparison - Total Delay (PM Northbound)

In addition to the four measures of effectiveness, other comparisons were made with the data and include average inter-vehicle times and arrival rates for each lane type. Inter-vehicle time is the difference between departure times for two consecutive vehicles at the toll plaza for each lane. The individual recorded times for each lane were averaged to obtain an overall inter-vehicle lane average. The overall inter-vehicle lane averages were rounded to the nearest second. Typically, lower volumes should produce higher average inter-vehicle times. Average inter-vehicle times increased for the manual and ACM lanes in the after study for both the southbound and northbound directions. Alternatively, the average inter-vehicle times for the ETC lanes actually decreased in the after study from an average of 3 seconds to 2 seconds. This does not directly correspond to the increase in throughput, since the increase in throughput for each ETC lane was not of the same magnitude. In general, when inter-vehicle times increase there are larger headways which result in less congestion.

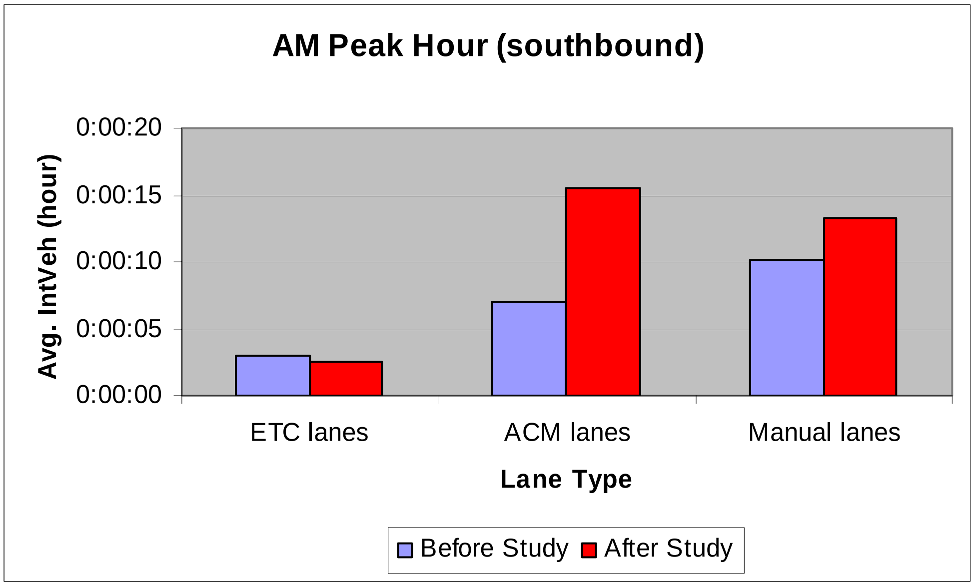

Figure 42 Comparison – Average Inter-vehicle Time (AM Southbound)

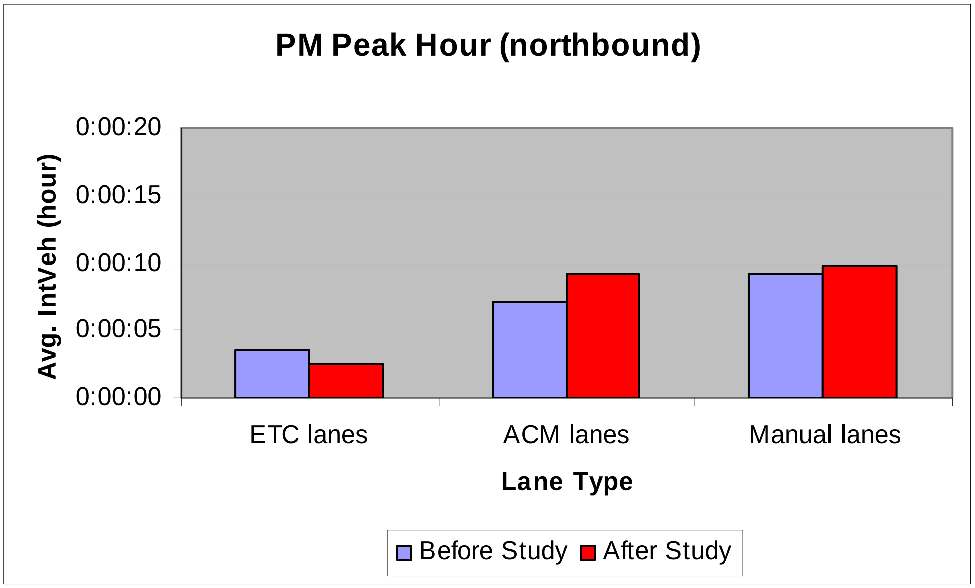

Figure 43 Comparison – Average Inter-vehicle Time (PM Northbound)

The arrival rate is the number of vehicle arrivals each minute recorded from the peak hour for each lane. For the non-dedicated ETC lanes, the vehicle is considered to arrive at a specific toll lane either when joining an existing queue or when pulling up to the toll booth for service (when no queue exists for the lane). The individual arrival times were recorded using the upstream video data. Since vehicles are not required to stop in the dedicated ETC lanes, the number of arrivals is equal to the number of departures. The arrival rates for the ETC lanes increased in the after study but a reduction in arrival rate was observed for the other lane types. More vehicles desired to use the ETC lanes, rather than the other toll lane types. The shift in arrival rate patterns accompanies the introduction of express ETC lanes at the plaza in the after study.

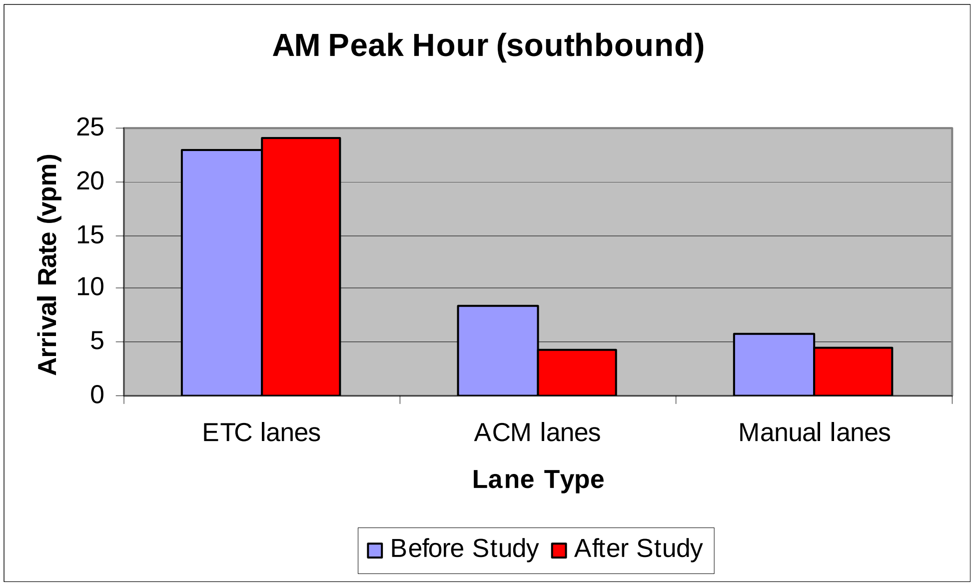

Figure 44 Comparison – Arrival Rate (AM Southbound)

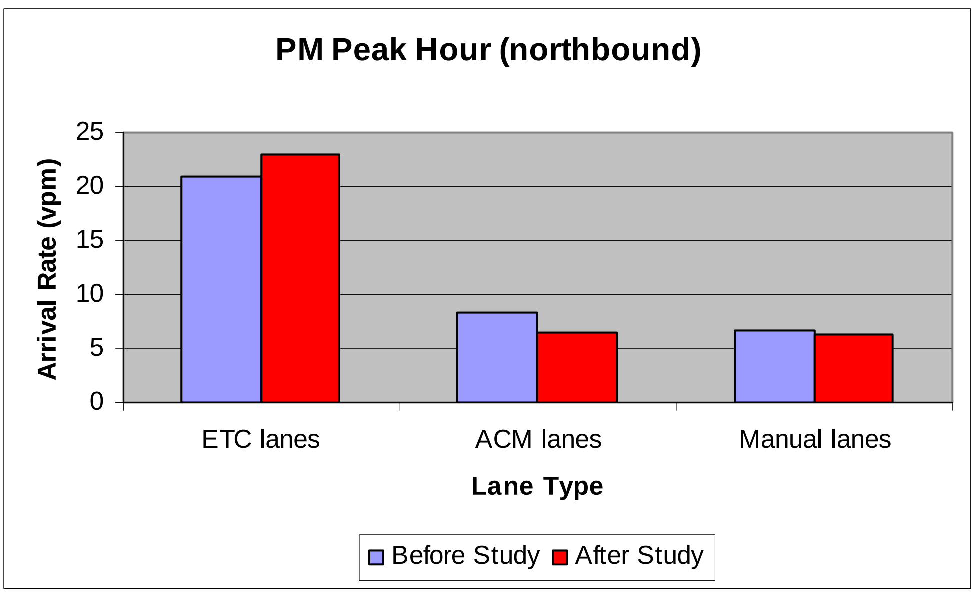

Figure 45 Comparison – Arrival Rate (PM Northbound)

Figure 46 shows the relationship between speed in the ETC lanes and the throughput for each dedicated ETC lane. During the before study, the left lane had slightly higher speed but lower volume. Volumes were much higher in the right lane that was located adjacent to the conventional toll lanes. This trend reversed in the after study since there were higher volumes in the left lane. At the same time, speeds in the left lane were slightly higher than the right lane but the differences were less than in the before study. Speed increases were observed for both lanes in the after study. These improvements can be attributed to the separation of the express ETC lanes and alignment of the downstream through lanes for highway speed traffic. The separation and realignment of the ETC lanes eliminated the upstream and downstream weaving that was necessary when dedicated ETC lanes were provided. The express ETC lanes were realigned so that the downstream through lanes for high speed traffic were located so that weaving movements were no longer necessary.

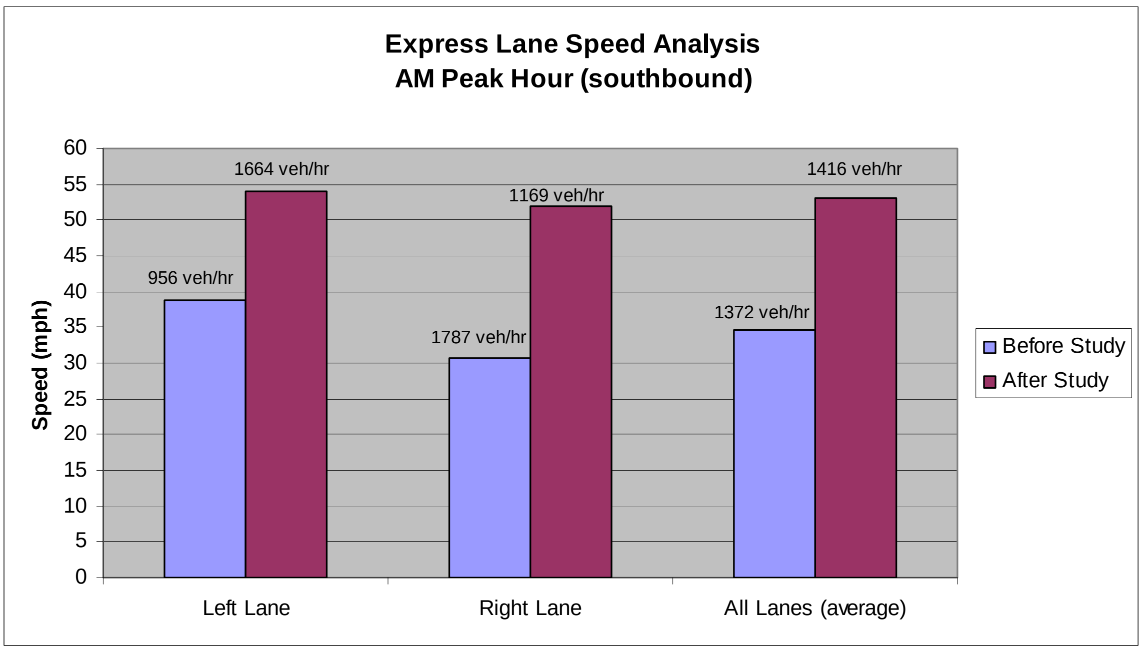

Figure 46 Comparison – Express Lane Speed Analysis

CHAPTER SIX: EXPRESS LANES ANALYSIS

6.1 Field Data and Statistics

Express lanes were analyzed in further detail in the following paragraphs. One-minute ETC volumes were calculated for each of the days and separated between the AM and PM time periods. Data from both the before study and after study were used. The one-minute volumes were used to calculate five-minute volumes. Tables 23 and 24 show the average five-minute volumes for each lane during the AM and PM time periods, respectively. Lanes are separated by whether they were the left or right lanes of that particular configuration. In addition, Figures 47 and 48 are graphical depictions of this data. During the AM before study time period, the right lane has higher volume. During the AM after study time period, the left lane has higher volume than the right. The same phenomenon is true for the volumes during the PM time periods. Based on the graphs, we can see the differences between each particular lane. Note the shift in usage for the ETC lanes. The left lane in the before study has the lowest of the four volumes in each graph. This is the lane that required the most weaving in order for ETC customers to use. Weaving was required upstream and downstream of the plaza in order to reach this lane and then maneuver back to the highway lanes, respectively. Notice that there is not as much of a difference between the volumes both ETC lanes in the after study. The left and right ETC lanes during the before study, on the other hand, have much different lane volumes.

Table 23 Analysis - Average Five-minute ETC Lane Volumes (AM)

AM (7:00 to 8:00)

	Before Study		After Study	
Time Interval	Left Lane	Right Lane	Left Lane	Right Lane
1	61	130	102	68
2	65	144	113	84
3	75	146	127	90
4	78	150	134	99
5	86	150	146	105
6	89	157	146	107
7	88	155	160	120
8	97	155	143	100
9	95	150	142	104
10	75	158	151	105
11	86	148	136	96
12	78	130	154	99

Table 24 Analysis - Average Five-minute ETC Lane Volumes (PM)

PM (5:00 to 6:00)

	Before Study		After Study	
Time Interval	Left Lane	Right Lane	Left Lane	Right Lane
1	55	134	124.5	77
2	46.5	127	136.5	91.5
3	50	126	141	98.5
4	58	138.5	136	101
5	67	138.5	135	96.5
6	64	148.5	135	107.5
7	59.5	144.5	149	104
8	63	138.5	125.5	88
9	59.5	144	141.5	100.5
10	57.5	152	137.5	101
11	61	146.5	129.5	86.5
12	60	149.5	127.5	78.5

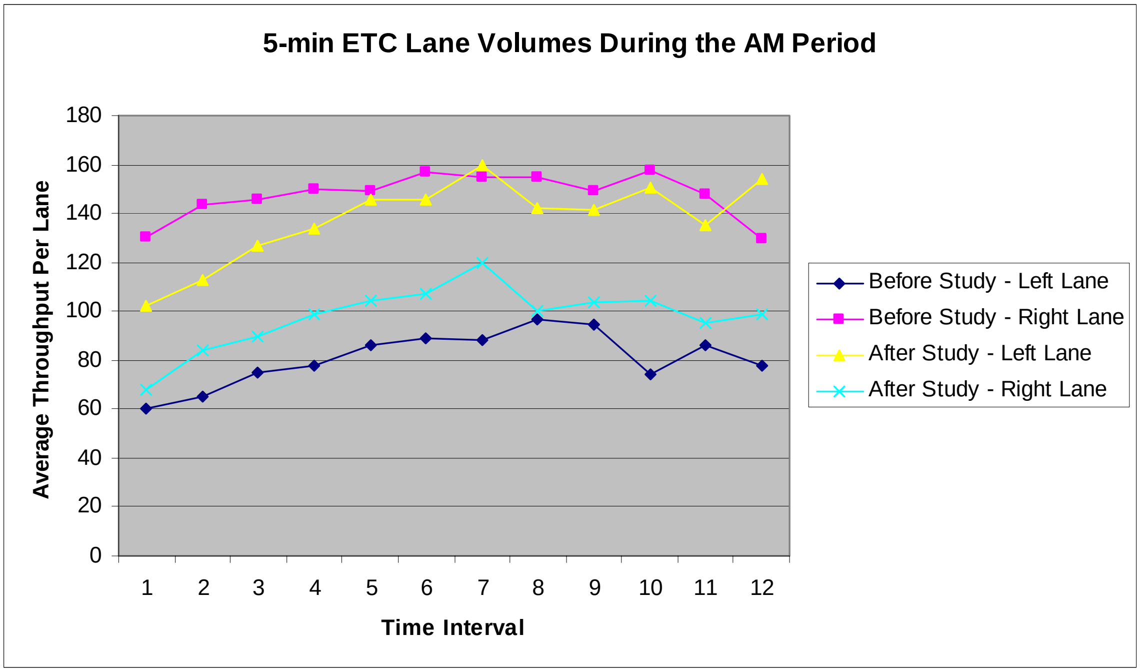

Figure 47 Analysis - Average Five-minute ETC Lane Volumes (AM)

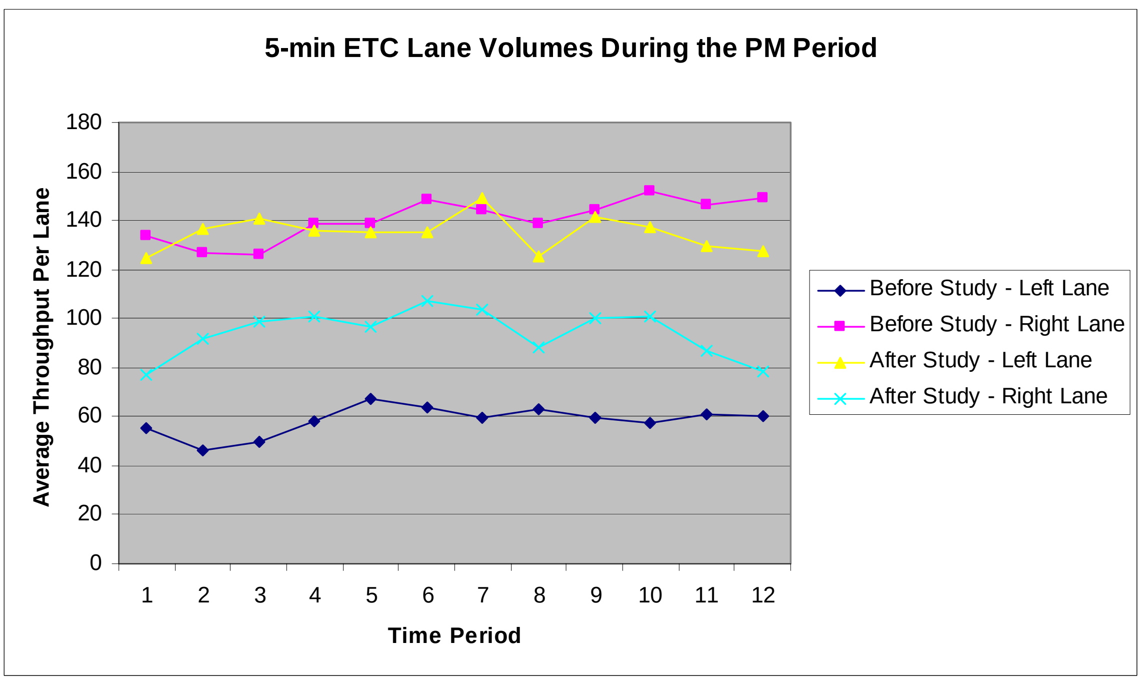

Figure 48 Analysis - Average Five-minute ETC Lane Volumes (PM)

A Chi-Square Test was performed on the 5-minute ETC volumes between days during the before study and days during the after study. The tests were separated by time period. Statistics were calculated between each particular lane. The following summarizes the statistical test.

Null Hypothesis (Ho): the ETC lane volumes are not significantly different

Alternative Hypothesis (Ha): the ETC lane volumes are significantly different

Results of the Chi-Square Test are included in Tables 25 and 26. Any results with a value less than 0.05 indicate that the mean difference is significant at the 0.05 level of significance. During the AM time period, although the right lane in the before Study is similar to the left lane in the after study, it is still significantly different since the p-value is less than 0.05. During the PM time period, the right lane in the before study is not significantly different than the left lane in the after study, since it's value is equal to 0.325 (greater than 0.05).

Table 25 Analysis - Chi-Square Test for ETC Lane Volumes (AM)

AM (7:00 to 8:00)

		Before Study		After Study	
		Left Lane	Right Lane	Left Lane	Right Lane
Before Study	Left Lane	N/A	0.000	0.000	0.000
	Right Lane	0.000	N/A	0.009	0.000
After Study	Left Lane	0.000	0.009	N/A	0.000
	Right Lane	0.000	0.000	0.000	N/A

Table 26 Analysis - Chi-Square Test for ETC Lane Volumes (PM)

PM (5:00 to 6:00)

		Before Study		After Study	
		Left Lane	Right Lane	Left Lane	Right Lane
Before Study	Left Lane	N/A	0.000	0.000	0.000
	Right Lane	0.000	N/A	0.325	0.000
After Study	Left Lane	0.000	0.325	N/A	0.000
	Right Lane	0.000	0.000	0.000	N/A

Overall averages were also calculated for the before study lanes and the after study lanes. This gives an overall picture of the differences between the before study and the after study ETC volumes (average per lane). Figure 49 shows the trend that the after study volumes are generally higher than those in the before study for the ETC lanes. Figure 50 shows the slight differences between the before study and after study volumes during each five-minute increment. Note that the after study volumes are consistently equal to or higher than the before study volumes during the same time increments (five-minutes).

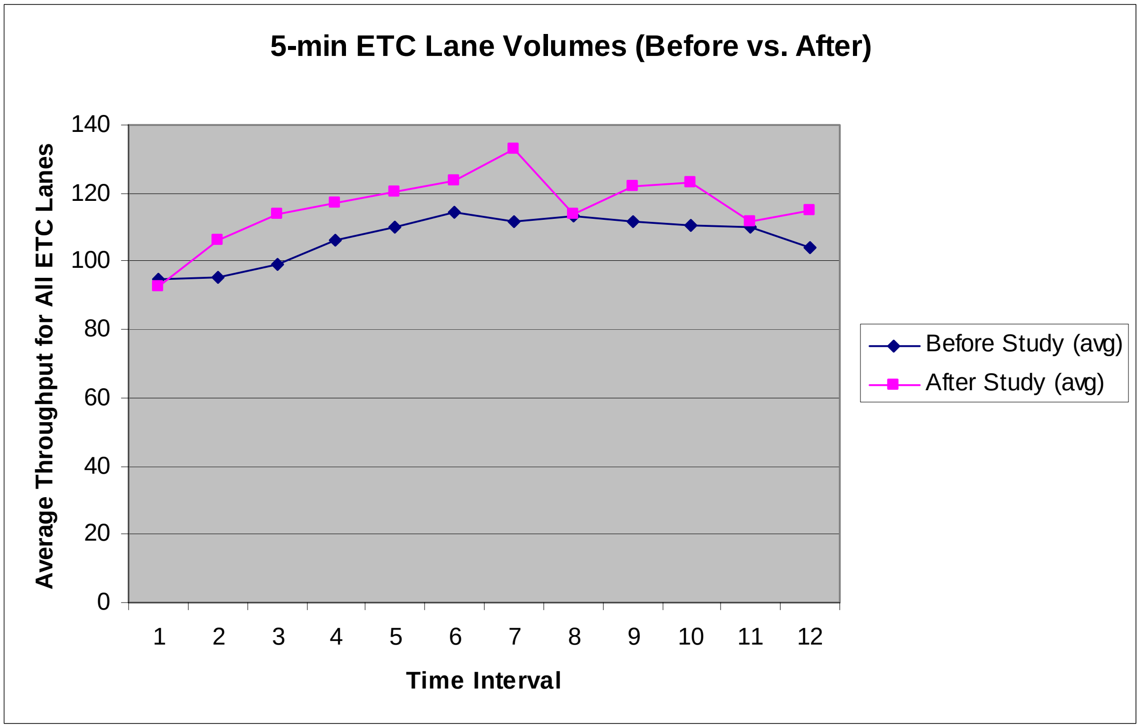

Figure 49 Analysis - Five-minute ETC Lane Volumes (Before Study vs. After Study)

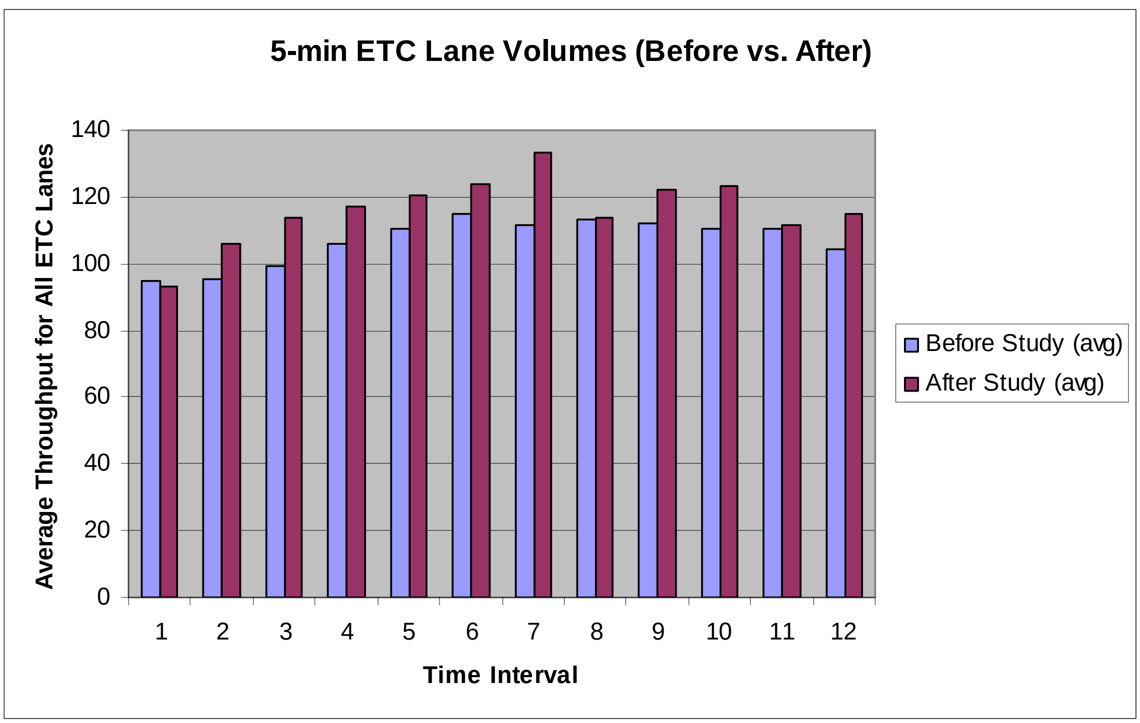

Figure 50 Analysis - Five-minute ETC Lane Volumes (Before Study vs. After Study)

A Scheffe's statistical test was performed to determine the difference in speeds between the before study dedicated ETC lanes and the after study express ETC lanes. Table 27 is a summary of Scheffe's test between the before study speeds and the after study speeds.

Null Hypothesis (Ho): the ETC lane speeds are not significantly different

Alternative Hypothesis (Ha): the ETC lane speeds are significantly different

According to the results, there is a significant difference in speeds between each before study ETC lane and all of the after study ETC lanes.

Table 27 Analysis - Statistical Results for ETC Lane Speeds

					Before Study (2002)							
					AM				PM			
		Date	Day	Date Day Lane	Feb6 wed 38	Feb6 wed 9	Feb20 Wed 38	Feb20 wed 9	Feb19 tues 8	Feb19 tues 39	Feb20 Wed 8	Feb20 wed 39
After Study (2003)	AM	Jun11	wed	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Jun11	wed	10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Jun12	thurs	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Jun12	thurs	10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	PM	Jun17	tues	7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Jun17	tues	8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Jun18	wed	7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		Jun18	wed	8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

(shaded) indicates that the mean difference is significant at the .05 level.

6.2 Capacity and Car-Following Equations

The capacity of an express ETC lane should approach that of a regular highway lane, since speeds through the toll collection point remain unchanged from the mainline highway (unless there are geometric constraints at the toll collection point). According to the Highway Capacity Manual, a toll road is similar to a freeway, except that tolls are collected at designated points along the facility (HCM 2000). Although toll collection usually involves interruptions of traffic flow, these facilities may generally be treated as freeways. However, special attention should be given to the unique characteristics, constraints, and delays caused by toll collection facilities.

The freeway capacity is the maximum sustained 15-min flow rate, expressed in passenger cars per hour per lane that can be accommodated by a uniform freeway segment under prevailing traffic and roadway conditions in one direction of flow. Capacity is related to the free-flow speed of the freeway segment being analyzed. By definition, the free-flow speed (FFS) is the mean speed of passenger cars that can be accommodated under low to moderate flow rates on a uniform freeway segment under prevailing roadway and traffic conditions. Factors that affect free-flow speed include the following (HCM 2000):

- number of lanes
- lane width
- lateral clearance
- interchange density or spacing

Other factors that are believed to influence the FFS (but for which little is known quantitatively) include the horizontal and vertical alignments, speed limit, level of enforcement, lighting conditions, and weather (HCM 2000). According to field observations of the express lanes at the University Plaza, lane widths were equal to 12 feet and the lateral clearances for all express ETC lanes were greater than or equal to 6 feet. Therefore, no geometric conditions existed that would theoretically reduce the lane capacity for vehicles traveling through the plaza.

Under base traffic and geometric conditions, freeways will operate with capacities as high as 2,400 pc/h/ln. This capacity is typically achieved on freeways with a FFS of 70 mi/h or greater (HCM 2000). As the FFS decreases, there is a slight decrease in capacity. For example, the capacity of a basic freeway segment with a FFS of 55 mi/h is expected to be approximately 2,250 pc/h/ln (HCM 2000).

In the same manner, capacities of multilane highways were also reviewed. In general, multilane highways have posted speed limits of 40 to 55 mi/h and usually have a total of four to six lanes (counting both directions). Both directions of travel are usually separated by either a median or two-way left-turn lane. The traffic flow characteristics of multilane highways range from the uninterrupted flow of freeways to the flow conditions on urban streets (HCM 2000).

The capacity of a multilane highway is the maximum sustained hourly flow rate at which vehicles reasonably can be expected to traverse a uniform segment under prevailing roadway and traffic conditions. The FFS for multilane highways is the mean speed of passenger cars under low-to moderate traffic flow. According to the Highway Capacity Manual, the capacity of a multilane highway with a FFS of 60 mi/h is approximately 2200 pc/h/ln. This represents the maximum 15-min flow rate accommodated under base conditions for highway with a FFS of 60 mi/h. The capacity of a multilane highway with a FFS of 45 mi/h is approximately 1850 pc/h/ln (HCM 2000). Therefore, the capacity of multilane highways decreases as the free-flow speed decreases. The same is also true for freeways. Applying this same concept to ETC lanes, as the speed is increased from 35 mi/h (dedicated ETC lanes) to 65 mi/h (express ETC lanes), we should expect a higher capacity for the express ETC lanes.

Equations and car-following theory were also used to prove that if the ETC speed is increased, then the throughput is expected to increase as well. The calculated capacity is computed using the average inter-vehicle time during the peak twenty minutes of the hour. The calculated capacity can be more conservative than the measured capacity due to the inability to collect inter-vehicle times of less than one second, so measured capacities were used instead.

The measured capacity is computed from the highest consecutive throughput (departures) of a selected time interval during the entire peak hour (i.e. 672 veh/20 min*3 = 2016 veh/h). Measured capacities were obtained during the before study for the dedicated ETC lanes and are included in Table 28. The corresponding average speeds for each lane were also obtained and are included in the table. The posted speed limit for each of the dedicated ETC lanes was 35 mph. The maximum measured capacity of 2016 veh/h corresponded to an ETC speed of 31 mph.

Table 28 Analysis - Measured Capacities during the Before Study

Day of the week	Description	Lane No.	Meas. Speed (mph)	Measured capacity (veh/h)	Calculated Spacing (ft)
Wednesday	February 6, 2002 AM SB	Lane 9	31	2016	81.19
Tuesday	February 19, 2002 AM SB	Lane 9	30	1947	81.36
Tuesday	February 19, 2002 PM NB	Lane 8	34	1650	108.8
Wednesday	February 20, 2002 AM SB	Lane 9	31	1968	83.17
Wednesday	February 20, 2002 PM NB	Lane 8	33	1724	101.07

Using the maximum measured capacity and associated ETC speed, the following equations were used to estimate the capacity for an express ETC lane at 65 mph. Where:

- h = headway (sec/veh)
- s = *spacing (ft/veh)*
- v = *speed (ft/sec)*
- L = *car length (ft) = 20 feet (Mohamed 2000)*
- q = *flow rate (veh/h)*
- R = *perception-reaction time (sec)*

Equation 1 was obtained from the Highway Capacity Manual (equation HCM 7-7 in the manual), and shows the relationship between the headway, spacing, and speed (HCM 2000):

$$h = \frac{s}{v} \qquad \text{(Equation 1)}$$

Equation 2 is a rearrangement of Equation 1:

$$v = \frac{s}{h} \qquad \text{(Equation 2)}$$

According to the Highway Capacity Manual, flow is inversely proportional to the headway, as shown in Equation 3 (equation HCM 7-8 in the manual). Equation 3, which can be substituted into the previous equation, is shown below (HCM 2000):

$$q = \frac{3600}{h} \qquad \text{(Equation 3)}$$

The spacing is a function of the velocity and flow rate (in this case, the measured capacity). For 2016 veh/h at 31 mph, the spacing is equal to 81.2 feet. Equation 4 shows the relationship between spacing, speed, and the flow rate:

$$s = \frac{v}{q} \qquad \text{(Equation 4)}$$

The basic car-following equation is shown below as Equation 5. Assuming an average car length of 20 feet, which matches the assumption used in TPSIM (Mohamed 2000), and assuming a safe stopping distance between cars, the spacing can be related to the reaction time. This is true since the car length and velocity are already known.

$$s = L + Rv \qquad \text{(Equation 5)}$$

In order to calculate the reaction time, this equation was rearranged to form Equation 6:

$$R = \frac{s - L}{v} \qquad \text{(Equation 6)}$$

The reaction time was calculated to be 1.346 sec. Using the calculated reaction time, car length, and velocity, we can use Equation 7 to calculate the expected capacity of an express ETC lane:

$$q = \left(\frac{1}{\frac{L}{v} + R} \right) 3600 \qquad \text{(Equation 7)}$$

The posted speed limit of the express ETC lanes is 65 mph. Using a reaction time of 1.346 sec and assuming that the ETC speed is increased to 65 mph, we now have a calculated capacity of 2,314 vph. Therefore, assuming that the reaction time is held constant, the capacity was increased from 2016 to 2314 vph when the ETC speed increases from 31 mph to 65 mph. This indicates an increase in capacity of 14.8 percent.

An alternative method involves calculating the new spacing at a reaction time of 1.346 sec and speed equal to 65 mph. This new spacing would be 148.39 ft/veh according to the car-following equation. Using the HCM equation, a flow of 2,314 vph was calculated based on the speed and spacing of 65 mph and 148.39 ft/veh, respectively.

CHAPTER SEVEN: COMPUTER SIMULATION

7.1 TPSIM Model Calibration

Three different days from the before study analysis were used to calibrate the TPSIM model for the University Mainline Toll Plaza. A calibration procedure was followed by first adjusting the input variables that least directly impact the individual operations of the vehicles. The order of adjusting these parameters began with the plaza geometric data and then the global parameters. The geometric dimensions of the University Plaza were verified. One of the geometric dimensions, the approach lane length, was an identified calibration parameter based on a previous research paper (Klodzinski 2002b). The calibration parameters from the previous Dean Plaza TPSIM model analyses were used as a starting point for the initial calibration. Incremental adjustments were made to each of these identified calibration parameters. The adjustments were based on testing the statistical difference between the model output and field measures of effectiveness (MOE) collected at the University Plaza for each of the before study days. The throughput was tested using the Chi Distribution. The average, maximum, and total queuing delays tested using the Wilcoxon Signed Rank Test.

The order of calibration was February 12 PM, followed by February 20 AM, and concluded with February 20 PM. Incremental adjustments were made to the first calibration parameter, the approach lane length, while all other parameters were held constant for February 12 PM. Two or three runs using the same input variables were completed and the MOE were analyzed. The values of each parameter were adjusted according to the results but were held constant once it was found that further improvements could not be made by making adjustments. Once satisfactory results were obtained for February 12 PM, February 20 AM was simulated and calibrated using the same procedure. Then, February 12 PM was simulated again, using the calibration parameters for February 20 AM. This process was continued until both days had acceptable results. Then, the calibration parameter values were used to simulate February 20 PM and the same process was followed using all three days until acceptable results were obtained. The final desired outcome was one set of input parameters for all evaluated MOEs at the University Plaza.

The approach lane length was the calibration parameter that least directly impacted the individual operations of vehicles, so it was adjusted first (Klodzinski 2002b). The following parameters were used to calibrate the model:

- Approach Lane Length - The length of the lanes upstream of the toll plaza prior to the transition zone. This is where vehicle arrivals are generated in the simulation. Deceleration begins in this upstream section.
- Average Approach Speed - The average speed of the vehicles as they approach the toll plaza before beginning to decelerate.
- Approach Speed Standard Deviation - The standard deviation of the approach speed.
- Average Deceleration Rate - The rate at which a vehicle decreases speed upon approach to the toll plaza or a queued vehicle.
- Deceleration Rate Standard Deviation

- Average Acceleration Rate - The rate at which a vehicle increases speed after deceleration. This value is applied to a vehicle after it has decelerated and if it is necessary to increase speed again (for example, if it was stopped in a queue and must speed up again)
- Acceleration Rate Standard Deviation
- Clearance - The minimum and maximum spacing between two vehicles.
- ETC Speed - The average speed of the vehicles using the dedicated ETC lane(s).
- Service Time - The length of time a vehicle spends at the booth to pay a toll.

The last parameter to be adjusted was the service time distribution, which was found to be the most influential of the parameters since delay is a direct result of service time. Even slight changes in the service time distribution had significant effects on the results for the delay output. The service time distribution is unique for each lane of the toll plaza and impacts all of the vehicles queued as well as approaching vehicles, since vehicles will select lanes not only based on their payment method but also the lane with the shortest queue. The service time collected from the field can inherently have some rounding errors over an entire hour since the service time cannot be determined with accuracy better than the nearest second.

Table 29 and Table 30 summarize the calibration parameter increments and values that were used during the calibration procedure:

Table 29 Calibration – Input Parameter Increments

Parameter	Unit	Minimum	Maximum	Increment
Approach Lane Length	ft	2100	2900	200
Average Approach Speed	mph	45	60	5
Approach Speed Standard Deviation	mph	5	10	1
Average Deceleration Rate	ft/s^2	3	4	0.5
Deceleration Rate Standard Deviation	ft/s^2	0.5	1	0.5
Average Acceleration Rate	ft/s^2	3	4	0.5
Acceleration Rate Standard Deviation	ft/s^2	0.4	0.8	0.2
Clearance	ft	10	70	10
ETC Speed	mph	35	40	5

Table 30 Calibration – Input Parameter Values

Parameter	University		Dean	
Approach Lane Length	2100	Ft	2000	ft
ETC Speed	35	mph	40	mph
Average Approach Speed	55	mph	60	mph
Average Approach Speed (Standard Deviation)	10	mph	8	mph
Deceleration Rate	4	ft/s^2	3.5	ft/s^2
Deceleration Rate (Standard Deviation)	0.5	ft/s^2	0.5	ft/s^2
Acceleration Rate	4	ft/s^2	3.5	ft/s^2
Acceleration Rate (Standard Deviation)	0.6	ft/s^2	0.4	ft/s^2
Clearance	50-70	Ft	20-40	ft

Table 31 includes a summary of the traffic and plaza characteristics for the three days that were chosen for calibration. In TPSIM, a truck is defined as any vehicle with 3 axles or more.

Table 31 Calibration – Traffic and Plaza Characteristics

Characteristic	Feb 12, 2002 PM	Feb 20, 2002 AM	Feb 20, 2002 PM
# of Approach Lanes	2	3	2
# of Manual Lanes	2	2	2
# of ACM Lanes	1	1	1
# of ETC Lanes	2	2	2
Plaza Volumes	3580	3985	3830
% of Manual Payments	22.7	18.2	21
% of ACM Payments	13.9	13	14
% of ETC Payments	63.4	68.8	65
% of Trucks	1	2	1

The Run Specification Window in Figure 51 is the first window for initializing a TPSIM simulation run and specifies the beginning and ending time for the simulation, which in this case is 7:00 AM to 8:00 AM, respectively. The Random Number Offset (RNO) was changed for each run of each day. The RNO is a "number seed" that is necessary to ensure that each run is unique for a specified set of input variables. Each different number seed introduces internal traffic variations based on the specified number.

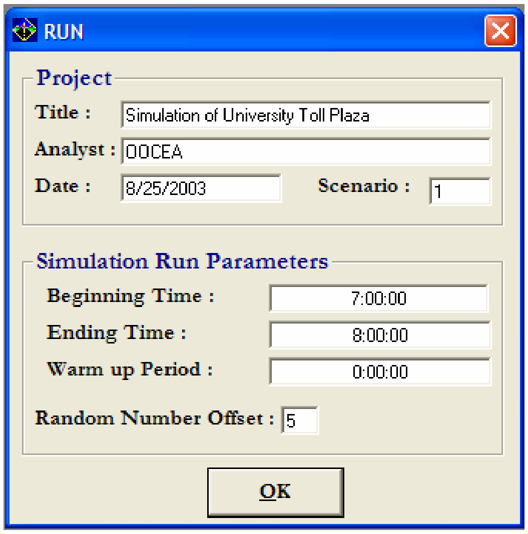

Figure 51 Calibration - Run Specifications Window

The Plaza Geometric Window in Figure 52 shows the geometric input that was used in each simulation. Only the number of approach lanes varied, depending on the direction of travel (northbound or southbound).

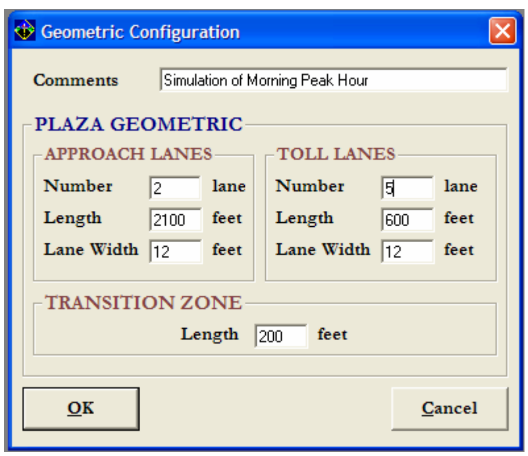

Figure 52 Calibration - Plaza Geometric Window

The Toll Lane Type and Schedule Window are shown in Figure 53. Each of the days in the before study had the same toll lane configurations and schedule. See Tables 1 and 2 for the toll lane types and configuration. All of the toll lanes were assumed to be open during the simulated hour. In other words, no lane closures were simulated.

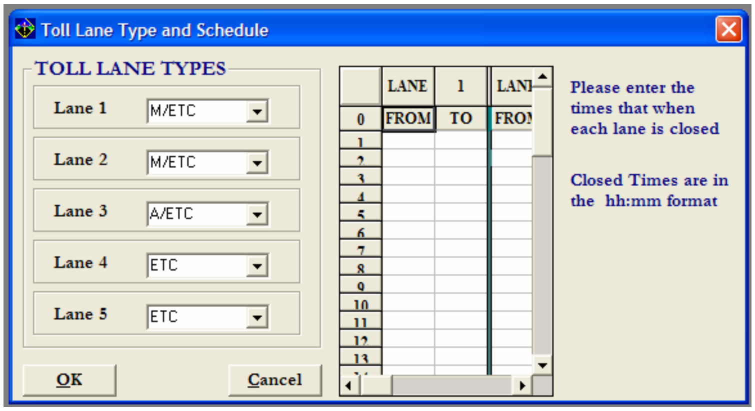

Figure 53 Calibration - Toll Lane Type and Schedule Window

The Global Parameters Window is shown in Figure 54. The reaction times for this calibration were identical to those used for the Dean Mainline Toll Plaza and it was assumed that the reaction time among vehicles followed a uniform distribution with a minimum of 0.46 seconds and a maximum of 1 second. But, for the Holland East Plaza, it was assumed that the reaction time among vehicles followed a uniform distribution with a minimum of 0.64 seconds and a maximum of 1.7 seconds.

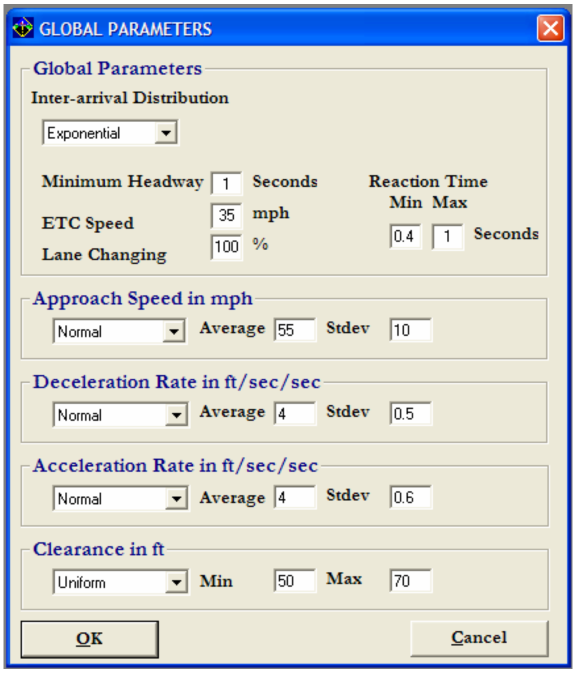

Figure 54 Calibration - Global Parameters Window

The Traffic Data Window in Figure 55 was used to select the hour of simulation. Traffic volumes were entered in the Traffic Volume Window shown in Figure 56. Traffic volumes for each 5-minute interval are given in Table 32. The 5-minute volumes were collected from the field. The individual lane volumes are summed together to represent the traffic of the entire plaza. The arrival time of each vehicle, extracted from the videotapes, was summed for each 5-minute interval for all lanes. This was completed for all three days.

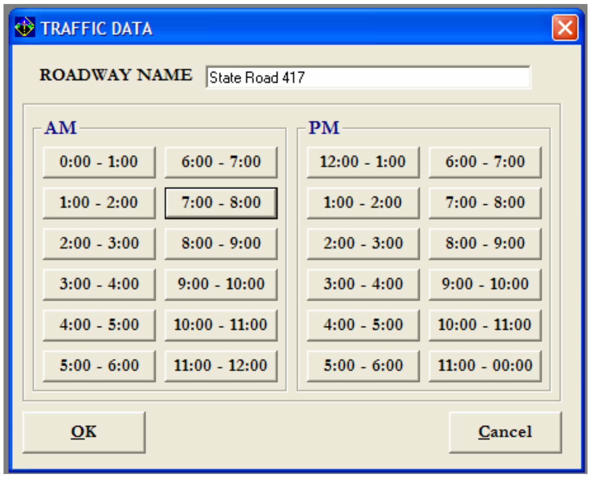

Figure 55 Calibration - Traffic Data Window

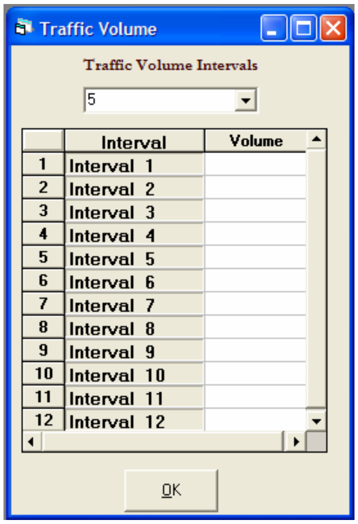

Figure 56 Calibration - Traffic Volume Window

Table 32 Calibration - Traffic Volume Values During 5-minute Intervals

Traffic Volume Values During 5-minute Intervals

Time Interval	February 12, 2002 PM	February 20, 2002 AM	February 20, 2002 PM
1	285	243	305
2	239	319	327
3	255	320	296
4	321	329	304
5	322	347	315
6	304	360	335
7	294	362	330
8	296	348	327
9	307	351	314
10	314	351	333
11	329	324	318
12	314	331	326

The Traffic Condition Window in Figure 57 is where the percentages of each vehicle type and vehicle class are selected. See Table 31 for the percentages for each of the before study days.

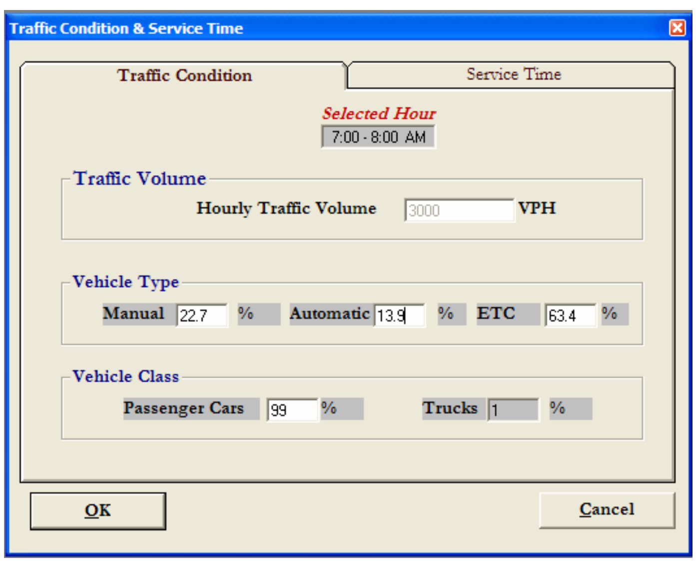

Figure 57 Calibration - Traffic Condition Window

The Service Time Window in Figure 58 is where service time distributions were specified for each lane. The service time was determined to have the most significant impact on the simulation model (Klodzinski 2002b). Scheffe's statistical test was performed for the service time distributions to ensure that each of the three days from the before study had similar service time distributions for the same lane types (manual, ACM). See Tables 33, 34, and 35 for service time distributions for each of the three before study days. The best fit for service time was a discrete distribution. Since the service time value can change for each customer, fitting a stochastic distribution for service time for each lane is the appropriate way to represent the fluctuation in service time. By extracting the service time for each vehicle in each lane from the videotapes, it has been found that the best fit for service time is a discrete distribution (Al-Deek 2001a, Klodzinski 2002b). The service times for ETC vehicles using the conventional lanes (Manual and ACM) are equal to zero seconds. Note that a uniform service time distribution with minimum and maximum service time values of zero seconds was automatically specified for the ETC lanes.

Initial service time distributions were obtained from the video analysis for each lane. The service time was found to be the input value that most directly affects individual lane performance. The service time was an identified calibration parameter and was the last value to be adjusted in the calibration process. The service time collected from the field can have some slight rounding errors over an entire hour since it impossible to determine the service time with accuracy better than the nearest second. Therefore, incremental adjustments were made to the service time distributions at the end of each calibration process.

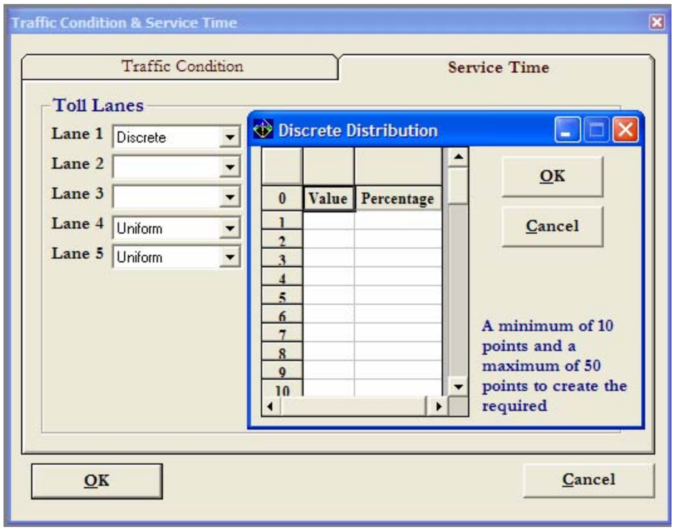

Figure 58 Calibration - Service Time Window

Table 33 Calibration - Service Time Distributions for February 12, 2002 PM

Serv. Time	Lane 5 M/E	Lane 6 M/E	Lane 7 A/E
0	11%	6%	11%
1	0%	0%	0%
2	15%	26%	25%
3	19%	25%	24%
4	14%	15%	22%
5	12%	9%	10%
6	9%	6%	5%
7	6%	4%	2%
8	3%	3%	1%
9	3%	2%	
10	2%	1%	
11	1%	1%	
12	2%	1%	
13	1%	1%	
14	1%		
15	1%		

Table 34 Calibration - Service Time Distributions for February 20, 2002 AM

Serv. Time	Lane12 M/E	Lane11 M/E	Lane10 A/E
0	7%	4%	13%
1	7%	2%	10%
2	13%	11%	16%
3	20%	19%	25%
4	14%	20%	15%
5	9%	15%	9%
6	6%	8%	6%
7	5%	4%	2%
8	5%	3%	1%
9	3%	3%	1%
10	2%	3%	1%
11	2%	1%	0%
12	2%	2%	1%
13	1%	1%	
14	0%	1%	
15	1%	1%	
16	1%	1%	
17	0%	0%	
18	1%	0%	
19	0%	1%	
20	1%		

Table 35 Calibration - Service Time Distributions for February 20, 2002 PM

Serv. Time	Lane 5 M/E	Lane 6 M/E	Lane 7 A/E
0	7%	4%	12%
1	5%	7%	3%
2	14%	21%	14%
3	19%	25%	21%
4	14%	15%	20%
5	12%	9%	14%
6	9%	6%	8%
7	6%	4%	4%
8	3%	3%	1%
9	3%	2%	1%
10	2%	1%	1%
11	1%	1%	0%
12	2%	1%	0%
13	1%	1%	0%
14	1%		0%
15	1%		1%

In order to successfully calibrate and apply TPSIM, calibration data must be chosen carefully. If multiple days are selected for calibration, they must:

- Have similar characteristics (plaza configuration)
- Have a service time that is not significantly different

Service time is the most significant value affecting the calibration process, especially when using delay for the calibration measures (Klodzinski 2002b). In order to investigate different scenarios the service times must not be significantly different; otherwise the scenarios will not have analytical value as a data test set.

Service time statistics were performed on the three before study days. Each of the three cash lanes for each day (two manual, one ACM) were compared to each of the lanes for the other days. Scheffe’s statistical test was used to find if there are any significant differences (at the 5% significance level) in service times of the conventional lanes among different days in the before study.

Null hypothesis (Ho): the two distributions are not significantly different

Alternative hypothesis (Ha): the two distributions are significantly different

A summary of the results for this statistical test are shown in Table 36. Based on the results, the service times for each of the M/E lanes are not statistically different than all of the other M/E lanes at the 0.05 level of significance. Similarly, the service times for each of the A/E lanes are not statistically different than all of the other A/E lanes at the 0.05 level of significance.

The differences that are indicated in the table occur between manual and ACM lanes. These differences are expected, since we know from previous data and reports that the service times of different lane types are usually different (Klodzinski 2002b). Therefore, we would expect there to be a statistical difference between the service times for manual and ACM lanes. This table also indicates that there is not a statistically significant difference between similar lane types (manual lanes with other manual lanes, and ACM lanes with other ACM lanes). In general, we should expect that lanes of the same type will have similar service time distributions.

Table 36 Calibration – Test of Significant Differences in Service Time (Scheffe's Test)

		Date	Feb12	Feb12	Feb12	Feb20	Feb20	Feb20	Feb20	Feb20	Feb20
		Day	Tues	Tues	Tues	Wed	Wed	Wed	Wed	Wed	Wed
Date	Day	Lane	5 M/E	6 M/E	7 A/E	5 M/E	6 M/E	7 A/E	10 A/E	11 M/E	12 M/E
Feb12	Tues	5 M/E	N/A	1.000	0.705	0.966	1.000	0.995	0.835	0.681	0.616
Feb12	Tues	6 M/E	1.000	N/A	0.579	0.987	1.000	0.985	0.731	0.791	0.736
Feb12	Tues	7 A/E	0.705	0.579	N/A	0.004	0.361	1.000	1.000	0.000	0.000
Feb20	Wed	5 M/E	0.966	0.987	0.004	N/A	0.998	0.137	0.011	1.000	1.000
Feb20	Wed	6 M/E	1.000	1.000	0.361	0.998	N/A	0.934	0.517	0.905	0.869
Feb20	Wed	7 A/E	0.995	0.985	1.000	0.137	0.934	N/A	1.000	0.013	0.008
Feb20	Wed	10 A/E	0.835	0.731	1.000	0.011	0.517	1.000	N/A	0.000	0.000
Feb20	Wed	11 M/E	0.681	0.791	0.000	1.000	0.905	0.013	0.000	N/A	1.000
Feb20	Wed	12 M/E	0.616	0.736	0.000	1.000	0.869	0.008	0.000	1.000	N/A

(shaded) indicates that the mean difference is significant at the .05 level.

The four measures of effectiveness (MOE) are defined as follows:

Throughput

The vehicle count downstream of the plaza.

Average Queuing Delay (AQD)

The time a vehicle spends waiting in a queue averaged over all vehicles in the queue upstream of the booth during the peak hour.

Maximum Queuing Delay (MQD)

The maximum time a vehicle spends in the queue at the toll plaza booth during the peak hour.

Total Queuing Delay (TQD)

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

The 5-minute field results for MOE's (throughput, AQD, MQD, and TQD) from the before study were used to compare with the TPSIM output. An Error Analysis Test was performed which involved statistical analysis to quantify the difference in each measure of effectiveness between the field data and the simulation outputs. In order to evaluate the performance of the simulation model, the results for the two manual transaction lanes were averaged for analysis. The two ETC lanes were also averaged so that a direct comparison could be made between the field and the model. The reason for computing this average is due to the fact that the simulation model does not distribute vehicles between the same lane types in the same manner as in the field. In order to account for the possible variability between individual simulation runs, an average of 10 runs (using different random number seeds) from the TPSIM model using the final calibration parameters was computed for each before study day. The first 5 minutes were excluded from the analysis since this is considered a warm-up period for the model. Outputs for each MOE were generated in 5-minute intervals to be used for comparison purposes.

Since throughput is an integer that can be counted in the field, the Chi-Square analysis was chosen to compare the field and simulated throughputs. A Chi-Square analysis tests whether or not the differences are statistically significant (Moore 1996). The main objective of the Chi-square test is to check if the distribution of throughput for each lane generated from TPSIM was identical to the throughput observed from the field. It is a measure of the distance the field data is from the simulated data. The following summarizes the test:

Null hypothesis (Ho): the two distributions were not significantly different

Alternative hypothesis (Ha): the two distributions are significantly different

Table 37 shows the Chi-square values for testing the five-minute interval throughput distribution for each lane. The level of significance was tested at the 95% confidence level. If the p-value is smaller than 0.05, then there is enough evidence to support rejecting the null hypothesis. The Chi-square value is used to determine the p-value based on the degrees of freedom (Moore 1996). Since the p-values for each lane and for each day are larger than 0.05, this indicates that at a 95% confidence level there is no significant difference between the simulated average tollbooth throughput and the observed values for all lanes under study.

Table 37 Calibration - Chi-Square Test Results for Throughput

Day	Lane	Chi-Square Value	P-Value	Conclusion
February 12, 2002 (PM)	M/ETC	3.57	0.98	*Identical Distributions*
	A/ETC	4.05	0.97	*Identical Distributions*
	ETC	1.44	1.00	*Identical Distributions*
February 20, 2002 (AM)	M/ETC	2.56	1.00	*Identical Distributions*
	A/ETC	2.73	0.99	*Identical Distributions*
	ETC	2.23	1.00	*Identical Distributions*
February 20, 2002 (PM)	M/ETC	2.85	0.99	*Identical Distributions*
	A/ETC	1.74	1.00	*Identical Distributions*
	ETC	0.83	1.00	*Identical Distributions*

Field results for throughput for each of the before study days were paired with each TPSIM output during every five-minute interval. The chi-squared test was used to compare observed and expected values. The observed and expected values (in this case the Field and TPSIM results per five-minute interval) were used to obtain a chi-square value for each pair using Equation 8:

$$\frac{(Field - TPSIM)^2}{(TPSIM)} \qquad \text{(Equation 8)}$$

Since the first five-minute observation is not used to calculate the statistics (this is considered a warm-up period), the chi-squared values for each of the remaining eleven pairs were added together to obtain an overall chi-squared value. The CHIDIST function in Excel returns the one-tailed probability of the chi-squared distribution and is associated with the chi-squared test. If the probability was greater than 0.05, then the Field and TPSIM results were statistically similar at the 95 percent confidence level.

Since delays are time based observations that are not counts that can be directly observed in the field, the Chi-square test was not an appropriate test to compare the delay observations. Therefore, the Wilcoxon Signed Rank Test was chosen for analysis of the delay MOEs. The Wilcoxon Signed Rank Test is a non-parametric test that tests the hypothesis that the two population probability distributions are identical against the alternative hypothesis that one is shifted to the right (or left) of the other. This is a matched-pairs design since we are comparing the field results with those from TPSIM. The differences between the measurements of each pair of values (field and simulated) were analyzed. If all of the differences were positive (or negative), the distributions were significantly different (one distribution is shifted a significant distance form the other). The matched pairs analysis tested the null hypothesis (Ho) that the distributions were identical as opposed to the alternative hypothesis (Ha) that there was a significant difference between the two distributions.

Null Hypothesis (Ho): the two distributions are not significantly different

Alternative Hypothesis (Ha): the two distributions are significantly different

The analysis was completed for the 95% confidence level. The T+ and T- values indicate the positive and negative values. The minimum of the two rank values was compared to To. If the chosen rank was greater than To, there was no evidence to reject the null hypothesis that the two distributions were the same. The To value can be derived from a statistical table based on the number of matched-pair samples (Mendenhall 1995). Another statistical reference is to use the p-value. A p-value greater than 0.05 indicates no significant difference in the distributions. This analysis was performed only for the manual and ACM lanes, since vehicles in the ETC lanes were not required to stop and therefore did not experience any delay. The statistical software, SPSS, was used to calculate T+, T-, To, and the corresponding p-value for the matched data pairs. See Table 38, 39, and 40 for results of the analysis for average queuing delay, maximum queuing delay, and total queuing delay, respectively. Note that all of the T+ and T- values are greater than the corresponding To values, which indicates that the two distributions were identical at the 95% confidence level.

Table 38 Calibration - Wilcoxon Signed Rank Test Results for Average Queuing Delay

Day	Lane	T+	T-	T0	P-Value	Conclusion
February 12, 2002 (PM)	M/ETC	20.0	46.0	11	0.248	*Identical Distributions*
	A/ETC	29.0	37.0	11	0.722	*Identical Distributions*
February 20, 2002 (AM)	M/ETC	31.0	35.0	11	0.589	*Identical Distributions*
	A/ETC	38.0	17.0	10	0.285	*Identical Distributions*
February 20, 2002 (PM)	M/ETC	39.0	27.0	11	0.594	*Identical Distributions*
	A/ETC	45.0	21.0	11	0.286	*Identical Distributions*

Table 39 Calibration - Wilcoxon Signed Rank Test Results for Maximum Queuing Delay

Day	Lane	T+	T-	T0	P-Value	Conclusion
February 12, 2002 (PM)	M/ETC	25.0	41.0	11	0.477	*Identical Distributions*
	A/ETC	34.0	32.0	11	0.929	*Identical Distributions*
February 20, 2002 (AM)	M/ETC	27.0	39.0	11	0.594	*Identical Distributions*
	A/ETC	34.5	31.5	11	0.894	*Identical Distributions*
February 20, 2002 (PM)	M/ETC	42.0	24.0	11	0.424	*Identical Distributions*
	A/ETC	38.0	28.0	11	0.656	*Identical Distributions*

Table 40 Calibration - Wilcoxon Signed Rank Test Results for Total Queuing Delay

Day	Lane	T+	T-	T0	P-Value	Conclusion
February 12, 2002 (PM)	M/ETC	22.0	44.0	11	0.328	*Identical Distributions*
	A/ETC	27.0	39.0	11	0.594	*Identical Distributions*
February 20, 2002 (AM)	M/ETC	38.0	28.0	11	0.657	*Identical Distributions*
	A/ETC	40.0	26.0	11	0.534	*Identical Distributions*
February 20, 2002 (PM)	M/ETC	42.0	24.0	11	0.424	*Identical Distributions*
	A/ETC	43.0	23.0	11	0.374	*Identical Distributions*

Since TPSIM was calibrated successfully, it has reached an acceptable level of reliability to represent traffic conditions at the University toll plaza with a 95% confidence level. This indicates that TPSIM can be used for further evaluation and application of the toll operations, which includes running scenarios.

7.2 TPSIM Scenarios

All three of the before study days that were selected for calibration were used in the experiment. Data from these days were used since each of these days had similar operational and geometric characteristics and the service time distributions were not statistically different between similar lane types for each day. The plaza configurations were exactly the same for each day in the before study. Data from February 6, 2002 in the before study was not used in the experimental design since the service time distribution for the manual lanes was statistically different than the other before study days.

All of the input parameters that were used in the before study calibration were used in this experiment with the exception of the ETC speed, the number of approach lanes and the plaza configurations. See Table 41 for a summary of the input parameter values that were used in the scenarios. The values for the ETC speed, the number of approach lanes and the plaza configurations vary and are specified later in the discussion of the experimental design.

Table 41 Scenarios – TPSIM Input Parameter Values

PLAZA GEOMETRIC WINDOW		
Approach Lanes – Quantity	*Varies*	
Approach Lanes – Length	2100	ft
Approach Lanes - Lane Width	12	ft
Toll Lanes – Quantity	5	
Toll Lanes – Length	600	ft
Toll Lanes - Lane Width	12	ft
Transition Zone – Length	200	ft
TOLL LANE TYPE AND SCHEDULE WINDOW		
Toll Lane Configuration	*Varies*	
GLOBAL PARAMETERS WINDOW		
Inter-arrival Distribution	Exponential	
Minimum Headway	1	sec
ETC Speed	*Varies*	mph
Reaction Time – Minimum	0.46	sec
Reaction Time – Maximum	1	sec
Lane Changing	100	%
Speed Distributions	Normal	
Average Approach Speed	55	mph
Average Approach Speed (Standard Deviation)	10	mph
Deceleration Rate	4	ft/s^2
Deceleration Rate (Standard Deviation)	0.5	ft/s^2
Acceleration Rate	4	ft/s^2
Acceleration Rate (Standard Deviation)	0.6	ft/s^2
Clearance Distribution	Uniform	
Clearance – Minimum	50	ft
Clearance – Maximum	70	ft

Five-minute volumes for each of the three before study days are included in Table 42. The five-minute volumes were collected from the field. The individual lane volumes were summed together to represent the traffic of the entire plaza. The arrival time of each vehicle, extracted from the videotapes, was summed for each 5-minute interval for all lanes. An average of the five-minute volumes from the three days was calculated and used as input in the experiment.

Table 42 Scenarios - Traffic Volume Values During 5 minute Intervals

5 minute Interval	February 12, 2002 PM	February 20, 2002 AM	February 20, 2002 PM	Average
1	285	243	305	278
2	239	319	327	295
3	255	320	296	290
4	321	329	304	318
5	322	347	315	328
6	304	360	335	333
7	294	362	330	329
8	296	348	327	324
9	307	351	314	324
10	314	351	333	333
11	329	324	318	324
12	314	331	326	324
Total	3580	3985	3830	3800

Table 43 is a summary of the percentages of vehicle types and the averages that were used in the experiment. For the purpose of running the experiment, it was assumed that the percent of each vehicle type did not change.

Table 43 Scenarios – Percentages of Vehicle Types

Veh Payment Type	February 12, 2002 PM	February 20, 2002 AM	February 20, 2002 PM	Average
Manual	22.7	18.2	21	20.6
Automatic	13.9	13	14	13.6
ETC	63.4	68.8	65	65.8

The average service time distributions for each of the conventional toll lanes in the before study were also calculated from the previous three calibration days. See Table 44 for a summary of the service time distributions that were used in the experiment.

Table 44 Scenarios - Service Time Distribution

Service Time (sec)	Manual 1	Manual 2	ACM
0	7%	4%	14%
1	5%	4%	1%
2	14%	16%	18%
3	20%	21%	27%
4	14%	17%	18%
5	10%	11%	9%
6	7%	7%	5%
7	6%	4%	2%
8	4%	3%	0%
9	3%	3%	1%
10	2%	2%	3%
11	1%	1%	0%
12	1%	2%	2%
13	1%	1%	
14	0%	1%	
15	1%	1%	
16	1%	2%	
17	2%		

A simulation experiment using TPSIM was designed to study the impact of changes made to three factors in the model. TPSIM, which was calibrated for the University mainline toll plaza in the previous section, will be used in this experiment to estimate and quantify the possible benefits of express ETC lanes under different scenarios. The experiment employs a 2 x 3 x 2 factorial design (ETC lane speed, number of approach lanes, plaza configuration), which resulted in 12 different scenarios. Three variables, the ETC lane speed, the number of approach lanes, and the plaza configurations (i.e., the number of ACM lanes) were used. The response quantitative variables (throughput, average queuing delay, and total queuing delay) were used as measures of the toll plaza operational performance in the experiments.

The ETC lane speed variable consists of two different ETC lane speeds; 35 mph and 65 mph. The 35 mph ETC lane speed represents conventional, dedicated ETC lanes that were used in the before study. The 65 mph ETC lane speed represents express ETC lanes that were employed at the toll plaza during the after study. The ETC lane speed variable was chosen so that operational differences could be measured by simply changing the type of ETC lane, and therefore the speed of that lane.

The variable for the number of approach lanes has three levels, which was either 2, 3, or 4. The number of approach lanes for the northbound and southbound directions during the before study was 2 and 3, respectively. The number of approach lanes in the northbound and southbound directions during the after study was 3 and 4, respectively.

The plaza configuration variable had two levels, depending on the number of Automatic Coin Machine (ACM) lanes, which was either one (2M-1A-2E) or two (2M-2A-2E). The plaza configuration variable was chosen so that the effects of adding an additional ACM lane could be quantified. The experimental designs using TPSIM are included in Table 45 and Table 46 for the 35 mph and 65 mph ETC speeds, respectively. A total of 12 different scenarios are indicated in the tables.

Table 45 Scenarios - Experimental Design for 35 mph ETC Speed

Scenario	No. of Approach Lanes	Plaza Configuration
1	2	2M-1A-2E
2	3	2M-1A-2E
3	4	2M-1A-2E
4	2	2M-2A-2E
5	3	2M-2A-2E
6	4	2M-2A-2E

Table 46 Scenarios - Experimental Design for 65 mph ETC Speed

Scenario	No. of Approach Lanes	Plaza Configuration
7	2	2M-1A-2E
8	3	2M-1A-2E
9	4	2M-1A-2E
10	2	2M-2A-2E
11	3	2M-2A-2E
12	4	2M-2A-2E

Several assumptions that were considered when conducting the simulation scenarios are included below:

- ETC lanes are located on the left side of the plaza (in the direction being simulated). This matches the ETC lane locations at the toll plaza in the field.
- All toll lanes are open during the simulated peak hour for all scenarios.

- The parameters of service time distributions, vehicle characteristics, and percentage of vehicle class were taken to be the averages of the three before study days.

TPSIM runs for the first scenario were used to make a determination of how many runs were necessary for each of the remaining scenarios. A total of twenty runs were used in the first scenario. A cumulative average was calculated after running each additional scenario. This produced a "moving average". As each additional run was made, the average was recalculated based on the results of the additional run. The graph for the average queuing delay is included in Figure 59 and shows the cumulative averages for Scenario 1. Based on the graph, the average appears to stabilize after running ten runs (using 10 different random numbers). According to the graph, making additional runs beyond the first ten had very little effect on the cumulative average. Using ten runs per scenario is also consistent with the number of runs in a previous research report (Klodzinski 2002a). Therefore, ten runs were used in this experimental design.

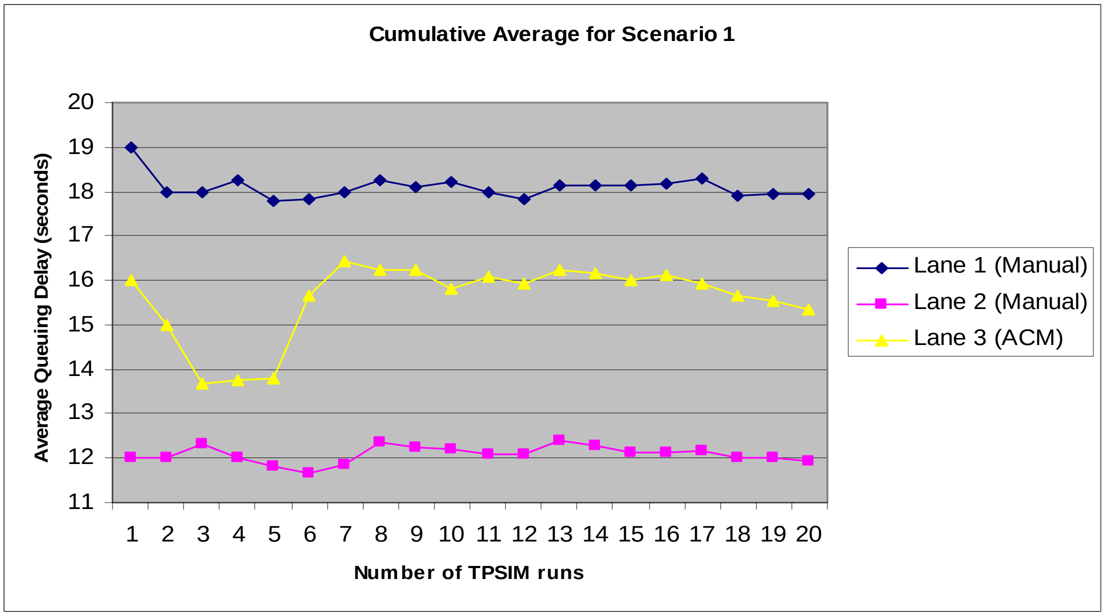

Figure 59 Scenarios – Number of Simulation Runs

Figures 60 to 62 show the average throughput per lane for each type of toll lane (manual, ACM, and ETC). These graphs indicate that changing the ETC speed and adding an additional ACM lane do not have an observed impact on the throughput for any of the lane types (since the input volumes were held constant). Minor reductions in throughput are observed when adding additional approach lanes. This could be attributed to the weaving upstream of the plaza since vehicles are required to make more lane changes to reach their desired toll lane. The ETC equipped vehicles may have also used other lane types (the mixed-use lanes) rather than weave to the exclusive ETC lanes, which may explain the ETC lane throughput results.

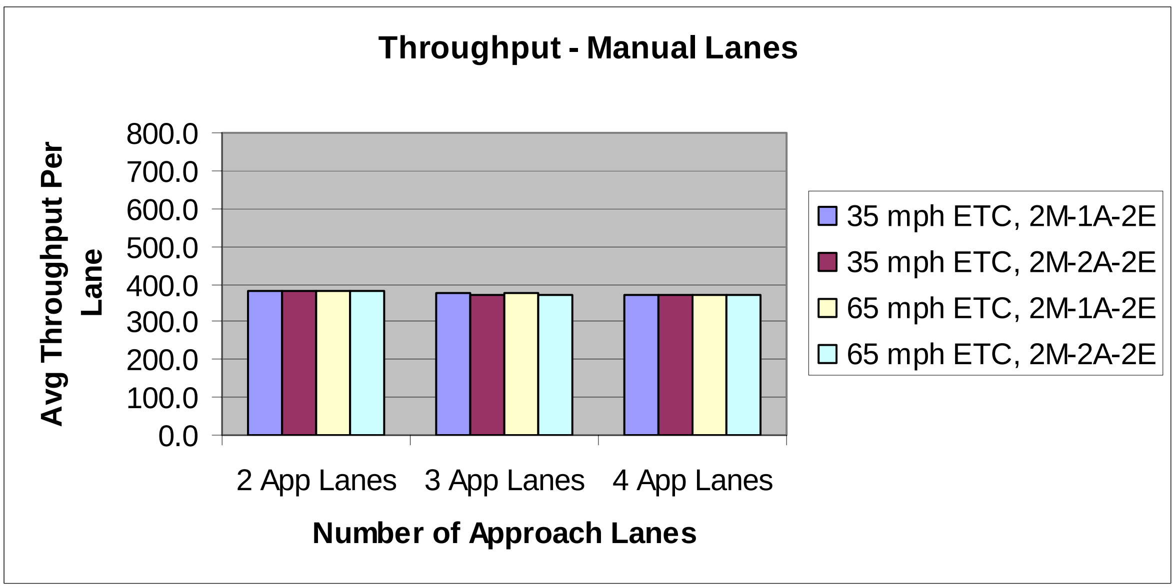

Figure 60 Scenarios – Throughput (Manual Lanes)

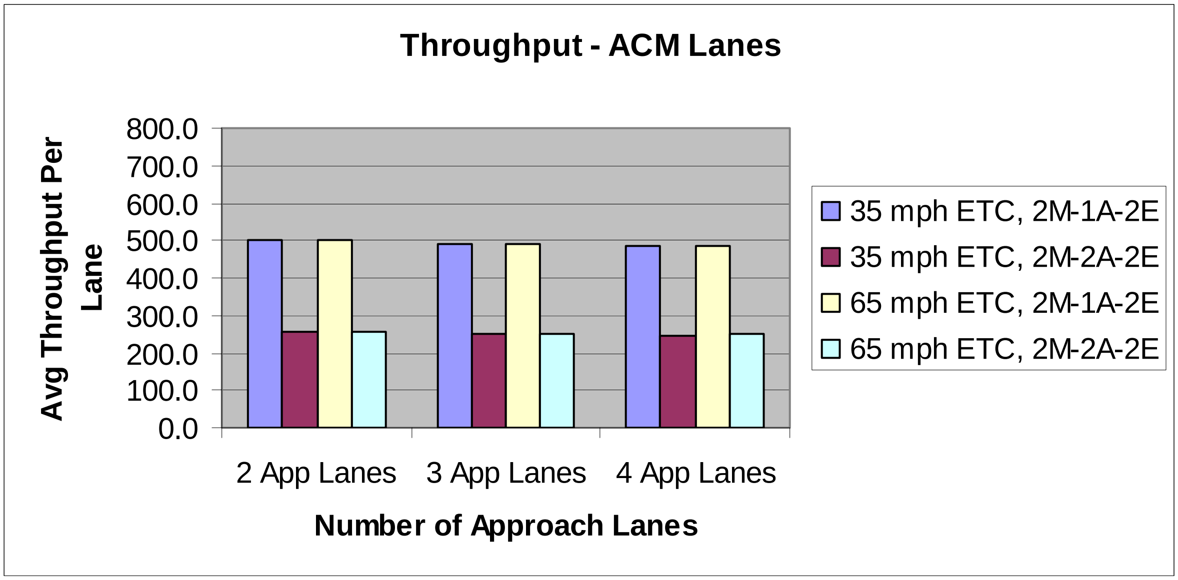

Figure 61 Scenarios – Throughput (ACM Lanes)

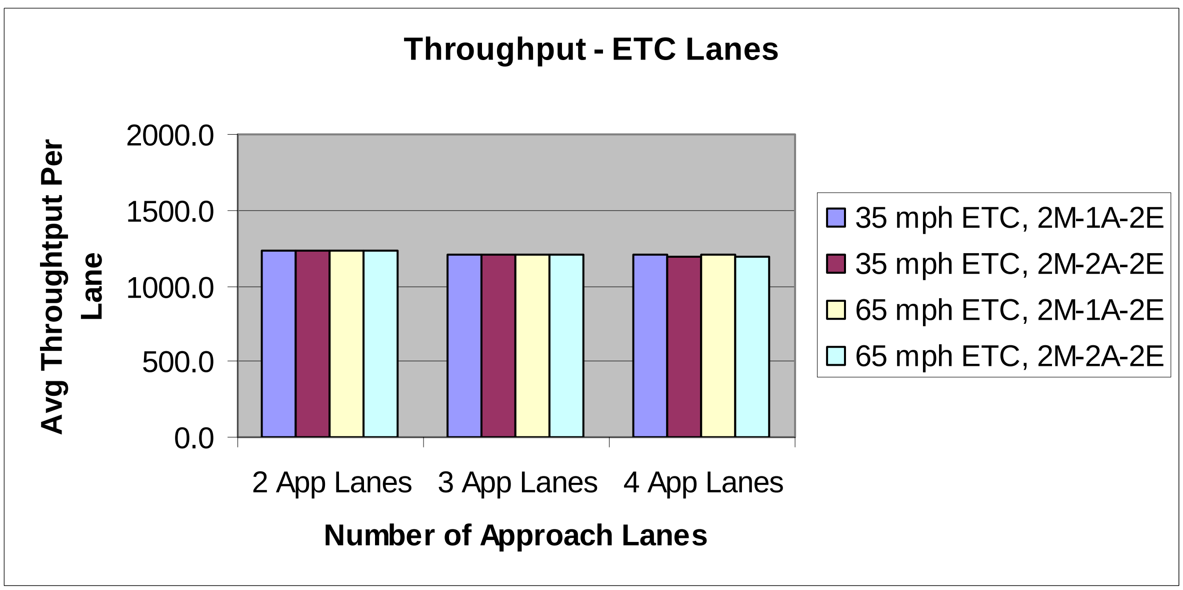

Figure 62 Scenarios – Throughput (ETC Lanes)

Figures 63 to 66 show results for the average queuing delay in the TPSIM scenarios. The average queuing delay was reduced by 60 percent (over 8 seconds) for the A/ETC lanes when adding a second A/ETC lane. Reductions of 30 percent (4.5 seconds) were observed for the entire plaza when adding a second A/ETC lane.

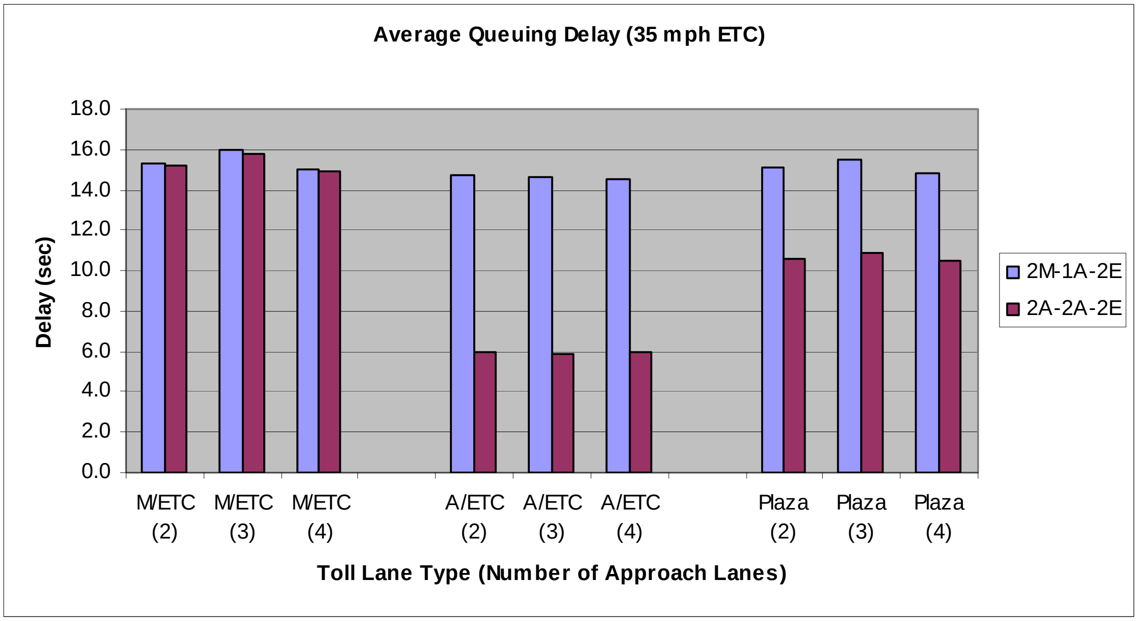

Figure 63 Scenarios - Average Queuing Delay (35 mph ETC)

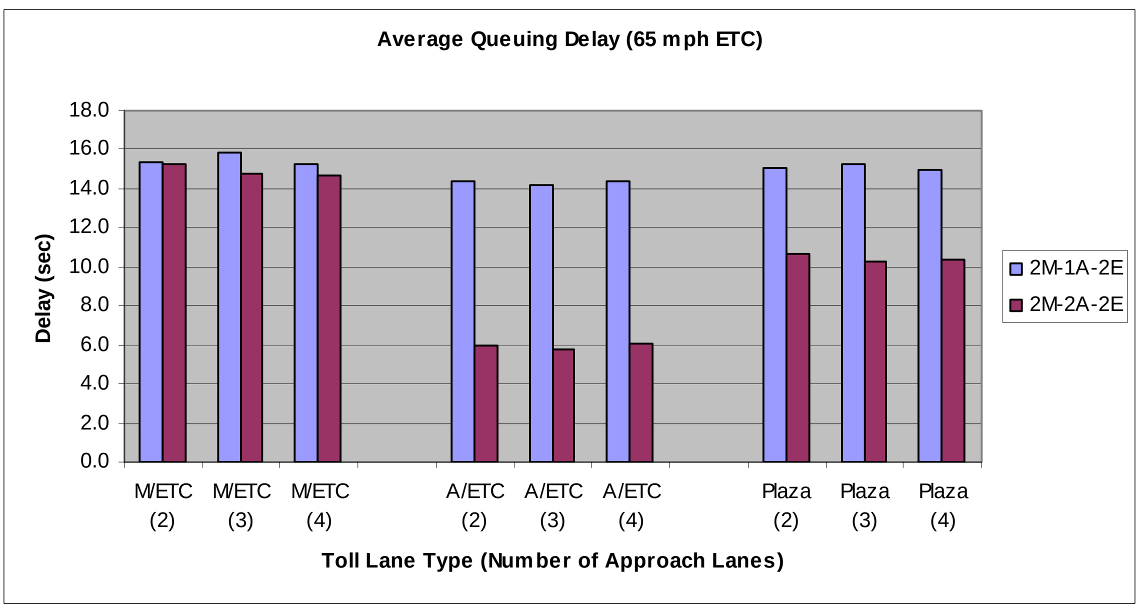

Figure 64 Scenarios - Average Queuing Delay (65 mph ETC)

Except for the case where there was only one A/ETC lane (2M-1A-2E) and 4 approach lanes, slight reductions in the average queuing delay were also observed when increasing the ETC speed from 35 to 65 mph. The delays may have increased for the 4 approach lane case since vehicles are not restricted upstream of the plaza and may reach the plaza quicker, thus causing slightly higher delays at the plaza.

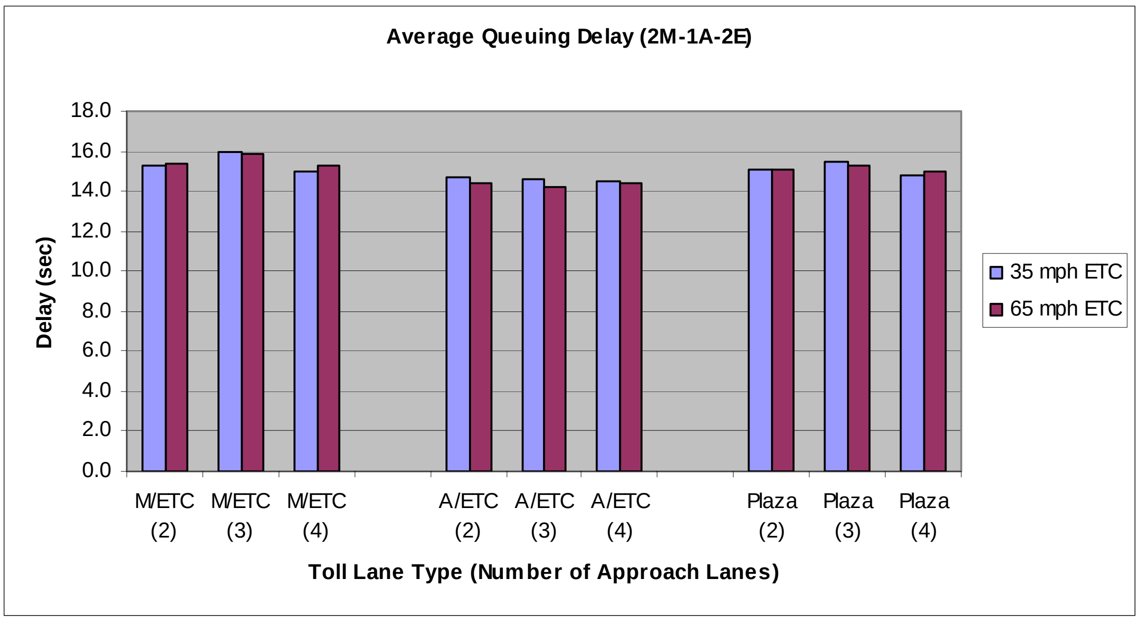

Figure 65 Scenarios - Average Queuing Delay (2M-1A-2E)

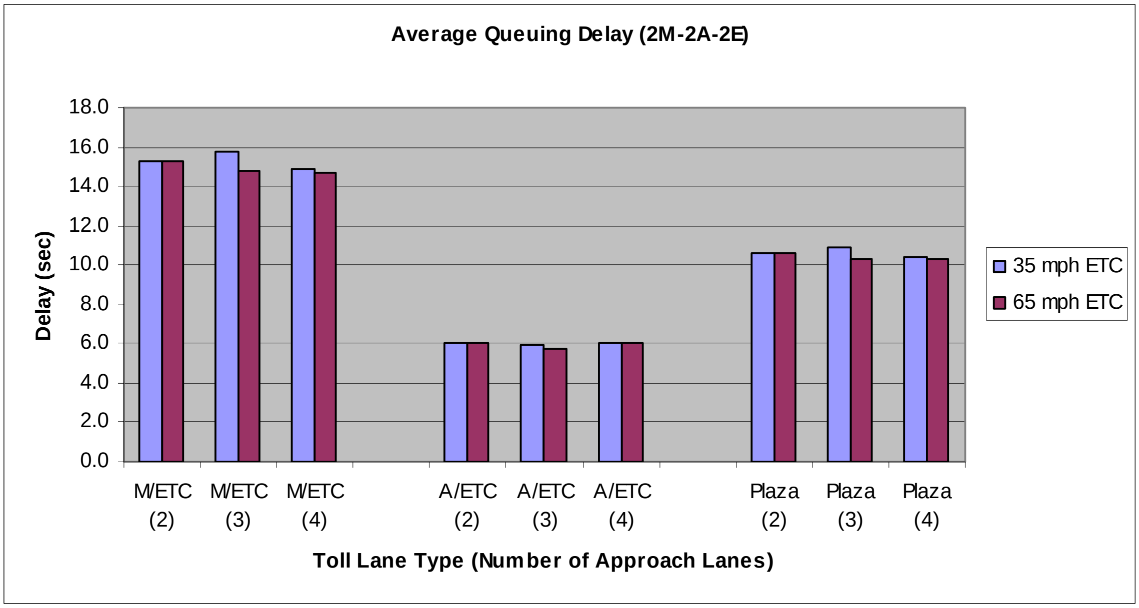

Figure 66 Scenarios – Average Queuing Delay (2M-2A-2E)

Figures 67 to 70 show results for the total queuing delay in the TPSIM scenarios. When changing the plaza configuration (adding an additional A/ETC lane), reductions in the total queuing delay were observed for the entire plaza. Slight reductions in delay were observed in the M/ETC lanes. The average queuing delay was reduced by 78 percent (over 5500 seconds per lane) in each of the A/ETC lanes. Reductions of over 40 percent (2500 seconds per lane) were observed for the entire plaza when adding a second A/ETC lane.

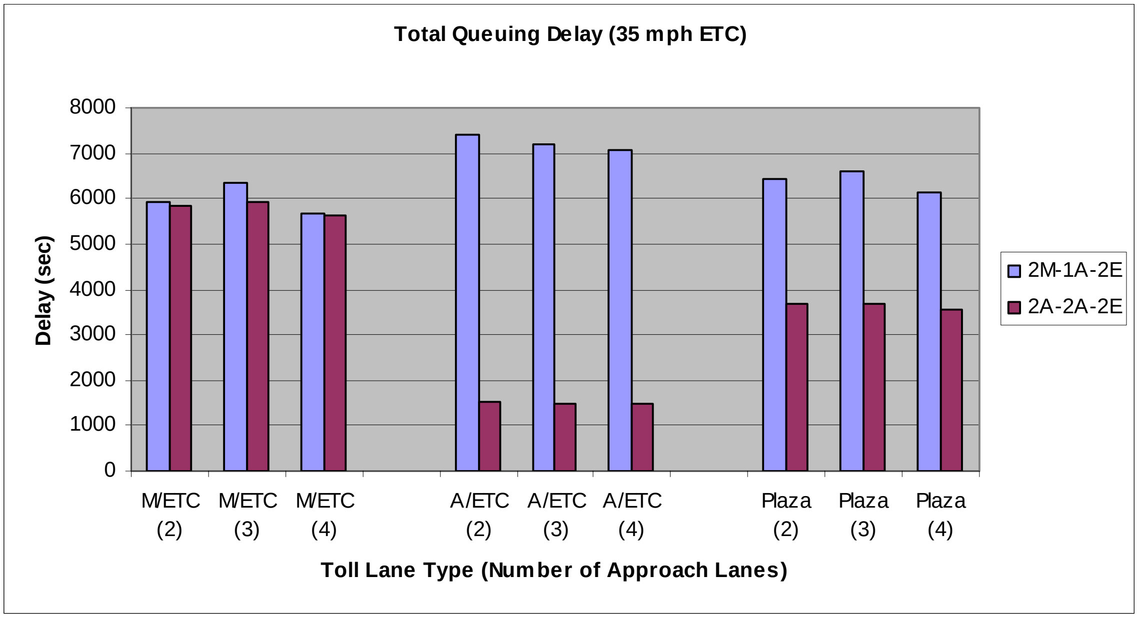

Figure 67 Scenarios – Total Queuing Delay (35 mph ETC)

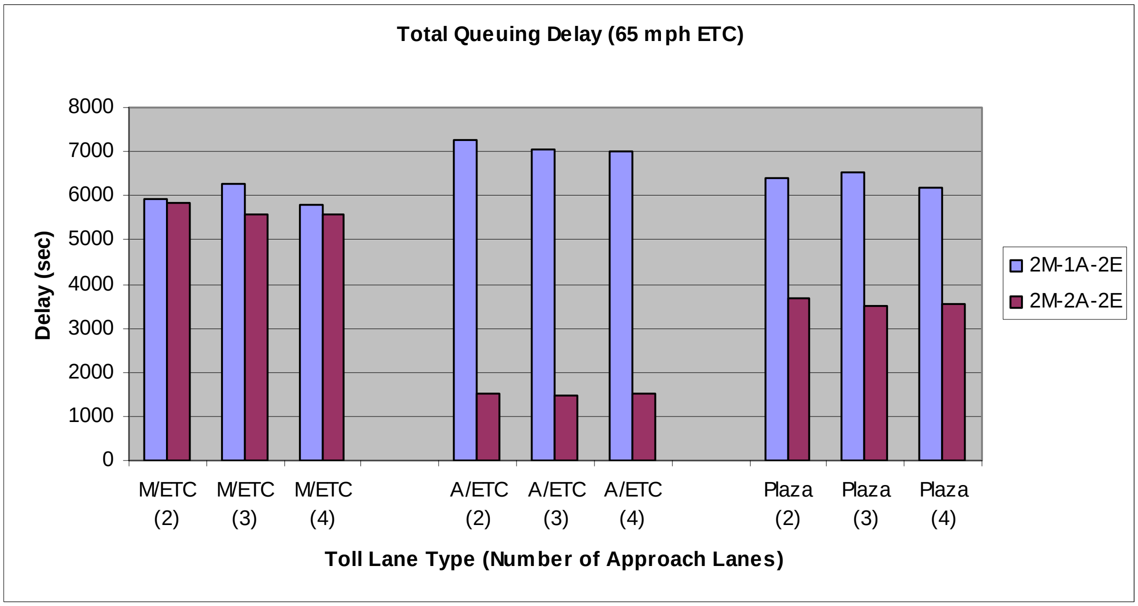

Figure 68 Scenarios – Total Queuing Delay (65 mph ETC)

Except for the case where there was only one A/ETC lane (2M-1A-2E) and 4 approach lanes, slight reductions in the total queuing delay were also observed when increasing the ETC speed from 35 to 65 mph. The delays may have increased for the 4 approach lane case since vehicles are not restricted upstream of the plaza and may reach the plaza quicker, thus causing slightly higher delays at the plaza.

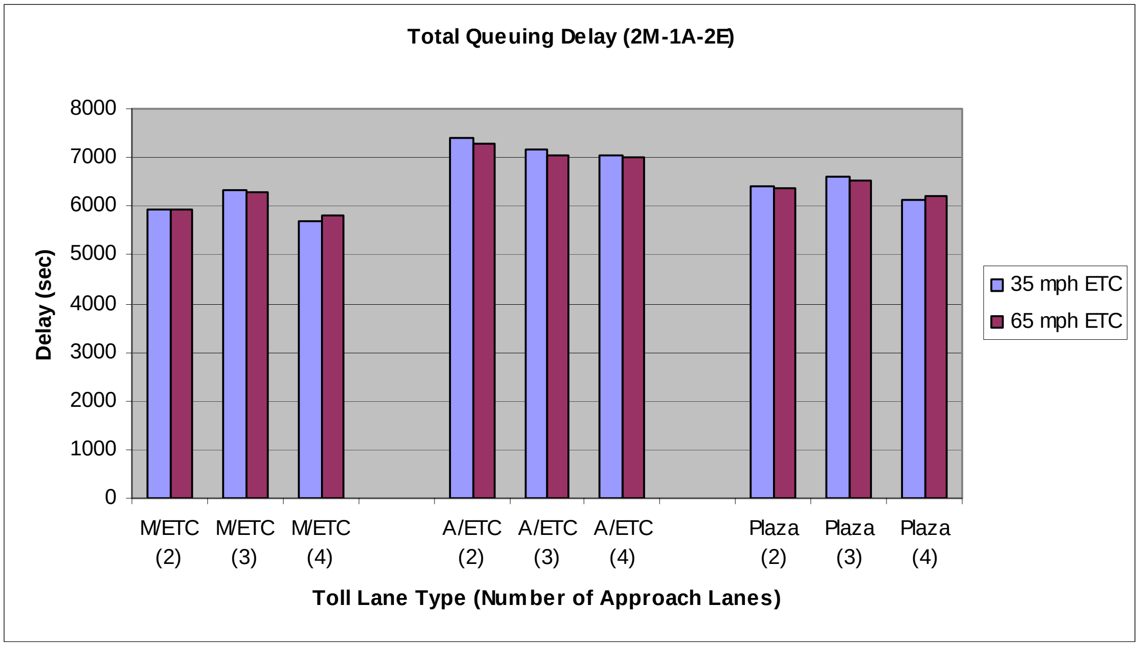

Figure 69 Scenarios – Total Queuing Delay (2M-1A-2E)

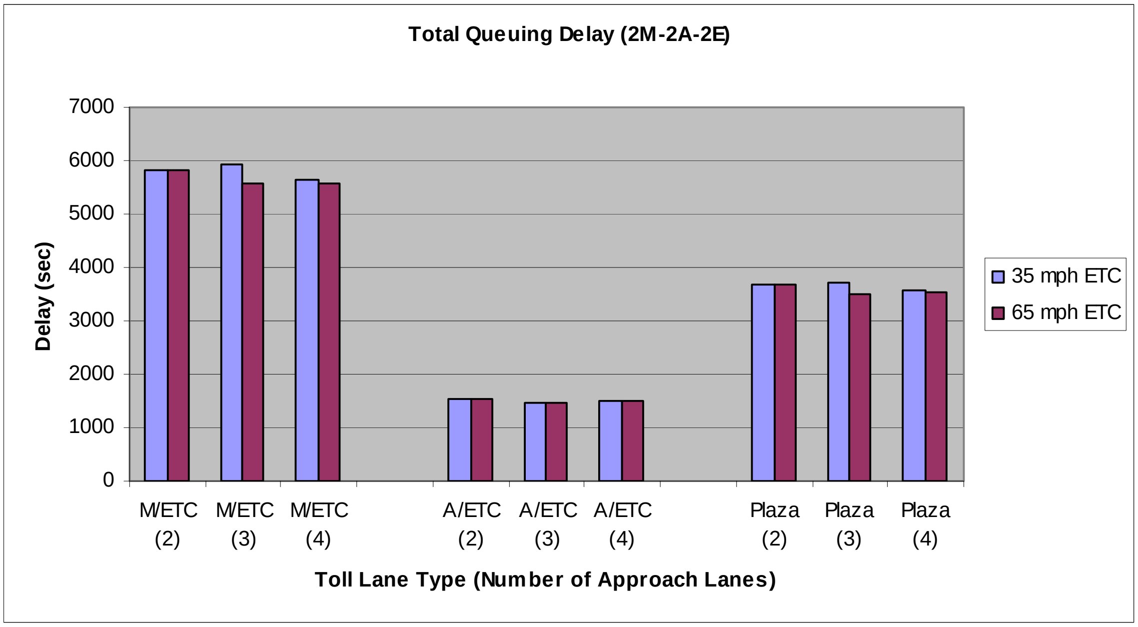

Figure 70 Scenarios – Total Queuing Delay (2M-2A-2E)

The TPSIM scenarios did not account for changes in the percent of ETC vehicles in each lane. In addition, the express ETC lanes were simulated adjacent to the cash lanes, therefore a separation similar to the after study was not simulated in the TPSIM model. These differences may be the reasons why the results for the TPSIM scenarios were different than those observed in the after study when adding the express ETC lanes at the plaza. But, reductions in delays for the entire plaza were also observed using TPSIM when making similar improvements to the plaza as in the after study.

CHAPTER EIGHT: CONCLUSIONS

The effectiveness of modifying a conventional toll plaza for implementation of an open road tolling concept with express ETC lanes was evaluated in this thesis. Speed controlled dedicated ETC lanes were replaced with express ETC lanes at the Orlando-Orange County Expressway Authority (OOCEA) University Mainline Toll Plaza. The analysis was accomplished by utilizing collected field data and simulated scenarios using Toll Plaza SIMulation (TPSIM) software developed by the University of Central Florida. Other improvements that were made to the facility include the addition of an ACM (or A/ETC) lane in each direction and one additional approach lane per direction.

A comparison of before and after results was performed. Compared to the before study, the throughput for the ETC lanes in the after study increased by 3.2% and 18% for the AM southbound and PM northbound directions, respectively. In the AM southbound, the throughput in the ACM and manual lanes decreased by 20.4% and 4.5%, respectively. This was due to a large drop in the ETC usage in these lanes (the ETC percentage dropped by 79%). In the after study, weaving and merging maneuvers downstream of the plaza were no longer required for the ETC lanes due to the location of the downstream travel lanes in relation to the express ETC lanes. In contrast, during the before study, the dedicated ETC lanes were located adjacent to the conventional lanes and drivers used the conventional toll lanes to decrease the required movements upstream and downstream of the plaza. In the PM northbound direction the throughput in the manual lanes decreased by 7.4% but there was a large increase in the throughput for the ACM lanes (which increased by 56.8%). In the before study, the percent of

ETC vehicles in the ACM lane during the PM northbound direction was 10.49%. In the after study, the average percent of ETC vehicles in both ACM lanes was 35.7%. The percentage of ETC vehicles increased in the ACM lanes because many ETC equipped vehicles used these lanes to reach the University Boulevard exit. It was easier for the ETC equipped vehicles to utilize the conventional toll lanes (especially the low volume ACM lanes) in order to exit at University Boulevard since the exit from the express ETC lanes at the time introduced excessive weaving movements for these vehicles. The exit ramp for University Boulevard is located downstream in close proximity to the plaza.

For average delay in the AM southbound direction, a decrease of 27.5% and 40.8% was observed for the ACM lanes and manual lanes, respectively. The decrease in average delay was of an even greater magnitude for the PM northbound direction. In the PM northbound direction, the average delays decreased by 75.5% in the ACM lanes and 60.2% in the manual lanes. Similar to the average delay, the total delay in the after study decreased for both the ACM lanes and manual lanes for both peak hours. The total delay in the AM southbound direction decreased by 32.1% in the ACM lanes and by 54% in the manual lanes. For the PM northbound direction, the total delays decreased in the ACM and manual lanes by 60.5% and 62.8%, respectively. The reduction in total delay was 32 percent or more for all lane types.

In addition to the four measures of effectiveness (throughput, average queuing delay, maximum queuing delay, and total queuing delay), other comparisons were made and included average inter-vehicle times, arrival rates, and percent ETC for each lane type. Average inter-vehicle times increased for the manual and ACM lanes in the after study for both the southbound and northbound directions. The increase in the manual and ACM lanes for the AM southbound direction was 121.4% and 30.3%, respectively. The increase for the average inter-vehicle times for the PM northbound direction was 30.8% and 6.4% in the ACM and manual lanes, respectively. Alternatively, the average inter-vehicle times for the ETC lanes actually decreased in the after study from an average of 3 seconds to 2 seconds. Although this corresponded to an increase in the ETC lane throughput for both peak hours, the increase in ETC lane throughput was not of the same magnitude as the reduction in inter-vehicle times. In general, when inter-vehicle times increase there are larger headways which result in less congestion. While the arrival rates for the ETC lanes increased in the after study, a reduction in arrival rate was observed for the other lane types.

The results for the percentage of ETC vehicles in each lane provided interesting conclusions. The ETC percentages for the ACM and manual lanes decreased in the after study for the southbound direction (80.8% reduction in the ACM lanes and 79% reduction in the manual lanes). This was a direct result of separating the express ETC lanes and splitting the plaza, since it decreased the downstream weaving maneuvers required by drivers. The opposite is true for the vehicles in the northbound direction (PM peak hour) where the percent of ETC vehicles increased in the ACM and manual lanes by 239.9% and 34.1%, respectively. This was due to the close proximity of the University Boulevard exit in the northbound direction. Many ETC vehicles used the conventional toll lanes in order to exit at University Boulevard since the exit from the express ETC lanes at the time introduced excessive weaving movements for these vehicles.

An analysis was performed for the speeds in the ETC lanes between the before and after study. During the before study, the left lane had a volume of 956 veh/hr and a speed of 39 mph. The volume in the right lane (located adjacent to the conventional toll lanes) was much higher at 1787 veh/hr, which was 831 veh/hr more than the left lane. But the speed in the right lane was only 31 mph, which was 8 mph lower than the left lane. This trend reversed in the after study for the express ETC lanes since there were higher volumes in the left lane (1664 veh/hr versus 1169 veh/hr in the right lane). At the same time, speeds in the left lane were slightly higher than the right lane (54 mph versus 52 mph) but the differences between these speeds were less than in the before study. Speed increases were observed for both lanes in the after study. Individual ETC lane usage was observed to shift and was a direct result of elimination of the weaving movements that were present with the dedicated ETC lanes and realignment of the express ETC lanes (allowing higher speeds through the toll collection point). The shifts in individual ETC lane usage and speeds can be attributed to the separation of the express ETC lanes and the location of the downstream through lanes for highway speed traffic.

The express ETC lanes were analyzed in further detail using field data. The average five-minute volumes for each ETC lane during the AM and PM time periods were graphed and compared. During the AM before study time period, the right lane had higher volume. During the AM after study time period, the left lane had higher volume than the right. The same phenomenon was true for the volumes during the PM time periods. There was an observed shift in usage for the ETC lanes. The left lane in the before study had the lowest of the four ETC volumes. This was the lane that required the most weaving in order for ETC customers to use. There was not as much of a difference in volumes between both ETC lanes in the after study. The left and right ETC lanes during the before study, on the other hand, had much different lane volumes. In addition, a Scheffe's statistical test was performed to determine the difference in speeds between the before study dedicated ETC lanes and the after study express ETC lanes. According to the results, there was a significant difference in speeds between each dedicated

ETC lane (before study) and all of the express ETC lanes (after study) since the after study speeds were higher.

The above conclusions led to further analysis of express ETC lanes using car-following theory and concepts contained in the highway capacity manual. Equations and car-following theory were used to prove that if the ETC speed was increased, then the throughput would increase as well. Measured capacities were obtained for the dedicated ETC lanes during the before study and the maximum measured capacity of 2016 veh/h corresponded to an ETC speed of 31 mph. During the initial after study, the estimated throughput based on a five minute maximum for the express lanes was 2040 veh/h, just over the maximum measured capacity of the dedicated ETC lanes. But, this was not considered a capacity measure of the express lanes since gaps observed in the departures were still considered high and therefore no time periods were available for a capacity analysis. However, during the fall of 2003, additional data was collected and the highest maximum measured capacity was just over 2,100 veh/h in the express lanes (corresponding to a speed of 58 mph). Using a reaction time of 1.346 sec and assuming that the ETC speed was increased to 65 mph (the posted speed limit of the express ETC lanes), this resulted in a calculated capacity of 2,314 veh/h. This calculated capacity at 65 mph was similar to a highway lane at a free-flow speed of 70 mi/h or greater. Therefore, the capacity was increased from 2016 to 2314 vph when the ETC speed increased from 31 mph to 65 mph. This indicated an increase in capacity of 14.8 percent (conversion from dedicated to express ETC lanes).

In addition, the toll plaza was calibrated using the TPSIM model for data from three different days during the before study that had similar characteristics (lane configurations and service time distributions). Upon successful calibration of the simulation model, a sensitivity analysis of the express ETC lanes was performed using TPSIM by varying the type of ETC lane, number of approach lanes, and the number of A/ETC lanes between different scenarios. The results from the TPSIM scenarios indicated that changing the ETC speed and adding an additional ACM lane did not have an observed impact on the throughput for any of the lane types (this is expected since the input volumes and service time distributions were held constant). The average queuing delay was reduced by 60 percent (over 8 seconds) in the A/ETC lanes when adding a second A/ETC lane. Reductions of 30 percent (4.5 seconds) were observed for the entire plaza when adding a second A/ETC lane. Slight reductions of the average queuing delay in the manual lanes were also observed for these scenarios. For most of the scenarios, slight reductions in the average queuing delay were also observed when increasing the ETC speed from 35 to 65 mph. When changing the plaza configuration (adding an additional A/ETC lane), the total queuing delay was reduced by 78 percent (over 5500 seconds per lane) in the A/ETC lanes. Reductions of over 40 percent (2500 seconds per lane) for the total queuing delay were observed for the entire plaza when adding a second A/ETC lane. Slight reductions of the total queuing delay in the manual lanes were also observed for these scenarios. For most of the scenarios, slight reductions in the total queuing delay were also observed when increasing the ETC speed from 35 to 65 mph. Differences between these results and the field data collected in the after study could be attributed to the fact that the model did not have the ability to simulate the complete separation of the express ETC lanes from the other conventional toll lanes. In the TPSIM model, all of the toll lanes were located adjacent to one another.

In the before study, ETC users had to decelerate upon approach to the plaza thus reducing the maximum benefit possible for minimizing travel time on the toll road. Customers who observed the benefit of reducing their travel time on the toll road (due to the high speed in the express ETC lanes) may have decided to switch to ETC. This could explain the reduction in ETC percentage for the conventional toll lane types that were observed in the after study for the AM southbound direction. Another benefit of the express lanes is that previous high weaving movements that were observed upstream of the plaza were eliminated since these lanes were separated from the conventional lanes. The decision point (whether or not to use the ETC lanes) was moved farther upstream of the plaza and therefore eliminated last minute decisions that could be made in the immediate vicinity of the plaza during the before study. The changes made to the University Mainline Toll Plaza between the before and after study resulted in benefits by reducing delays and increasing the capacity of the toll plaza (by adding an additional A/ETC lane per direction and converting dedicated ETC lanes to express ETC lanes). Other improvements included additional approach and departure lanes. The benefits were measured using field data and confirmed when performing the TPSIM scenarios. A customer's travel time along the toll facility will be reduced by using the express ETC lanes (since they are not required to decelerate at the toll plaza). These benefits may have led to changes in the number and percentage of ETC users. Changes in ETC usage in the conventional mixed-use lanes directly impacted the throughput and delays for each of these lanes, since ETC equipped vehicles have a service time of zero seconds. The re-distribution of customers at the plaza was a great benefit to the entire population.

Since the operational performance of the express ETC lanes was the primary focus of this research, it is recommend that other factors like driver comfort level, safety considerations, and driver perception (the perceived benefit of using the express ETC lanes) be evaluated for possible benefits of express ETC lanes in further research.

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