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WORK ZONE EFFECTS ON PERFORMANCE OF A TOLL PLAZA

by

JINGYU LIU

B.S. Tongji University, 2007

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil, Environmental & Construction Engineering in the College of Engineering and Computer Science at the University of Central Florida Orlando, Florida

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ABSTRACT

A no-lane closure workzone is typical during the construction of open road tolling lanes of a toll plaza. The influence of no-lane closure on toll plazas’ performance is unknown because very few studies have been conducted to address this topic. Open road tolling (ORT) has become the new trend of operating an efficient toll plaza. So, the upgrading of a toll plaza from gated ETC to ORT has become common. The better a toll road authority knows about the influence of construction and congestion effects on its operations, the better it can serve the customers. This research focus on the effects of a no-lane closure workzone on the toll plaza performance, and with the collected data, a model was developed predicting 15 minute throughput and queue length. This research mainly focuses on work zone effects during the construction of ORT lanes.

Three distinct phases can be identified during the construction of ORT. Phase 1 is building temporary gates at the outer sides of the toll plaza structure without any lane closure, which is mostly studied in this thesis; phase 2 is constructing ORT lanes in the middle of the toll plaza while using the temporary gates; and phase 3 is the opening of the ORT lanes and removal of the temporary gates.

To better study the workzone impact on toll plaza performance, three sites with different characteristics such as toll value, lane configurations and demand were selected. They are Lake Jesup Mainline Plaza along the Seminole Expressway (SR-417), the Beachline West Expressway Toll Plaza along the Beachline Toll Road (SR-528) and Conway Toll Plaza along the Holland East-West Expressway (SR-408) in the Orlando area of Central Florida.
Data collected includes demand, throughput, processing rates, and queue lengths of different toll categories. For Beachline West Toll Plaza (SR-528) and Lake Jesup toll plaza (SR-417), data was collected for time periods before and during the no-lane closure construction of phase 1 of the ORT construction. For Conway Toll Plaza (SR-408), data was collected for time periods during ORT lane construction (phase 2) and after opening ORT lanes (phase 3).

Comparisons were conducted between non-construction stage and construction stage for no-lane closure workzone effects using data from SR-417 and SR-528, and comparisons between ORT lane-construction and completion of the construction stage for ORT impact study using data from SR-408. Results show that when the toll plaza is operating at or close to its capacity, the no-lane closure workzone can have a negative impact on its performance, but when the toll plaza’s demand is lower than the capacity, the no-lane closure workzone has no impact on the toll plaza’s performance. And the operational ORT lanes have a positive influence on the capacity and throughput of the toll plaza.

After the impact of no-lane closure workzone on toll plaza has been analyzed, all the data from three toll plazas were put together and a model was built using the variables of Demand/Capacity ratio, percentage of each category of vehicle by payment type (ETC, Automatic or Manual), number of Manual lanes and workzone or no-workzone. A linear regression model was developed to predict the throughput and queue length.
ACKNOWLEDGMENTS

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<th>Definition</th>
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<tr>
<td>AAWT</td>
<td>Average Annual Weekday Traffic</td>
</tr>
<tr>
<td>ACM</td>
<td>Automatic Coin Machine</td>
</tr>
<tr>
<td>AVI</td>
<td>Automatic Vehicle Identification</td>
</tr>
<tr>
<td>EB</td>
<td>Eastbound</td>
</tr>
<tr>
<td>ETC</td>
<td>Electronic Toll Collection</td>
</tr>
<tr>
<td>FTE</td>
<td>Florida Turnpike Enterprise</td>
</tr>
<tr>
<td>HCM</td>
<td>Highway Capacity Manual</td>
</tr>
<tr>
<td>LOS</td>
<td>Level of Service</td>
</tr>
<tr>
<td>MOE</td>
<td>Measure of Effectiveness</td>
</tr>
<tr>
<td>NB</td>
<td>Northbound</td>
</tr>
<tr>
<td>OOCEA</td>
<td>Orlando Orange County Expressway Authority</td>
</tr>
<tr>
<td>ORT</td>
<td>Open Road Tolling</td>
</tr>
<tr>
<td>SB</td>
<td>Southbound</td>
</tr>
<tr>
<td>VPH</td>
<td>Vehicles per Hour</td>
</tr>
<tr>
<td>WB</td>
<td>Westbound</td>
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1. INTRODUCTION

1.1. Background Statement

When the first road covered with a layer of crushed stone was built in 1792 in Pennsylvania, the boom in road construction began. Over the years, the roads were built all over the country, and because of the decreasing federal support of existing and new freeways toll roads now begin to play an important role in the traffic system. The US transportation trust fund is rapidly shrinking and state departments of transportation around the US are facing budget shortages. In the last two rounds of federal highway program reauthorization, the use of toll roads have expanded and now is becoming more popular. Toll roads, in general, can generate funds for repayment of toll revenue bonds, thus the state can collect enough money to finance the operation, maintenance, improvement and construction of new facilities. By the end of year 2006, there were a total of 4917 miles of toll roads built in the United States, including 223 miles of urban toll roads and 2695 miles of rural. (Toll Facilities in the United States)

A toll plaza is the essential part of toll roads where the toll is collected. There are three difference basic options for tolling: Manual Toll Collection, which has been the most common approach for collecting tolls. In this option, drivers are required to stop and pay a toll collector sitting or standing in a tollbooth. Automatic Coin Machine (ACM) requires the driver to stop and drop the toll in coins into the collection machine. Electronic Toll Collection using the Automatic Vehicle Identification (AVI) technology which can
accurately identify a specific vehicle at highway speeds and charge the motorist the toll without requiring the driver to stop at tollbooths. “Though many toll authorities have already applied AVI by utilizing it in the application of electronic toll collection (ETC), increasing traffic volumes are prompting toll authorities to seek even better ways of utilizing technology to benefit their customers. The next step in the evolution of integrating ITS technology and toll road operations is the concept of open road tolling (ORT). (9). ORT technology is the trend in the future as traffic volume goes higher; many traditional toll agencies are implementing the ORT to improve the efficiency of their toll plazas.

There are three phases of the construction in implementing ORT technology.

- Phase I. Build temporary gates at each side of the toll plaza without any lane closure, set signs, guardrails and cones along the road as shown in Figure 1.1.

![Figure 1.1 Phase I construction](image)

- Phase II. Shut down the far left lanes for both directions (also the central lanes of the...
toll plaza), use the temporary gates to maintain the toll plaza’s LOS, and commence construction of ORT lanes in the middle of the toll plaza, as depicted in Figure 1.2.

Figure 1.2 Phase II construction

- Phase III. Construction is completed, the ORT lanes are open to traffic and the temporary gates are removed.

The construction during the first and second phase caused workzone existence. Each vehicle traveling in a work zone is affected by features such as additional signs, narrowed lanes, barrels or barriers close to the travelway, trucks entering the construction area, reduced speed limits, and workers near the open lanes. (1) This research examines the influence of a no-lane closure workzone in phase one on toll plaza performance and the influence of opening the ORT lanes by comparing phases two and three.

The number of toll road construction and rehabilitation projects continues to increase in the United States is needed. The resulting work zones limit the number of vehicles operating within the affected toll roads system (1). Although the conventional workzone
concept is the workzone with lane closure, a no-lane closure workzone also has some characteristics that may limit the number of vehicles operating within the affected toll roads system, such as the signs warning the drivers of workzone ahead on the side of road approaching workzone, the guardrails and cones at side of the road, workers appearing, and double fine for speeding at workzone. All these factors may influence the drivers’ behaviors thus to have an impact on the toll plaza’s performance.

1.2. Research Objectives

The major challenge that faces toll authorities when expanding on an existing toll facility is to do so without adversely affecting the performance of the system in terms of efficiency and safety. This thesis attempts to study the no-lane closure work zone activity to expand on an existing toll plaza, and evaluate its impact on the system performance. More specifically, speed reduction zones coupled with utilization of shoulders and other short term lane striping are applied to alleviate closing lanes. A complementary task to this assessment is to build a toll plaza throughput and queue length model. The three parts of the thesis are

1. Using toll plaza data collected from 2007-2009 to make comparisons between non-construction and no-lane closure construction (phase 1) stage and to analyze the no-lane closure workzone effects.

2. Make comparisons between inner lane construction (phase 2) and construction completed stage (phase 3) to analyze the ORT impact on the throughput and queue
at the toll plaza.

3. Using data collected from all sites to develop a model predicting throughput and queue length.
2. LITERATURE REVIEW

2.1 Freeway Workzone Effect and Toll Plaza Evaluation Issue

Numerous studies have been conducted in the field of toll plaza operation and the impact of freeway work zone on traffic flow. For example, Dixon states “Each vehicle traveling in a work zone is affected by features such as additional signs, narrowed lanes, barrels or barriers close to the travel way, multi-axle vehicles entering the construction area, reduced speed limits, and workers near the open lanes” (1). A lane closure generates the greatest constriction to vehicles in a freeway work zone. Drivers accustomed to the original configuration change their travel behavior to traverse the area adjacent to the closed lane. “The result is generally the formation of a queue of vehicles upstream of the lane closure.” (1), “based on field research and data analyses, delay are recommended to be the most credible MOE for evaluating the LOS at a toll plaza. More specifically, the 85th percentile of the cumulative individual vehicular delays was found to capture the delay with better precision” (2). While there is considerable literature and reports on specific toll plaza and toll road work zone issues, there is no comprehensive research for the work zone effects on toll plaza performance.

Chao (3) conducted a research at the toll plaza on Garden State Parkway, one of the two major toll highways in New Jersey to study several design problems in toll plaza systems. The ultimate goal of this paper was to provide a decision tool to dynamically control tollbooth configuration designs during the different time of the day and the week to best
serve vehicle drivers. The author chose several criteria to evaluate the analysis of toll plaza systems, such as: average vehicle delay, variance of vehicle waiting time, and the reason for choosing variance of vehicle waiting time.

Klodzinski and AL-Deek (2) developed a new way to evaluate a toll plaza’s level of service by comparing several evaluation methods including density, V/C ratio and delay. Because toll plaza exhibits a wide range of densities and is difficult to measure, density and V/C ratio was abandoned. They concluded that the 85th percentile of the cumulative individual vehicular delays was accurately capturing the delay experienced by the majority of the drivers. In another report submitted by them, Simulation And Evaluation Of The Orlando-Orange County Expressway Authority (OOCEA) Electronic Toll Collection Plazas Using TPSIM(4), the authors evaluated the use of throughput, average queuing delay, maximum queuing delay and total queuing delay as a method of evaluation.

Zarillo, Radwan and Ramasamy (5) in the report of TNCC Validation and Enhancement, made an introduction of the software SHAKER, including the initial calibration of SHAKER. The basic parameters they included in the model were average vehicle length, distance between vehicles, vehicles’ acceleration and deceleration, drivers’ reaction time, stop-time at payment and percentage of multi-axle vehicles using each payment type. Then, the report showed the SHAKER’s equations for computing lane throughput (vph) of a toll collection facility.
Antonis F (6) holds the opinion that when the arriving flow exceeds the work zone capacity, to maximize throughput is the most common goal of many of the researches. So, he proposed a real-time merging traffic control scheme for work zone management that uses a local ramp metering strategy where, in contrast, only a part of the arriving traffic flow is controlled so as to maximize the merge area throughput. This is the general framework for real-time merging traffic control developed recently. The potential control concept efficiency was demonstrated by use of microscopic simulation applied to a hypothetical work zone infrastructure with and without merging traffic control. The goal was to demonstrate the potentially achievable benefits of this proposed control strategy.

Dixon (1) and Maze (7) both focused their attention on the capacity study at lane closure section. After conducting a field study at the road work zone, they collected a set of data and fitted a revised speed-flow relationship. They also carried out a capacity analysis at “End of Transition Area”, “Day Versus Night Observations”, and “Capacity Adjacent to Active Work”.

Klodzinski, et.al. (9), conducted a case study for University plaza to evaluate the impacts from deployment of an ORT concept for a mainline toll plaza. The measurement used to evaluate the toll plaza quality of service in this paper were throughput, average delay, total delay, 85% percentile delay, average inter vehicle time, average queue, maximum queue, ETC speed, and ETC percentage.
In conclusion, no work has been focused on the problem of work zone effects on toll plaza operation; thus it is believed that this thesis will address a topic that has not been well researched.

### 2.2 Workzone Capacity Study

In the HCM 2000, capacity is defined as “the maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour.” The HCM 2000 (Chapter 22, Freeway Facilities) distinguishes between short-term and long-term work zones and recommends that a value of 1600 pc/h/ln be used as the base capacity value for short-term freeway work zones, regardless of the lane closure configuration.

The HCM methodology takes the following variable into consideration for specific work zone’s prevailing conditions: the intensity of work activity, effect of heavy vehicles, and the presence of ramps. The following equation captures these variables: (Equation 22-2, HCM 2000)

\[ C_a = (1600 + I - R) \times f_{HV} \times N \]

Where:

\[ C_a = \text{adjusted mainline capacity (veh/h)} \]
\( f_{hv} \) = adjustment for heavy vehicles; defined in HCM Equation 22-1

I = adjustment factor for type, intensity, and location of the work activity (ranges from -10% to +10% of base capacity, or -160 to +160 pc/h/ln)

R = adjustment for ramps, as described in the preceding paragraph

N = number of lanes open through the short-term work zone

However, the work zone capacity used in the Highway Capacity Manual is based on studies conducted in Texas. These values may not be applicable to work zones in other states because Texas has a large number of frontage roads (1).

Dixon et al. (1) conducted a work zone capacity analysis in North Carolina. She defined and determined work zone capacity values for rural and urban freeways without continuous frontage roads and identified the part of a work zone where the capacity is lowest. According to the paper, we can conclude that when the maximum flow happens upstream of the work zone governed by the merging activity, a queue is formed. This study examined the speed-flow relationship, and the evaluation was based on the following variables:

- Night versus day construction
- Intensity of work activity (heavy, moderate, or light)
- Proximity of work to active lanes
- Proximity of interchanges to the work zone
- Work zone configuration and site location
Al-Kaisy and Hall (10) concentrated their study on freeway capacity for long-term reconstruction zones and developed the site specific work zone capacity models. The data was collected at six reconstruction sites in Ontario, Canada, with different types of closure. The authors concluded that the capacity ranges between 1,853 and 2,252 pcphpl, with a mean estimate of capacity at 2,000 pcphpl. Initially, they developed two types of site-specific capacity models, and finally a generic capacity model was built. These capacity models depend on the base capacity which was modified by several factors including:

- heavy vehicles
- driver population
- light conditions
- inclement weather
- work activity on site
- configuration of the lane closure
- rain

The first model which is multiplicative is as follows:

\[ C = C_b \times f_{HV} \times f_d \times f_w \times f_s \times f_r \]

Where:

- \( C \) = Work zone capacity (vphpl),
- \( C_b \) = Base work zone capacity (pcphpl),
- \( f_{HV} \) = Adjustment factor for heavy vehicles (from HCM2000),
- \( f_d \) = Driver population factor,
- \( f_w \) = Light conditions factor,
- \( f_s \) = Inclement weather factor,
- \( f_r \) = Work activity on site factor.
\( f_{dl} \) = Adjustment factor for off-peak weekday driver population (off-peak = \( f_{d1} \), else=1),

\( f_{d2} \) = Adjustment factor for weekend driver population (weekend = \( f_{d2} \), else=1),

\( f_w \) = Adjustment factor for work activity (work activity=\( f_w \), no work activity=1),

\( f_s \) = Adjustment factor for side of lane closure (left lanes closed=\( f_s \), right lanes closed=1),

\( f_r \) = Adjustment factor for rain (rain=\( f_r \), no rain=1).

Optimization was used to derive the parameters of the model and the base capacity. The optimization procedure resulted in the following parameter values: \( C_b = 2.050 \), \( E_{HV} =2.778 \), \( f_{dl} = 0.961 \), \( f_{d2} = 0.825 \), \( f_w = 0.966 \), \( f_s = 0.943 \), \( f_r = 0.976 \) and the coefficient of determination was 0.63.

Benekohal and Chitturi (11) found a methodology for estimating both operating speeds and capacity at interstate work zones. Data were collected at 11 work zones in Illinois with time-coded video recording equipment. They recorded headways, speeds, and travel times. The following speed-flow relationship was developed from the data to establish the lower part (congested part) of the speed-flow curve:

\[
q = 145.68 \times U^{0.6857}
\]

Where:

\( q \) = Flow in passenger cars per hour per lane (pcphpl)

\( U \) = Speed in mi/h (input speed must be lower than the speed at capacity)
The free flow part of the curve is based on information from the HCM 2000 and on field data collected in work zones. The authors stated that the capacity model is based on the principle that work zone operating factors (such as work intensity, lane width, lateral clearance, etc.) causes reductions in the “operating speed”. Operating speed in a work zone is defined as the speed at which the vehicles would travel through the work activity area after reducing their speed due to work intensity, lane width, lateral clearance, and other factors. The adjusted capacity was estimated as follows:

\[ C_{adj} = C_{U0} \cdot f_{HV} \cdot PF \]

Where:

- \( C_{adj} \) = adjusted capacity (vphpl)
- \( C_{U0} \) = capacity at operating speed U0
- \( f_{HV} \) = heavy vehicle factor
- \( PF \) = platoon factor (which accounts for the underutilization of available capacity, and is a function of drivers’ aggressiveness, traffic volume, and work zone operations)

The model was validated for a two-to-one lane closure, but the authors recommended additional data collection from work zones with different lane closure configurations to further verify the validity of their methodology.

Because of unavailable of real-world work zone data, based on CORSIM simulation, Elefteriadou et al (12) developed analytical models and procedures for estimating the capacity of a freeway work zone based on the data collected in Florida, considering
various geometric and traffic parameters as follows:

- Number of closed lanes
- Lane width
- Lateral clearance
- Grade of roadway segment
- Passenger-car equivalency factor and heavy vehicle presence
- Driver population along work zones
- Merge strategies (late vs. early merge)
- Light conditions
- Effect of rain
- Presence of ramps along the work zone
- Intensity of work activity.

Their models were developed for three types of work zone configurations (2-to-1, 3-to-2, and 3-to-1 lane closure). And for each lane closure configuration, two different types of model were developed; a planning model which is the simplest and applies when a capacity estimate is required but the work zone is not in place and an operational model which requires more data as input, and may be used for estimating the capacity of an existing work zone. The capacity model equation as follows:

$$C_{a,i} = f_i \cdot f_d \cdot f_r \cdot (C_{\text{max}} - v_{R})$$

Where:
\[ C_{\text{adj}} = \text{adjusted capacity (veh/h)} \]
\[ f_l = \text{adjust for light condition} \]
\[ f_d = \text{adjust for driver population} \]
\[ f_r = \text{adjust for rain} \]
\[ C_{\text{unadj}} = \text{adjust for unadjusted capacity (veh/h)} \]
\[ v_k = \text{adjust for presence of ramp} \]

The literature review showed that there have been several models developed to estimate freeway work zone capacity. They focused on different aspects of work zone capacity. Some methods approaches concentrated on the geometric aspects of the work zone, such as lane width, presence of interchanges, etc., while some others focus on traffic stream parameters, such as driver population, and presence of multi-axle vehicles in the traffic stream.
3. METHODOLOGY

The major highways of Central Florida are Interstate 4, East-West Expressway (Toll SR-408), Beachline Expressway (Toll SR-528), Central Florida Greenway (Toll SR-417), Florida’s Turnpike (Toll SR-91), and Daniel Webster Western Beltway (Toll SR-429).

Toll SR-528 (The Martin Andersen Beachline Expressway) is a 40-mile east-west tolled, limited-access transportation corridor serving Central Florida and the Space Coast. Florida’s Turnpike Enterprise operates the western-most eight miles as the Beachline Expressway West, which begins at Interstate 4 near the International Drive resort area and ends at Cape Canaveral. As a result, tourist traffic is heavy with drivers traveling around the various hotels, tourist attractions and restaurants, as well as Orlando International Airport. The Beachline West underwent a major widening project beginning in the summer of 2007 (9).

The research team in the Center for Advanced Transportation Systems Simulation (CATSS) at the University of Central Florida, under a contract with the Florida Department of Transportation and the supervision of the Florida Turnpike Enterprise (FTE), collected data at selected plazas in the system. This data was used to calibrate and validate the TNCC and SHAKER models with the ultimate goal of integrating these models in a decision support system. This system can assist decision makers in the FTE to better operate and manage facilities. The Beachline West toll plaza is one of these sites being investigated in this study. Since this site meets the research requirement for this
thesis it was picked for that purpose.

After data collection was completed at west toll plaza of SR 528, Conway toll plaza at SR-408 operated by Orlando - Orange County Expressway Authority (OOCEA) was selected as second site because the plaza was at the end of phase 2 construction. Lake Jesup on SR-417 was selected as third site and the data was collected for pre-construction stage in 2007 and for phase 1 construction for ORT implementation in 2009. These are the only three available sites that were under ORT construction at the toll plazas during the year of 2008 and 2009 in Orlando area.

Here is an Orlando area map showing the location of all the three sites included in this study.

![Orlando map marked the selected toll plaza sites](image)

Figure 3.1 Orlando map marked the selected toll plaza sites
3.1 Identification of Study Purpose Scope and Approach

According to the literature review for no-lane closure workzone effects on toll plaza performance study, work zone’s effects can be categorized into four main types: safety, quality of service, capacity and travel demand. Since, no-lane closure workzone does not cause frequent lane change in the road section, and very few accidents happen at the toll plaza area, we did not take safety into consideration.

For travel demand, we do not have enough access to the resource which is necessary to analyze the change in demand after the opening of ORT lanes. So, this criterion was not analyzed in this study.

After excluding the two aspects of safety and travel demand from the workzone effects study, the research focused on the effect of work zone related to capacity and quality of service. The goal was to study the impact of work zone on toll facility performance and this was achieved by collecting data for before and after work zone implementation. Same analysis procedure was applied to ORT impact study. A comprehensive model was developed based on the same set of data from all three sites.

3.1.1 Selection of evaluation criteria

The criteria for evaluation are capacity and quality of service. The capacity of a toll plaza here is defined as the maximum throughput when constant queue existed. And the quality of service is represented by the queue length in this study.
The characteristics such as speed, processing time, location of the workzone of ETC lane, ACM lane and manual lane are different for each site. So, this study intended to study these criteria separately for each type of lane treatment.

3.1.2 Obtain evaluation criteria

To obtain the measure of effectiveness (MOEs) for the two selected criteria, the following data were collected:

- **Throughput** – recorded as the number of vehicles that pass through the toll plaza within a period of time. Recording specific individual vehicle arrival times allows for throughput to be determined for any time frame desired.

- **Demand** – is the throughput plus the length of the queue, if present. This was measured by counting the number of vehicles in the queue at any given time and adding that value to the throughput for the same period.

- **Processing Time** – is the calculated difference between the arrival and departure time at the toll plaza. The arrival time is the instant that the vehicle makes a complete stop within the toll collectors range. It was observed that a number of drivers attempt to offer their payment to the toll collector while their vehicle is still slowly crawling. In this case the arrival time is classified as the instant the individual begins the transaction with the toll collector. The departure time is recorded upon the onset of acceleration following the payment. The processing
times can be very short so it is important to be as precise as possible; therefore, the arrival and departure times are extracted from the video with 1/30\textsuperscript{th} of a second accuracy.

- **Move-ahead-time** – The elapsed time between the lead vehicle departure time and following vehicles arrival time at the plaza. Calculated as the Inter-arrival time minus the Processing time.

- **Queue Length** – is measured as the number of vehicles building up in each lane who are waiting to be served by toll attendant or ACM. Queue length was measured by simply counting the number of vehicles in the queue. Through the benefits of video review this can be recorded at any point in time.

- **Vehicle Type** – two categories of vehicles were recorded, either a vehicle was recorded as a passenger car or a multi-axle vehicle. A multi-axle vehicle is considered any vehicle having or towing with more than two axels touching the pavement.

- **Lane Type** – four types of lanes were observed. They are Electronic Toll Collection lanes (ETC), Open Road Tolling (ORT), Manual Attendant Assisted lanes, and Automatic Coin Machine (ACM) lanes.

- **AM/PM** – Video analysis of periods occurring in the morning peak (7-9AM) were classified as AM and periods occurring in the afternoon peak (4-6PM) were classified as PM based on the transaction data showing the highest throughput hours.
3.2 Data Collection and Preparation

Data was obtained in two ways, one way is field data collection by setting cameras at the toll plaza and then extract them from the video, and the other way is obtaining Detailed Audit Report from the Toll Plaza Authority. The west toll plaza of SR-528 has only field data and the other two sites have Detailed Audit Reports. Field data was collected at the following three sites, Lake Jesup Mainline Plaza along the Seminole Expressway (SR-417), the Beachline West Expressway Toll Plaza along the Beachline (SR-528) and Conway toll plaza along the Holland East-West Expressway (SR-408).

The data collection procedure is same for all the three sites. For example, as shown in Figure 3.1, field data was collected at Beachline (SR 528) West Toll Plaza westbound for before and during on site construction to compare the non-construction condition and work zone conditions. The workzone condition is shown as the shaded area and two extra lanes were added in each direction.

Figure 3.1 Work Zone at Beachline (SR 528) West Toll Plaza
To collect the needed data, four cameras were set up at the Beachline (SR 528) West Toll Plaza as shown in Figure 3.2. Two cameras were set up per direction: one camera was located at the downstream of the plaza and the second camera was located at the upstream of the plaza. The downstream camera captured throughput, vehicle type, processing rate and time and payment type, while the upstream camera captured the queue length and traffic demand.

![Figure 3.2 Camera location and vision area](image)

The Beachline (SR 528) West Toll Plaza has eleven (11) lanes in total, five lanes in eastbound (two change receipt lanes, one ACM lane, and two ETC lanes), and six lanes in westbound (two change receipt lanes, two ACM lanes, and two ETC lanes). The configuration of Beachline (SR 528) West Toll Plaza is shown in Figure 3.3. The configurations for the Lake Jesup and Conway toll plaza are shown in Figure 3.4, 3.5 and 3.6 respectively.
Figure 3.3 Configuration of Beachline (SR 528) West Toll Plaza

Figure 3.4 Configuration of Lake Jesup Toll Plaza (SR 417)
3.3 Analysis of Workzone Effect and ORT Impact Study

Data such as throughput, number of each type of lanes, and processing time was extracted
from the video recorded by the downstream camera. For throughput, we used 1-minute interval and 15-minute interval to count the number of vehicles that went through the toll plaza. The data inventory in Table 3-1 below shows the availability of 1-minute interval data and 15-minute interval data. Passenger car and multi-axle vehicle data were recorded respectively. Processing rate and time can also be extracted from the video taken by downstream camera. Queue lengths can be seen from the video upstream. A sample data in 1-minute interval form extracted from the video is provided in Table 3-2.
Table 3-1: Field Data Site Locations – Data Inventory

<table>
<thead>
<tr>
<th>Site</th>
<th>Lake Jessup (non-c)</th>
<th>Lake Jessup (const)</th>
<th>West 528 (non const)</th>
<th>West 528 (const)</th>
<th>Conway (no ORT)</th>
<th>Conway (DRT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queue data collected</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Throughput data collected</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>M lanes</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>A lanes</td>
<td>N/A</td>
<td>N/A</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>EP lanes</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>ORT lanes</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>1 min data breakdown for M&amp;A</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>1 min data breakdown for E</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>15 min data breakdown</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Const. at this site</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td># of hours data available M&amp;A</td>
<td>12</td>
<td>12</td>
<td>2</td>
<td>2.5</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td># of hours data available E</td>
<td>12</td>
<td>12</td>
<td>10</td>
<td>2.5</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
Table 3-2: Extracted data sample

<table>
<thead>
<tr>
<th>Toll Location</th>
<th>Date/Time</th>
<th>per min</th>
<th>M</th>
<th>M</th>
<th>A</th>
<th>E_p</th>
<th>E_p</th>
<th>M</th>
<th>M</th>
<th>A</th>
<th>E_f</th>
<th>E_f</th>
<th>Throughput Total</th>
<th>Queue length</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB 528</td>
<td>02-25-2008</td>
<td>0-1</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>31</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3:00 - 4:00 PM</td>
<td>1-2</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>33</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>37</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-4</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>11</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>41</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
In Chapter 4, statistic analysis was conducted using available data to examine the difference in performance between construction and non-construction stages. Throughput and queue length were the two criteria in the comparison between the two stages.

3.4 Toll Plaza Model

All the collected data were combine and reclassified in 15 minute intervals, resulting in four data points per hour. Then, a statistical model was built based on the data.

The following variables were considered for building the model; percentage of ETC lane users, percentage of Manual lane users, percentage of ACM lane users, percentage of ORT users, Demand, Multi-axle vehicle percentage in ETC lanes, Multi-axle vehicle percentage in Manual lanes, Multi-axle vehicle percentage in ORT lanes, stop time, Number of ETC lanes, Number of Manual lanes, Number of Automatic lanes, Number of ORT lanes, Toll value, Have workzone or not, Have ORT lanes or not, Demand/capacity, Demand /throughput. Throughput and Queue length are the two variables to be predicted by this model.
4 DATA ANALYSIS

4.1 Highway 528 Beachline West Toll Plaza

4.1.1 Non-ETC Data Description

For non-construction stage, field data was collected at Beachline West (SR-528) on November 13, 2007 from 4pm to 6pm. And for construction stage, field data was collected on February 25, 2008 for 2.5 hours from 3:30 pm to 6:00 pm. Traffic characteristics such as demand, throughput, processing rates, and queue lengths of different toll categories were extracted from the digital video. There are two manual lanes, one ACM lane and two ETC lanes at this toll plaza. For the purpose of this analysis, outer manual lane is referred to as M1, inner manual lane as M2, ACM lane as A, and inner ETC lane is referred to as E1, outer ETC lane as E2, as shown in figure 3.3.

To find the workzone effects on toll plaza performance, data analysis conducted is explained in the following sections. There are three types of data analysis; combined data, congestion period data, and multi-axle vehicle factoring data. Combined data includes two hours of throughput and queuing data for Nov 13th, and two hours and half for Feb 25th in the evening peak for both non-construction and construction condition. But during the two hours, not every minute has high traffic volume, sometimes; volume is very low for both conditions. It biased the results, so, congestion period data is picked out to
conduct another analysis. Because of the potential impact of multi-axle vehicle traffic on workzone performance, a third analysis based on multi-axle vehicle factoring data during congestion period, was conducted.

4.1.2 Non-ETC Capacity Analysis for SR 528 Beachline West Toll Plaza

Throughput of Manual and Automatic lanes was extracted from the raw data in one minute interval. The one minute interval data is then grouped for every consecutive 5 minutes, 15 minutes, 30 minutes and 60 minutes. For example, using the 120 minutes data, 1 minute interval format has produced 120 data points, 5 minutes interval format has produced 115 data points, 15 minutes interval format has produced 105 data points, 30 minutes interval format has produced 90 data points, and 60 minutes interval format has produced 60 data points.

Examining all the throughput data points for every 1, 5, 15, 30 and 60 minutes, the maximum throughput for each time interval was found as shown in Table 4.1. The capacity, which is defined as maximum throughput per hour for each time interval, was calculated by multiplying the throughput figure with the adjustment factors of 60, 12, 4, 2 and 1 for 1, 5, 15, 30 and 60 minutes data, respectively. The calculated capacity using different time interval is shown in Table 4.2.
Table 4.1: Maximum throughput in each time interval for SR 528 west toll plaza

<table>
<thead>
<tr>
<th>SR 528</th>
<th>Maximum Throughput</th>
<th>2007-Nov (non-const)</th>
<th>2008-Feb (const)</th>
</tr>
</thead>
<tbody>
<tr>
<td>interval</td>
<td>M1</td>
<td>M2</td>
<td>A</td>
</tr>
<tr>
<td>1'</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>5'</td>
<td>40</td>
<td>39</td>
<td>34</td>
</tr>
<tr>
<td>15'</td>
<td>103</td>
<td>99</td>
<td>91</td>
</tr>
<tr>
<td>30'</td>
<td>199</td>
<td>192</td>
<td>164</td>
</tr>
<tr>
<td>60'</td>
<td>364</td>
<td>369</td>
<td>306</td>
</tr>
</tbody>
</table>

Table 4.2.: Calculated capacity using different time interval for SR 528 west toll plaza

<table>
<thead>
<tr>
<th>SR 528</th>
<th>Capacity</th>
<th>2007-Nov (non-const)</th>
<th>2008-Feb (const)</th>
</tr>
</thead>
<tbody>
<tr>
<td>interval</td>
<td>M1</td>
<td>M2</td>
<td>A</td>
</tr>
<tr>
<td>1'</td>
<td>540</td>
<td>540</td>
<td>540</td>
</tr>
<tr>
<td>5'</td>
<td>480</td>
<td>468</td>
<td>408</td>
</tr>
<tr>
<td>15'</td>
<td>412</td>
<td>396</td>
<td>364</td>
</tr>
<tr>
<td>30'</td>
<td>398</td>
<td>384</td>
<td>328</td>
</tr>
<tr>
<td>60'</td>
<td>364</td>
<td>369</td>
<td>306</td>
</tr>
</tbody>
</table>

The two tables above show that the smaller the time interval is the higher capacity it gets. But according to the field observation, a throughput of 9 vehicles per minute happened about only twice in two hour’s period, and therefore the capacity based on one minute max throughput is not that reliable. As time interval increases, the capacity drops because the demand does not exceed the capacity when using the bigger time interval. Also according to field observation, constant demand existed not longer than 15 minutes; so capacity for 5 minutes interval was picked as the reliable capacity.
4.1.3 Comparison between non-construction and construction condition for Manual and Automatic lanes

4.1.3.1 Comparison between non-construction and construction condition using whole data set for Manual and Automatic lanes (mix traffic)

A T-test is conducted in Minitab to compare the difference between non-construction stage (Nov 13\textsuperscript{th} 2007, Westbound, PM peak from 4 to 6pm) and construction stage (Feb 25\textsuperscript{th} 2008, Westbound, PM peak from 3:30 to 6:00 pm) using 1 minute interval data for the two Manual lanes and Automatic lane. T-test is based on 95% confidence interval and the results are shown in Table 4.3.

<table>
<thead>
<tr>
<th>Lane Type</th>
<th>Day</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Nov-13-M1</td>
<td>120</td>
<td>5.59</td>
<td>1.8</td>
<td>0.16</td>
<td>0.005</td>
<td>0.983</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M1</td>
<td>150</td>
<td>5.59</td>
<td>1.94</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>Nov-13-M2</td>
<td>120</td>
<td>5.57</td>
<td>1.72</td>
<td>0.16</td>
<td>-0.247</td>
<td>0.213</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M2</td>
<td>150</td>
<td>5.81</td>
<td>1.46</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Nov-13-A</td>
<td>120</td>
<td>4.66</td>
<td>2.12</td>
<td>0.19</td>
<td>-0.568</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>Feb-25-A</td>
<td>150</td>
<td>5.23</td>
<td>2.04</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 indicated no significant difference in throughput between non-construction and construction for both outer and middle Manual lanes. But, throughput difference between non-construction and construction for automatic lane was significant with a P-Value of 0.027. After examining the data, it was found that the traffic was heavy going through the Automatic lane from 3:30 to 4:00pm for the construction stage. So, another T-test was
conducted using data in same period from 4pm to 6pm for both non-construction and construction data. Results of t-test comparing the non-construction and construction for the same time period (4-6pm) are shown in Table 4.4.

<table>
<thead>
<tr>
<th>Lane Type</th>
<th>Day</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Nov-13-M1</td>
<td>120</td>
<td>5.59</td>
<td>1.8</td>
<td>0.16</td>
<td>-0.033</td>
<td>0.889</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M1</td>
<td>120</td>
<td>5.63</td>
<td>1.9</td>
<td>0.17</td>
<td>-0.308</td>
<td>0.132</td>
</tr>
<tr>
<td>M2</td>
<td>Nov-13-M2</td>
<td>120</td>
<td>5.57</td>
<td>1.72</td>
<td>0.16</td>
<td>-0.308</td>
<td>0.132</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M2</td>
<td>120</td>
<td>5.88</td>
<td>1.42</td>
<td>0.13</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
<tr>
<td>A</td>
<td>Nov-13-A</td>
<td>120</td>
<td>4.66</td>
<td>2.12</td>
<td>0.19</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>Feb-25-A</td>
<td>120</td>
<td>5.1</td>
<td>2.03</td>
<td>0.19</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
</tbody>
</table>

From Table 4.4, it is clear that there is no significant difference between non-construction and construction condition for manual and automatic lanes when same time period (4-6pm) data was compared.

Figure 4.1 and Figure 4.2 show the frequency percentage of one minute throughput of non ETC lanes at SR 528 west toll plaza. The x-axis represents the throughput per minute. Frequency of each throughput is calculated and then converted to percentage as shown in y-axis. Most of the throughputs are from 4 to 8 vehicles per minute and it follows a normal distribution. When using the whole data set, the following two charts are almost of same pattern.

Figure 4.3 and Figure 4.4 shows the plot of throughput per minute versus cumulative frequency percentage and it is shaped as an S curve.
Figure 4.1 Throughput per minute frequency percentage chart using the whole data points. Non-construction

Figure 4.2 Throughput per minute frequency percentage chart using the whole data points. Construction
Figure 4.3: Throughput per minute cumulative frequency percentage chart using the whole data points. Non-construction

Figure 4.4: Throughput per minute cumulative frequency percentage chart using the whole data points. Non-construction
4.1.3.2 Comparison between non-construction and construction condition using congestion data for Manual and Automatic lanes (mix traffic)

During the two hours of data collection, the demand was not always over the capacity, and therefore the true capacity could not be obtained using the whole data set. So, we used congestion data for this analysis during which there were constant queues for both non-construction and construction stage. The inter-arrival time (departure time minus arrival time of next vehicle) value of less than six seconds was used to determine the congested time period. Figure 4.5 and Figure 4.6 shows the comparison for congestion periods. The X-axle represents the number of vehicles going through each gate per minute, and Y-axle is the frequency percentage the number appears. An obvious drop in capacity of M1 is observed according to the chart, with the bars shift to the left.

![Figure 4.5 Throughput per minute frequency percentage chart using the congestion data during non-construction](image)
Figure 4.6 Throughput per minute frequency percentage chart using the congestion data points during Construction

Results of t-test comparing the non-construction and construction for the congestion period are shown in Table 4.5.

Table 4.5: T-test results using congestion data in one minute interval

<table>
<thead>
<tr>
<th>Lane Type</th>
<th>Day</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Nov-13-M1</td>
<td>35</td>
<td>6.71</td>
<td>1.23</td>
<td>0.21</td>
<td>0.588</td>
<td>0.042</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M1</td>
<td>103</td>
<td>6.13</td>
<td>1.7</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>Nov-13-M2</td>
<td>57</td>
<td>6.4</td>
<td>1.41</td>
<td>0.19</td>
<td>0.316</td>
<td>0.169</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M2</td>
<td>110</td>
<td>6.1</td>
<td>1.21</td>
<td>0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Nov-13-A</td>
<td>48</td>
<td>5.98</td>
<td>1.94</td>
<td>0.28</td>
<td>0.65</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>Feb-25-A</td>
<td>101</td>
<td>5.51</td>
<td>2.18</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5 shows a P-Value of 0.042 for inner manual lane (M1). This shows a significant difference in outer manual lane throughput between non-construction and construction for both directions. It means the capacity under non-construction condition is higher than the construction condition. We can infer that the construction at the side of the toll plaza
impacted the capacity of the outer lane and therefore the capacity was less in the outer manual lane. But for inner manual lane (M2) and automatic lane (A), there was no significant difference between non-construction and construction condition.

4.1.3.3 Comparison between non-construction and construction condition using both whole data and congestion data for Manual and Automatic lanes (Multi-axle vehicle-factor applied)

In order to examine whether the multi-axle vehicle traffic affects the toll plaza’s performance, multi-axle vehicle factor ($E_T=1.5$) was applied to the throughput according to Exhibit 21-8 in the Highway Capacity Manual 2000. For each minute, a passenger car equivalent was calculated using the number of multi-axle vehicles in the time period multiplied by the multi-axle vehicle equivalent factor ($E_T=1.5$). T-test results using data points at same time period in one minute interval with T-factor applied are shown in Table 4.6. Results during congestion periods are shown in Table 4.7.

<table>
<thead>
<tr>
<th>Lane Type</th>
<th>Day</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Nov-13-M1</td>
<td>120</td>
<td>5.67</td>
<td>1.78</td>
<td>0.16</td>
<td>-0.054</td>
<td>0.819</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M1</td>
<td>120</td>
<td>5.72</td>
<td>1.87</td>
<td>0.17</td>
<td>-0.258</td>
<td>0.200</td>
</tr>
<tr>
<td>M2</td>
<td>Nov-13-M2</td>
<td>120</td>
<td>5.64</td>
<td>1.7</td>
<td>0.16</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M2</td>
<td>120</td>
<td>5.9</td>
<td>1.4</td>
<td>0.13</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
<tr>
<td>A</td>
<td>Nov-13-A</td>
<td>120</td>
<td>4.66</td>
<td>2.12</td>
<td>0.19</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
<tr>
<td></td>
<td>Feb-25-A</td>
<td>120</td>
<td>5.1</td>
<td>2.03</td>
<td>0.19</td>
<td>-0.442</td>
<td>0.101</td>
</tr>
</tbody>
</table>
Table 4.7: T-test results using congestion data in one minute interval with T-factor applied

<table>
<thead>
<tr>
<th>Lane Type</th>
<th>Day</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Nov-13-M1</td>
<td>35</td>
<td>6.74</td>
<td>1.25</td>
<td>0.21</td>
<td>0.549</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M1</td>
<td>103</td>
<td>6.19</td>
<td>1.67</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>Nov-13-M2</td>
<td>57</td>
<td>6.42</td>
<td>1.41</td>
<td>0.19</td>
<td>0.307</td>
<td>0.164</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M2</td>
<td>110</td>
<td>6.11</td>
<td>1.2</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Nov-13-A</td>
<td>48</td>
<td>5.98</td>
<td>1.94</td>
<td>0.28</td>
<td>0.464</td>
<td>0.193</td>
</tr>
<tr>
<td></td>
<td>Feb-25-A</td>
<td>101</td>
<td>5.51</td>
<td>2.18</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

After applying Multi-axle vehicle-factor to throughput data of highway 528 west toll plaza, results were consistent with the mix traffic. Figure 4.7 and 4.8 are the Throughput per minute frequency percentage chart using the congestion data points with T-factor applied at construction and non construction stage. We can compare them to figure 4.5 and 4.6, they are very similar, and T-tests show similar results too.

Figure 4.7: Throughput per minute frequency percentage chart using the congestion data points. T-factor applied during construction
4.1.4 E-pass Data description

For non-construction stage, field data was collected at Beachline West (SR-528) on November 13, 15, 27, and 29, 2007 from 4pm to 6pm. And for construction stage, field data was collected on February 20 and 25, 2008 for 2 hours from 4pm to 6pm. Throughput were extracted from the digital video. There are two ETC lanes at this toll plaza; inner ETC lane is referred to as E1, outer ETC lane as E2.

4.1.5 Comparison between non-construction and construction condition for ETC lanes

T-test was conducted to compare ETC throughput between construction and non-construction stage. The comparison was based on 15 minute interval throughput; all data were combined together under two categories: construction and non-construction.
Figure 4.9 shows the comparison of throughput for both E1 and E2 under construction and non construction condition. And in Figure 4.10, E1 and E2 are combined together as one E lane. The x-axis is the time in every 15 minutes, and y is the throughput in each 15 minutes.

Figure 4.9: ETC inner and outer lane throughput per 15 minutes

Figure 4.10: ETC lanes as a whole throughput per 15 minutes
Table 4.8 shows the T-test results of throughput comparison for SR 528 ETC using 15 minute interval data.

<table>
<thead>
<tr>
<th>Lane</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Construction</td>
<td>16</td>
<td>142.8</td>
<td>19</td>
<td>-43.31</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Non-const</td>
<td>32</td>
<td>186.1</td>
<td>20.9</td>
<td>3.7</td>
<td>0.029</td>
</tr>
<tr>
<td>E2</td>
<td>Construction</td>
<td>16</td>
<td>160.2</td>
<td>17.7</td>
<td>13.03</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Non-const</td>
<td>32</td>
<td>147.2</td>
<td>20.3</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>ETC</td>
<td>Construction</td>
<td>16</td>
<td>303</td>
<td>30.4</td>
<td>-30.28</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Non-const</td>
<td>32</td>
<td>333.3</td>
<td>36.3</td>
<td>6.4</td>
<td></td>
</tr>
</tbody>
</table>

Inner ETC lane, that is E1, has a significant decrease in throughput during construction at 95% confidence interval. Conversely, outer ETC lane, labeled as E2, has a slightly higher throughput during construction. To analyze the ETC throughput as a whole, E1 and E2 were combined, and the result shows that the construction resulted in a much lower throughput with a P-value of 0.004.

According to field observation, long queues were built up during the peak hours at SR 528 Beachline west toll plaza during construction, but the queue is as long as 2 miles, and there is a curve 0.5 miles before the toll plaza, queue can not be observed beyond that. This blocked the ETC vehicles at the road section which explains the significant decrease of throughput during construction. As for the difference between E1 and E2, it maybe because people tend to keep on the far left lane (E2) when there is a long queue.
4.1.6 Comparison between non-construction and construction condition for queues at non-ETC lanes

Queue length data was collected at the end of every 15 minutes at the toll plaza. Figure 4.11 shows the queue length comparison between construction and non-construction condition. Light color bars represent for non ETC lanes’ queue length under construction condition and dark color bars are for non-construction condition. It was found that the construction condition has much higher queue length than the non-construction.

![Figure 4.11. Queue length comparison of Non ETC lanes](image)

T-test was conducted to analyze the difference between construction and non-construction condition, and Table 4.9 shows a significant increase of queue length during the construction time, with a P-Value of less than 0.031 for all the lanes.
Table 4.9: T-test results of non ETC lanes’ queue length comparison for WB SR 528 in 15 minute interval

<table>
<thead>
<tr>
<th>Lane Type</th>
<th>Day</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Nov-13-M1</td>
<td>8</td>
<td>2.75</td>
<td>3.58</td>
<td>1.3</td>
<td>-61.1</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M1</td>
<td>8</td>
<td>63.9</td>
<td>64.1</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>Nov-13-M2</td>
<td>8</td>
<td>2.5</td>
<td>3.16</td>
<td>1.1</td>
<td>-61.4</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Feb-25-M2</td>
<td>8</td>
<td>63.9</td>
<td>64</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Nov-13-A</td>
<td>8</td>
<td>2.5</td>
<td>3.3</td>
<td>1.2</td>
<td>-61.3</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>Feb-25-A</td>
<td>8</td>
<td>63.8</td>
<td>64.2</td>
<td>23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.7 Demand study for non-construction and construction condition

To make sure the difference in throughput is not caused by the increase or decrease of demand, a comparison between non-construction and construction condition about the demand and throughput was conducted. Table 4.10 shows the throughput and demand for each lane category under non-construction and construction. Since the traffic demand was very high from 5-6 pm, queue built up over one mile and the comparison was separated by each hour.

Table 4.10: Throughput and demand for each lane category under non-construction and construction

<table>
<thead>
<tr>
<th>SR 528</th>
<th>Stage</th>
<th>Total</th>
<th>E(total)</th>
<th>E1</th>
<th>E2</th>
<th>Non-E</th>
<th>M(total)</th>
<th>M1</th>
<th>M2</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-5pm</td>
<td>Non-const</td>
<td>Throughput</td>
<td>2029</td>
<td>1169</td>
<td>665</td>
<td>504</td>
<td>860</td>
<td>606</td>
<td>307</td>
<td>299</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demand</td>
<td>2029</td>
<td>1169</td>
<td>665</td>
<td>504</td>
<td>860</td>
<td>606</td>
<td>307</td>
<td>302</td>
</tr>
<tr>
<td></td>
<td>Const</td>
<td>Throughput</td>
<td>2182</td>
<td>1117</td>
<td>527</td>
<td>590</td>
<td>1027</td>
<td>689</td>
<td>331</td>
<td>358</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demand</td>
<td>2222</td>
<td>1117</td>
<td>527</td>
<td>590</td>
<td>1057</td>
<td>714</td>
<td>346</td>
<td>368</td>
</tr>
<tr>
<td>5-6pm</td>
<td>Non-const</td>
<td>Throughput</td>
<td>2414</td>
<td>1380</td>
<td>745</td>
<td>635</td>
<td>1034</td>
<td>728</td>
<td>359</td>
<td>369</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demand</td>
<td>2420</td>
<td>1380</td>
<td>745</td>
<td>635</td>
<td>1034</td>
<td>734</td>
<td>359</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>Const</td>
<td>Throughput</td>
<td>2121</td>
<td>1168</td>
<td>512</td>
<td>656</td>
<td>953</td>
<td>680</td>
<td>334</td>
<td>346</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demand</td>
<td>2521</td>
<td>1368</td>
<td>512</td>
<td>656</td>
<td>1053</td>
<td>912</td>
<td>400</td>
<td>412</td>
</tr>
</tbody>
</table>
Figure 4.12 and 4.13 are generated from the table above.

Figure 4.12 Throughput and demand comparison from 4-5pm at Conway plaza

Figure 4.13 Throughput and demand comparison from 5-6pm at Conway plaza

From the table and the charts, we can infer that the demand is almost equal to throughput
for both construction and non-construction condition from 4 to 5 pm. Not much queue existed during this period, and the total throughput and demand under construction is higher than non-construction. ETC vehicles throughput under construction is slightly lower than non-construction. Non ETC throughput under construction is higher than non-construction.

From 5 pm to 6 pm, the peak hour, figure 4.13 shows a higher demand under construction than non-construction, but a lower throughput under construction than non-construction. It also shows similar total throughput and demand for non-construction stage, and a higher total demand at construction stage but with lower throughput. The same situation happened to both ETC total throughput and non ETC throughput. After studying the demand for SR 528 west toll plaza, it can be concluded that the demand remains almost the same and it will not have negative impact on the throughput.

4.1.8 Summary of findings

According to the analysis in this section, the findings are summarized as follows:

Demand for SR 528 west toll plaza remains almost the same and it does not have any impact on the following study. For non ETC lanes (two manual and one automatic) the outer Manual lane, which is the closest lane to the workzone at the side of plaza, has a relatively lower throughput during construction than non-construction. The difference is statistically significant to prove that the workzone has a negative effect on the outer lane of the toll plaza. As for inner manual lane and automatic lane, there was no significant
difference between construction and non-construction. Workzone dose not affect these inner lanes. But long queues were seen during construction stage and the queue is significantly more than non-construction time. Therefore, workzone has a negative effect on the queue length.

For ETC lanes, E1 and E2 have different results when analyze them separately. Throughput of E1, the inner ETC lane, significantly decreased but E2 has a slightly increase in throughput. When the two ETC lanes were combined as one, the total ETC throughput decreased significantly during the construction because of the blocked ETC vehicles.
4.2 Highway 417 Lake Jesup toll plaza

4.2.1 Data description

For non-construction, field data was collected at Lake Jesup SR-417 on September 4 and 5, 2007 from 7am to 9am and 4pm to 6pm. And for construction, field data was collected on April 14, 15,16,28,29, from 7am to 9am and 4pm to 6pm., May 26 27 28, from 7am to 9am and Jun 2 and 3, 4pm to 6pm in 2009. Traffic characteristics such as demand, throughput, and queue lengths of different toll categories were extracted from the digital video and Detailed Audit report provided by Florida Turnpike Enterprise. There are two manual lanes, and two ETC lanes at this toll plaza. For analysis, outer manual lane is referred as M1, inner manual lane as M2, and ETC lanes as E.
Table 4.11 Throughput of Manual lanes for SR 417 at peak 2 hours

<table>
<thead>
<tr>
<th>Date</th>
<th>AM</th>
<th></th>
<th>PM</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SB</td>
<td></td>
<td>SB</td>
<td></td>
<td></td>
<td>NB</td>
</tr>
<tr>
<td>M1</td>
<td>M2</td>
<td></td>
<td>M1</td>
<td>M2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-14-09</td>
<td>409</td>
<td>406</td>
<td>401</td>
<td>431</td>
<td>459</td>
<td>440</td>
</tr>
<tr>
<td>4-15-09</td>
<td>416</td>
<td>422</td>
<td>434</td>
<td>468</td>
<td>563</td>
<td>493</td>
</tr>
<tr>
<td>4-16-09</td>
<td>371</td>
<td>436</td>
<td>404</td>
<td>460</td>
<td>451</td>
<td>510</td>
</tr>
<tr>
<td>4-28-09</td>
<td>381</td>
<td>379</td>
<td>406</td>
<td>369</td>
<td>515</td>
<td>443</td>
</tr>
<tr>
<td>4-29-09</td>
<td>396</td>
<td>407</td>
<td>219</td>
<td>434</td>
<td>485</td>
<td>448</td>
</tr>
<tr>
<td>5-26-09</td>
<td>407</td>
<td>385</td>
<td>442</td>
<td>371</td>
<td>411</td>
<td>424</td>
</tr>
<tr>
<td>5-27-09</td>
<td>443</td>
<td>418</td>
<td>388</td>
<td>389</td>
<td>441</td>
<td>413</td>
</tr>
<tr>
<td>5-28-09</td>
<td>412</td>
<td>373</td>
<td>433</td>
<td>482</td>
<td>449</td>
<td>447</td>
</tr>
<tr>
<td>6-02-09</td>
<td>422</td>
<td>384</td>
<td>411</td>
<td>380</td>
<td>453</td>
<td>424</td>
</tr>
<tr>
<td>6-03-09</td>
<td>593</td>
<td>572</td>
<td>390</td>
<td>420</td>
<td>432</td>
<td>509</td>
</tr>
<tr>
<td>9-04-07</td>
<td>430</td>
<td>471</td>
<td>507</td>
<td>512</td>
<td>542</td>
<td>536</td>
</tr>
<tr>
<td>9-05-07</td>
<td>467</td>
<td>472</td>
<td>496</td>
<td>543</td>
<td>512</td>
<td>543</td>
</tr>
</tbody>
</table>

Throughputs during construction time were lower than the non-construction time and no queue was observed at the end of the peak period under construction condition. It is due to the lower demand during construction than non-construction time. So, dates with higher throughput were picked out to do the analysis in the next step.

T-test showed data from June 3rd is much different from other dates and it had abnormally higher throughput. It could be because of some special event and so we excluded this day for the analysis.

4.2.2 Non-ETC capacity analysis for SR 417 Lake Jesup toll plaza

Throughput of Manual lanes were extracted from the raw data (non-construction) and
Detailed Audit (construction) in one minute interval for both peak (AM, PM) in both direction (Northbound, Southbound). The one minute interval data was then summed to every consecutive 5 minutes, 15 minutes, 30 minutes and 60 minutes. For example, using 120 minutes data, 1 minute interval format has 120 data points, 5 minutes interval format has 115 data points, 15 minutes interval format has 105 data points, 30 minutes interval format has 90 data points, and 60 minutes interval format has 60 data points.

With all the data points of the throughput for every 1, 5, 15, 30 and 60 minutes, the maximum throughput for each time interval was found. The capacity which is maximum throughput per hour for each time interval was calculated by multiplying 60, 12, 4, 2 and 1 for 1, 5, 15, 30 and 60 minutes data respectively. The maximum throughput and calculated capacity using different time interval is shown in Table 4.12.
Table 4.12 Maximum throughput and calculated capacity using different time interval for SR 417 Lake Jesup

<table>
<thead>
<tr>
<th>SR417LJ</th>
<th>Max Throughput M</th>
<th>Capacity M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007(non-cons)</td>
<td>2009(cons)</td>
</tr>
<tr>
<td></td>
<td>M1</td>
<td>M2</td>
</tr>
<tr>
<td>interval</td>
<td>1'</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>5'</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>15'</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>30'</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td>60'</td>
<td>337</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There were 13 (non-construction) and 14 (construction) vehicles per minute going through M1 observed in SR 417 Lake Jesup plaza compared to 9 vehicles per minute for SR 528 west, the SR 528 west has a toll value of $0.75 compared to $2.00 at SR 417 Lake Jesup thus reducing the processing time because two dollars toll fee do not require the operator to give change, but for 0.75 dollars, people usually use one dollar bill and get change.

4.2.3 Comparison between non-construction and construction condition for Manual lanes

4.2.3.1 Comparison between non-construction and construction condition using whole data set for Manual lanes (mix traffic)

Data for SR 417 Lake Jesup toll plaza was analyzed for two directions and two peak periods, thus forming four different categories: Northbound AM, Northbound PM, Southbound AM, and Southbound PM. Northbound AM was not available because of the closure of one of the NB manual lanes during morning peak period. Therefore, the
analysis was conducted for three categories: NBPM, SBAM and SBPM. Comparison between non-construction and construction conditions for Manual lanes was conducted for the three categories respectively.

4.2.3.1.1 Northbound PM peak

Figure 4.14 and 4.15 show the frequency percentages of one minute throughput of the two manual lanes at SR 417 Lake Jesup toll plaza for non-construction and construction phase. The x-axis represents the throughput per minute. Frequency of each throughput is calculated and then converted to percentage, as shown in y-axis. Most of the throughputs are from 2 to 7 vehicles per minute and it follows a normal distribution. When using the whole data set, a shift to the left is observed in the chart below, it shows fewer throughputs during construction, which is due to the drop in demand. Same shift happen to all the charts in this section, for SBAM, SBPM.
4.2.3.1.2 Southbound AM peak

Figure 4.16 and 4.17 show the frequency percentage of one minute throughput of the two manual lanes at 417 Lake Jesup toll plaza for non-construction and construction phase at SBAM. The x-axis represents the throughput per minute. Frequency of each throughput is calculated and then converted to percentage, as shown in y-axis. Most of the throughputs are from 3 to 7 vehicles per minute and it follows a normal distribution. When using the whole data set, a shift to the left is observed in the chart below due to the drop in demand, same as the NBPM analysis.
Figure 4.16. Throughput per minute frequency percentage using the whole data points during non-construction

Figure 4.17 Throughput per minute frequency percentage using the whole data points during construction

4.2.3.1.3 Southbound PM peak

Figure 4.18 and 4.19 show the frequency percentage of one minute throughput of the two manual lanes at 417 Lake Jesup toll plaza for non-construction and construction phase at SBPM. The x-axis represents the throughput per minute. Frequency of each throughput is
calculated and then converted to percentage, as shown in y-axis. When using the whole data set, because of the drop in demand, just the same as the previous analysis, a shift to the left is observed in the figures.

Figure 4.18. Throughput per minute frequency percentage using the whole data points during non-construction

Figure 4.19. Throughput per minute frequency percentage using the whole data points during construction
4.2.3.1.4 T-test results for NBPM, SBAM and SBPM

T-tests were conducted in Minitab to compare the difference between different days under same condition. Table 4.13 shows the T-test results and all P-value are less than 0.05. It means during construction, there is a significant decrease in throughput. It might be due to the decrease in demand, because few queues were observed in field. So, the next step was to compare the throughput by using congestion data.

Table 4.13 T-test results using whole data set in one minute interval

<table>
<thead>
<tr>
<th>SR417LJ</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBPM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>240</td>
<td>4.48</td>
<td>1.99</td>
<td>0.13</td>
<td>0.45</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>4.03</td>
<td>1.96</td>
<td>0.089</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>240</td>
<td>4.39</td>
<td>1.84</td>
<td>0.12</td>
<td>0.319</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>4.07</td>
<td>1.75</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBAM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>240</td>
<td>3.75</td>
<td>1.49</td>
<td>0.096</td>
<td>0.475</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>3.28</td>
<td>1.62</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>240</td>
<td>3.93</td>
<td>1.61</td>
<td>0.10</td>
<td>0.354</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>3.57</td>
<td>1.57</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBPM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>240</td>
<td>4.18</td>
<td>1.69</td>
<td>0.11</td>
<td>0.76</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>3.42</td>
<td>1.7</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>240</td>
<td>4.4</td>
<td>1.98</td>
<td>0.13</td>
<td>0.651</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>3.74</td>
<td>1.56</td>
<td>0.082</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.2.3.2 Comparison between non-construction and construction condition using congestion data for Manual lanes (mix traffic)

Figure 4.20 to 4.25 shows the frequency percentage of one minute throughput of the two manual lanes at SR 417 Lake Jesup toll plaza, categorized as NBPM, SBAM, and SBPM. Each category has one chart for non-construction and one for construction condition. The x-axis represents the throughput per minute. Frequency of each throughput is calculated and then converted to percentage as shown in y-axis. Most of the throughputs are from 3 to 8 vehicles per minute and it follows a normal distribution. When using the congestion data, the patterns look similar in the charts below.

4.2.3.2.1 Northbound PM peak
Figure 4.20. Throughput per minute frequency percentage using congestion data. Non-construction

Figure 4.21. Throughput per minute frequency percentage using congestion data. Construction

4.2.3.2.2 Southbound AM peak

Figure 4.22. Throughput per minute frequency percentage using congestion data. Non-construction
Figure 4.23. Throughput per minute frequency percentage using congestion data.

Construction

4.2.3.2.3 Southbound PM peak

Figure 4.24. Throughput per minute frequency percentage using congestion data.

Non-construction
Figure 4.25. Throughput per minute frequency percentage using congestion data.

Construction
4.2.3.2.4 T-test results for NBPM, SBAM and SBPM

T-test was conducted for each category and the results are shown in Table 4.14. The results show there was no significant difference in throughput for all the directions during peak time.

<table>
<thead>
<tr>
<th>SR417LJ</th>
<th>M1</th>
<th>M2</th>
<th>Non-const</th>
<th>Construction</th>
<th>Non-const</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBPM</td>
<td></td>
<td></td>
<td>124</td>
<td>92</td>
<td>124</td>
<td>105</td>
</tr>
<tr>
<td>Mean</td>
<td>5.15</td>
<td>5.38</td>
<td>4.77</td>
<td>5.19</td>
<td>5.19</td>
<td>5.19</td>
</tr>
<tr>
<td>StDev</td>
<td>2.27</td>
<td>2.08</td>
<td>2.08</td>
<td>1.82</td>
<td>1.82</td>
<td>1.82</td>
</tr>
<tr>
<td>SE Mean</td>
<td>0.2</td>
<td>0.22</td>
<td>0.19</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>Estimate for difference</td>
<td>-0.227</td>
<td>-0.416</td>
<td>0.474</td>
<td>0.31</td>
<td>0.128</td>
<td></td>
</tr>
<tr>
<td>P-Value</td>
<td>0.446</td>
<td>0.108</td>
<td>0.081</td>
<td>0.189</td>
<td>0.667</td>
<td></td>
</tr>
</tbody>
</table>

4.2.4 Comparison between non-construction and construction condition for queues at non-ETC lanes

Queue length data was collected at the end of every 15 minutes. Figure 4.26 to 4.28 shows the queue length comparison and the construction condition seems to have similar queue length than the non-construction according to the figure.
Figure 4.26. Queue length comparison of Non ETC lanes-NBPM

Figure 4.27 Queue length comparison of Non ETC lanes-SBAM
T-test results for the queue analysis are shown in table 4.15 below, all the P-values, for NBPM, SBAM and SBPM, are larger than 0.1, that means even at 90% confidence interval, the difference of queue length between construction and non-construction are not significant.

All queue analysis results show no significant difference between construction and non-construction stage.
4.2.5 Summary of findings

According to the analysis for SR 417 Lake Jesup toll plaza, the findings are summarized as following:

Since the demand is not reaching capacity at Lake Jesup toll plaza, we used the congested data for analysis. Results showed the non-construction throughput is higher than construction time when using whole data set during the 2 hours of peak because of the decrease of demand.

After picking the data from congestion time period, the T-test results show no significant difference in throughput for both construction and non construction stages, and for queue length analysis, there was no significant difference either. It shows the workzone not affect this toll plaza at all on both throughput and queue length.

4.3 Highway 408 Conway toll plaza

4.3.1 Data description

Field data collected at SR 408 Conway toll plaza westbound includes two phases, before ORT lanes open and after ORT lanes open. Before ORT lanes open field data was collected at Conway SR-408 westbound on September 16, 17 and 18, 2008 from 7am to 9am. And for after ORT lanes open, field data was collected on Dec 10, 11, and 12 2008 from 7am to 9am. Traffic characteristics such as demand, throughput, and queue lengths of different toll categories were extracted from the digital video and Detailed Audit report.
provided by OOCEA. Before ORT lanes open, the plaza had seven lanes, three Manual
lanes, one Automatic, and three ETC lanes. For analysis, lanes are referred as M1, M2,
M3, A, E1, E2, and E3 from outer manual lane to outer ETC lane. After ORT lanes open,
there were eight lanes in total, three Manual lanes, two Automatic, one ETC and two
Open-tolling. And they are referred as M1, M2, M3, A1, A2, E, O1, and O2 from outer
manual lane to outer ORT lane.

4.3.2 Non-ETC capacity analysis for SR 408 Conway toll plaza

Throughput of Manual lanes was extracted from both the raw data and Detailed Audit in
one minute interval, for Westbound AM peak. The one minute interval data was then
summed to every consecutive 5 minutes, 15 minutes, 30 minutes and 60 minutes. For
example, using 120 minutes data, 1 minute interval format has 120 data points, 5 minutes
interval format has 115 data points, 15 minutes interval format has 105 data points, 30
minutes interval format has 90 data points, and 60 minutes interval format has 60 data
points.

With all the data points of the throughput for every 1, 5, 15, 30 and 60 minutes, the
maximum throughput for each time interval was found, the capacity which is defined as
maximum throughput per hour for each time interval was calculated by multiplying 60,
12, 4, 2 and 1 for 1, 5, 15, 30 and 60 minutes data respectively. The maximum throughput
and calculated capacity using different time interval is shown in Table 4.16.
Table 4.16: Maximum throughput and calculated capacity using different time interval for SR 408 Conway Toll Plaza

<table>
<thead>
<tr>
<th>SR 408</th>
<th>Max Throughput M</th>
<th>Capacity M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sep (cons)</td>
<td>Dec (after-cons)</td>
</tr>
<tr>
<td>interval</td>
<td>M</td>
<td>A</td>
</tr>
<tr>
<td>1'</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>5'</td>
<td>36</td>
<td>47</td>
</tr>
<tr>
<td>15'</td>
<td>100</td>
<td>125</td>
</tr>
<tr>
<td>30'</td>
<td>180</td>
<td>233</td>
</tr>
<tr>
<td>60'</td>
<td>374</td>
<td>455</td>
</tr>
</tbody>
</table>

4.3.3 Comparison between construction and after construction condition for Manual and Automatic lanes

According to the data, multi-axle vehicles going through the non-ETC lanes were less than 2%, which has very little influence and so the analysis was based only on mix traffic data with both passenger car and multi-axle vehicles.

T-tests were conducted in Minitab to compare the difference between construction (September) and after construction (December) using one minute interval data. For both construction and after construction, the three manual lanes, M1 to M3 were compared separately. Figure 4.29 showing the throughput comparison of M1 M2 and M3 were listed blow.
Figure 4.29. Throughput per minute comparison for M1

Figure 4.30 Throughput per minute comparison for M3
For Automatic lanes, after construction, there are one extra Automatic lane added to the toll plaza, thus, T-tests are conducted for A-sep VS A1-dec, A-sep VS A2-dec, and A-sep VS A1+A2-dec, chart with the throughput of A-sep, A1-dec, A2-dec and A1+A2-dec is shown below.

T-tests results of comparisons for non-ETC Lane’s throughput in 1 minute interval are
listed in table 4.17 below.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Results</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 &amp; M1</td>
<td>Sep &gt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>M2 &amp; M2</td>
<td>Sep &gt; Dec</td>
<td>0.002</td>
</tr>
<tr>
<td>M3 &amp; M3</td>
<td>Sep &gt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>A &amp; A1</td>
<td>Sep &gt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>A &amp; A2</td>
<td>Sep &gt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>A &amp; A1+A2</td>
<td>Sep &lt; Dec</td>
<td>0.006</td>
</tr>
</tbody>
</table>

From the results, we can see, throughput decreased significantly in all Manual lanes because of the opening of ORT lanes attracted some traffic, and throughput per Automatic lane also decreased after construction was completed because of the extra ACM lane, but the total throughput for Automatic lanes increased in December after construction was completed.

4.3.4 Comparison between construction and after construction condition for Express lanes

4.3.4.1 Throughput comparison between construction and after construction condition for Express lanes

Before the construction was completed, the Conway toll plaza had three ETC lanes, and after the construction, two of the ETC lanes are changed to ORT lanes. So, the comparison is first divided into two groups, one is E1-sep and E-dec (the only ETC lane that did not change to ORT lane), the other is E2-sep, E3-sep and O1-dec and O2-dec, as shown in figure 4.33.
Figure 4.33. Conway toll plaza configuration

Before

<table>
<thead>
<tr>
<th>E3</th>
<th>E2</th>
<th>E1</th>
<th>A</th>
<th>M3</th>
<th>M2</th>
<th>M1</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>O1</td>
<td>E</td>
<td>A2</td>
<td>A1</td>
<td>M3</td>
<td>M2</td>
</tr>
</tbody>
</table>

After

Comparison were made between the two groups, and then, take all the express lanes as a whole, conduct another comparison. Figure 4.34, 4.35 and 4.36 showing the throughput comparisons for the two groups are listed below.
EEE means the total throughput of three ETC lanes in September, EOO means the total throughput of ETC lane and two ORT lanes in December.

T-tests results of comparisons for ETC Lane’s throughput in 1 minute interval are shown in table 4.18 below:

Table 4.18 Comparisons for ETC Lane’s throughput in 1 minute interval
<table>
<thead>
<tr>
<th>Comparison</th>
<th>Results</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 &amp; E</td>
<td>Sep &gt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>E2 &amp; O1</td>
<td>Sep &lt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>E3 &amp; O2</td>
<td>Sep &lt; Dec</td>
<td>0.000</td>
</tr>
<tr>
<td>EEE &amp; EOO</td>
<td>Sep &lt; Dec</td>
<td>0.000</td>
</tr>
</tbody>
</table>

From the charts and the T-test results, we can infer that the ORT lanes increased the throughput significantly. Although the ETC throughput was decreased in December, the total vehicles passing through the express lanes (both E and O) increased significantly after construction was completed.

4.3.4 Speed comparison between construction and after construction condition for Express lanes

From the Detailed Audit Reports, speeds of vehicle in express lanes were recorded, and the speed-time pattern is shown in the figures below from figure 4.37 to figure 4.40. They show that the speed in the express lanes have significantly increased after the opening of ORT lanes.
Figure 4.37. Express lane speed pattern before ORT open

Figure 4.38. Express lane speed pattern after ORT open

Figure 4.39. Speed comparisons for all Express lanes from 7-9am
And T-test results showing the difference for Express Lane’s speed using 1 minute interval data are in table 4.19 below. ETC lanes have much lower throughput than ORT lanes, and the only ETC lane left in December is lower than in September, with zero p-values, the difference is statistically significant.

Table 4.19 Comparisons for Express Lane’s speed in 1 minute interval

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Results</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 &amp; E Sep</td>
<td>Sep &gt; Dec</td>
<td>0</td>
</tr>
<tr>
<td>E2E3 &amp; O1O2 Sep</td>
<td>Sep &lt; Dec</td>
<td>0</td>
</tr>
</tbody>
</table>

4.3.5 Speed-flow relationship of standard ETC and ORT lanes

The speed-flow relationship in the three ETC lanes in September is shown below:
This chart is from the far left ETC lane, the other two lanes have a similar pattern, and the following one is from December, the ORT lane.

The speed-flow relationship of September looks like the regular one, but the December speed-flow relationship is totally different.

The explanation may be that, when in September, the capacity can not always satisfy the demand, thus it has a similar pattern as usual, but after the ORT lanes open, the capacity is always higher than demand, so, the speed and flow are totally random, has no
relationship.

4.3.6 Comparison between non-construction and construction condition for queues at Manual and Automatic lanes

Queue data was collected in field at end of each 15 minutes, for the 2 hours AM peak. Each day has eight data points, which is 48 data points in total; 24 for before and 24 for after. Figure 4.41 shows the queue length in terms of number of vehicles waiting in line.

Figure 4.41 Queue length comparisons of Non ETC lanes at SR 408 Conway

T-test was conducted to compare the queue length difference, and the result in table 4.20 below shows the significant decrease of queue length in December with a P-value of 0.000.
Table 4.20: Queue length comparison of Non ETC lanes in 15 minutes interval

<table>
<thead>
<tr>
<th>Queue</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>SE Mean</th>
<th>Estimate for difference</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep</td>
<td>24</td>
<td>13.12</td>
<td>7.74</td>
<td>1.6</td>
<td>7.71</td>
<td>0.000</td>
</tr>
<tr>
<td>Dec</td>
<td>24</td>
<td>5.24</td>
<td>2.47</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.7 Summary of findings

After the completion of the construction, and the ORT lanes put into use, the toll plaza’s configuration has changed. It has one more Automatic lane than before and two of the ETC lanes are upgraded to open tolling. According to the analysis in this section, some findings of Conway toll plaza at SR-408 can be summarized as following:

ORT lanes increased the capacity of the toll plaza significantly, with higher throughput in express lanes and lower queue length at the non ETC lanes. And number of Epass vehicles going through Epass lanes have increased due to the higher speed limit and increased capacity. Vehicles going through Manual lanes have dropped significantly and vehicles using Automatic lanes have increased. But vehicles per Automatic lane have dropped due to the opening of the extra Automatic lane.
5. TOLL PLAZA MODEL

From all the previous analysis on the no-lane closure workzone and open road tolling impact study, we know both the no-lane closure workzone and open road tolling have some impact on the toll plaza’s performance under certain conditions. The three toll plazas of this study are different in characteristics, thus provide us with a wide range of data variety.

In order to study how different factors, such as percentage of each payment type users, the number of each type of lanes, and the demand to capacity ratio, have influenced the performance of the toll plaza, a model predicting throughput and queue length was built based on these data. Such model can be helpful to the toll plaza’s operator, thus improve the plaza’s performance.

Data collected from three different sites and for different stage construction of each site, construction or non-construction, were combined to build a statistical model. Because some of the data were collected before this study started, they were gathered in 15-minute intervals; however the new data were collected in one-minute intervals. The data inventory was shown in table 3.1 in section 3 of this thesis.

As one minute interval is too small to be analyzed, and some data are not available in this small time interval; it was decided to build the model based on 15 minute interval data.
5.1 Raw data description

Raw data can be obtained from the previous analysis, they are:

- Passenger car throughput for each lane (M/A/E/O)
- Multi-axle vehicle throughput for each lane (M/A/E/O)
- Number of lanes (M/A/E/O)
- Queue length of non-ETC lanes
- Toll value of the plaza
- Have workzone or not
- Have ORT lanes or not
- Demand of the toll plaza
- Capacity of the toll plaza

Data in one minute interval are summarized to 15 minute interval, so for one hour, we can get four data points out of it.

With the raw data, we can get 15 minute total throughput of the whole toll plaza, and with the number of total throughput, percentage of vehicles going through each type of lane can be calculated, then, multi-axle vehicle percentage in each lane type can also be calculated, variables to be considered in the toll plaza model are listed in the following part.
5.2 Variables in the model

Data was extracted in 15 minutes interval, each data point contains the information from 15 minute raw data. According to what we get from the data collection, variables considered in this model are:

E%-Percentage of vehicles passing through all standard ETC lanes

M%- Percentage of vehicles passing through all Manual lanes

A %- Percentage of vehicles passing through all Automatic lanes

O %- Percentage of vehicles passing through all ORT lanes

Demand- Throughput plus the length of the queue at the end of each 15 minutes, if present

T-e %- Multi-axle vehicle percentage in ETC lanes

T-m %- Multi-axle vehicle percentage in Manual lanes

T-o %- Multi-axle vehicle percentage in ORT lanes

Total lane Num- Total number of lanes of the toll plaza

Num E%- Num of ETC lanes over total lane number*100

Num M%- Num of Manual lanes percentage over total lane number*100

Num A%- Num of Automatic lanes percentage over total lane number*100

Num O%- Num of ORT lanes percentage over total lane number*100

Toll value- Toll value at the toll plaza

Workzone- Have workzone or not, 0 for no workzone, 1 for workzone exists

ORT- Have ORT lanes or not, 0 for no ORT lanes at this site, 1 for ORT lanes applied at the plaza.
D/C- Demand over capacity ratio for the 15 minutes, capacity for each stage is listed below in table 5.1.

Table 5.1 capacity of all sites and all stages

<table>
<thead>
<tr>
<th>site</th>
<th>stage</th>
<th>capacity</th>
<th>Manual</th>
<th>Auto</th>
<th>ETC</th>
<th>ORT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR 417</td>
<td>non-const</td>
<td>99</td>
<td>85</td>
<td>573</td>
<td>N/A</td>
<td>757</td>
<td></td>
</tr>
<tr>
<td></td>
<td>const</td>
<td>97</td>
<td>80</td>
<td>561</td>
<td>N/A</td>
<td>738</td>
<td></td>
</tr>
<tr>
<td>SR 528</td>
<td>non-const</td>
<td>202</td>
<td>91</td>
<td>361</td>
<td>N/A</td>
<td>654</td>
<td></td>
</tr>
<tr>
<td></td>
<td>const</td>
<td>200</td>
<td>100</td>
<td>305</td>
<td>N/A</td>
<td>605</td>
<td></td>
</tr>
<tr>
<td>SR 408</td>
<td>no-ORT</td>
<td>300</td>
<td>125</td>
<td>1176</td>
<td>N/A</td>
<td>1601</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ORT</td>
<td>288</td>
<td>88</td>
<td>400</td>
<td>1124</td>
<td>1900</td>
<td></td>
</tr>
</tbody>
</table>

The capacity in each type includes all the lanes and these figures were taken from section 4. All the variables listed above are on the right side of the equation, and the Throughput and Queue length are the two variables to be predicted by this model.

5.3. Build the model using Minitab

5.3.1 Throughput model

A linear regression model was first attempted and the data was input into Minitab software. The reason for picking Linear regression is that it is easy to apply, and clearly shows the relationship between each variable and throughput/queue length. The Y dependent variable and the X independent variables are as following:

Y= throughput/ queue.

X= the variables listed above.

The following variables were found to be highly correlated with other X variables, thus
were not included in the model:

A %, O %, T-e %, T-m %, T-o %, Workzone, Num A %, Num O %, Toll value, ORT, E %,
total N lane, Num E %, Demand and demand/C.

The following variables remained in the regression model:

M %, Num M, and Num A,

The statistical coefficients of the developed model are shown in Table 5.2 below.

Table 5.2 Toll plaza coefficient of each variable (throughput)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-735.55</td>
<td>81.63</td>
<td>-9.01</td>
<td>0.000</td>
</tr>
<tr>
<td>M %</td>
<td>-9.504</td>
<td>1.075</td>
<td>-8.84</td>
<td>0.000</td>
</tr>
<tr>
<td>Num M</td>
<td>738.27</td>
<td>32.31</td>
<td>22.85</td>
<td>0.000</td>
</tr>
<tr>
<td>Num A</td>
<td>97.69</td>
<td>15.67</td>
<td>6.24</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The regression equation is

\[
\text{Throughput} = -736 - 9.50 \text{ M}\% + 738 \text{ Num M} + 97.7 \text{ Num A}
\]

\[S = 65.8694 \quad \text{R-Sq} = 97.1\% \quad \text{R-Sq(adj)} = 97.1\%\]

P-values for each coefficient are all very significantly small and R-Sq is 97.1%, indicating that the model has very good fit.

With the coefficients of this throughput prediction model, it shows that, only the percentage of manual lane user, the number of manual and ACM lanes are significantly influencing the throughput of the toll plaza, and the higher percentage of manual lane users are, the lower throughput the toll plaza can reach, with more number of manual and
ACM lanes, throughput is higher. That means, when more users use manual lanes, which has the lowest capacity, the throughput will be lower. With more number of manual and ACM lanes, the toll plaza also get higher throughput.

5.3.2 Queue length model

Following the same steps, we input all the data into Minitab and try the linear regression. Variables A %, O %, T-e %, T-m %, T-o %, Workzone, Num A %, Num O %, Toll value, ORT, M %, Num E %, Num M %, Demand, and demand/C were found to be highly correlated with other X variables, and were excluded from the model. A %, E %, total N lane, Toll value, and Workzone remained in this model, and the coefficient are shown in Table 5.3 below.

Table 5.3 Toll plaza coefficient of each variable (queue length)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>680.9</td>
<td>167.4</td>
<td>4.07</td>
<td>0.000</td>
</tr>
<tr>
<td>A %</td>
<td>-7.388</td>
<td>4.151</td>
<td>-1.78</td>
<td>0.077</td>
</tr>
<tr>
<td>total N lane</td>
<td>-57.05</td>
<td>12.19</td>
<td>-4.68</td>
<td>0.000</td>
</tr>
<tr>
<td>E %</td>
<td>-1.4434</td>
<td>0.5146</td>
<td>-2.81</td>
<td>0.006</td>
</tr>
<tr>
<td>Toll value</td>
<td>-177.22</td>
<td>49.61</td>
<td>-3.57</td>
<td>0.000</td>
</tr>
<tr>
<td>Workzone</td>
<td>30.83</td>
<td>10.46</td>
<td>2.95</td>
<td>0.004</td>
</tr>
</tbody>
</table>

The regression equation is

Queue = 681 - 7.39 A % - 57.0 total N lane - 1.44 E % - 177 Toll value + 30.8 Workzone

S = 52.7268  R-Sq = 30.3%  R-Sq(adj) = 27.6%
P-value for each coefficient is less than 0.1, though R-Sq is 30.3%, but this model is the one with highest R-Sq value among all the models attempted.

The equation of this queue length prediction model shows that, percentage of ACM and ETC lane users, total number of lanes; Toll value and Workzone are significant variables. The existence of workzone increases the queue length, and percentage of ACM and ETC lane users all decrease the queue, because that means less user using the manual lane, which has the lowest capacity. The more total number of lanes is, the higher capacity that toll plaza can reach, and fewer queues will occur when the demand does not change. As toll value increase, queue gets shorter, it is because the toll values in this study are 0.75 Dollars, 1 Dollar and 2 Dollars, processing time is affected by giving change back to the driver, so, the smaller toll value caused more processing time, reduced the capacity and resulted longer queue.
6. SUMMARY AND CONCLUSIONS

This thesis focused on studying the no-lane closure work zone activity to expand on an existing toll plaza, evaluate its impact on the system performance, more specifically, speed reduction zones coupled with utilization of shoulders and other short term lane striping were applied to alleviate closing lanes, and build a toll plaza throughput and queue length model.

Toll plaza data were collected for selected days spread out over the years 2007, 2008, and 2009, a series of comparisons between non-construction and no-lane closure construction stage are conducted to analyze the no-lane closure workzone effects. The analysis results shows:

When the toll plaza is busy, the outer Manual lane, which is the closest lane to the workzone at the side of plaza, has a relatively lower throughput during construction than non-construction. The significant difference shows workzone has a negative effect on the outer lane of the toll plaza. As for inner manual lane and automatic lane, there was no significant difference between construction and non-construction because its location is not next to the workzone. Workzone does not affect these inner lanes. But long queues were seen during construction stage and the queue is significantly more than non-construction stage because of the workzone. Therefore, workzone has a negative effect on the queue length, when there is workzone, the queue is longer. And the total ETC throughput decreased significantly during the construction because of the blocked
ETC vehicles caused by the long queue.

When the toll plaza is not busy, demand/capacity ratio is much smaller than 1, the throughput for both outer and inner non-ETC lanes are not significantly different, no-lane closure workzone has no impact on it. And queue length has no significant difference too; in this case, no-lane closure workzone does not influence the toll plaza performance at all. As for ORT lanes impact, it increased the capacity of the toll plaza significantly, with higher throughput in express lanes and lower queue length at the non ETC lanes. And number of ETC vehicles going through ETC lanes have increased due to the higher speed limit and increased capacity.

A linear regression model was developed using the collected data for the purpose of predicting throughput and queue length at the plazas. The throughput model contained three variables and they were percentage of manual lanes, number of manual lanes, and number of ACM lanes. The queue model included five variables and they were: work zone dummy variable, toll value charged, percentage of ACM lane users, percentage of ETC lane users, and the total number of lanes.

6.1 Evaluation and Limitations

No-lane closure workzone impact on the toll plaza performance is a topic that few studies covered before, with this study, the toll roads operators will know better about what is happening when they implementing the ORT system, and will their toll plaza be influenced by the on site workzone or not, thus to take countermeasure to deal with.

The biggest limitation of this study is the insufficiency of diverse sites, especially for
modeling, each site has its own characteristics, and the three sites studied in this thesis can not include all the toll plaza configurations. For Conway SR 408, the configuration significantly changed before and after the study. Another limitation is we do not have a control group for each site, because of the difficulty in finding a similar plaza under similar situation and do the data collection.

6.2 Future Research Topics

From the results of this thesis, we know the no-lane closure workzone effects depends on how busy is the toll plaza, but how exactly busy is the toll plaza can be a possible future research topics, if the data from more sites with varies demand/capacity ratio is available, the value of this ratio which can decide whether the no-lane closure workzone have an impact or not will be found. And with adequate congestion data, a model can be built with more accuracy.
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