IMPLEMENTING TOLL PLAZA ANALYSIS INTO FREEPLAN

By

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To my family and friends, for their love and support
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Finally, I need to thank my family, friends, and classmates. No one has been anything but kind, supportive and helpful during my time here at the University of Florida. To each and every one of you: I’m never going to give you up, I’m never going to let you down.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS .......................................................................................................................... 4

LIST OF TABLES ...................................................................................................................................... 7

LIST OF FIGURES .................................................................................................................................. 8

CHAPTER

1 INTRODUCTION ..................................................................................................................................... 12
   Background ......................................................................................................................................... 12
   Problem Statement .............................................................................................................................. 12
   Research Objective and Tasks ........................................................................................................... 13

2 LITERATURE REVIEW ....................................................................................................................... 15
   Simulation Approach .......................................................................................................................... 20
     TPSIM ............................................................................................................................................... 20
     PARAMICS ....................................................................................................................................... 21
   ETC-Only Lanes ................................................................................................................................ 22

3 RESEARCH APPROACH ...................................................................................................................... 30
   Preliminary Research .......................................................................................................................... 31
   Determine Simulation Setup Parameters ............................................................................................ 32
   Geometric Configurations for Simulation ........................................................................................... 32
   Capacity ............................................................................................................................................. 35
   Density and Delay ............................................................................................................................... 37
   ETC-Only Lanes ................................................................................................................................ 37
   Model Development ............................................................................................................................ 39
   Implementation into FREEPLAN......................................................................................................... 40

4 RESULTS AND ANALYSIS ................................................................................................................. 44
   Methodology Development ................................................................................................................... 44
     Step One .......................................................................................................................................... 44
       One payment type ........................................................................................................................... 44
       Multiple payment types ................................................................................................................... 44
     Step Two .......................................................................................................................................... 45
       One payment type ........................................................................................................................... 46
       Multiple payment types ................................................................................................................... 46
     Step Three ...................................................................................................................................... 50
       One payment type ........................................................................................................................... 51
       Multiple payment types ................................................................................................................... 52
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Processing rate at toll facilities by customer group</td>
<td>26</td>
</tr>
<tr>
<td>2-2</td>
<td>LOS ranges based on delay</td>
<td>26</td>
</tr>
<tr>
<td>2-3</td>
<td>Delay and $v/c$ ratio scenarios</td>
<td>26</td>
</tr>
<tr>
<td>2-4</td>
<td>Capacity evaluation of interchange 11A in Westborough, Massachusetts</td>
<td>26</td>
</tr>
<tr>
<td>3-1</td>
<td>Ranges of variables used to collect simulation data</td>
<td>41</td>
</tr>
<tr>
<td>4-1</td>
<td>Level of service criteria for toll plaza segments</td>
<td>59</td>
</tr>
<tr>
<td>4-2</td>
<td>Capacity of ETC-only lanes based on free-flow speed</td>
<td>59</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>2-1</td>
<td>Flowchart for estimating density through a toll plaza segment (part 1)</td>
<td>27</td>
</tr>
<tr>
<td>2-2</td>
<td>Flowchart for estimating density through a toll plaza segment (part 2)</td>
<td>28</td>
</tr>
<tr>
<td>2-3</td>
<td>Graph of $v/c$ ratio vs. density used to calculate density for non-ETC traffic</td>
<td>29</td>
</tr>
<tr>
<td>3-1</td>
<td>Diagram of 3-lane, single payment type simulation geometry</td>
<td>42</td>
</tr>
<tr>
<td>3-2</td>
<td>Diagram of 4-lane, single payment type simulation geometry</td>
<td>42</td>
</tr>
<tr>
<td>3-3</td>
<td>Diagram of 5-lane, single payment type simulation geometry</td>
<td>42</td>
</tr>
<tr>
<td>3-4</td>
<td>Diagram of 4-lane, multiple payment type simulation geometry</td>
<td>42</td>
</tr>
<tr>
<td>3-5</td>
<td>Diagram of 6-lane, multiple payment type simulation geometry</td>
<td>42</td>
</tr>
<tr>
<td>3-6</td>
<td>Diagram of 4-lane (1 ETC-only lane, 3 manual payment lanes), multiple payment type simulation geometry</td>
<td>43</td>
</tr>
<tr>
<td>4-1</td>
<td>Average speed of ETC-only lanes versus discharge for free-flow speeds of 20 mi/h, 30 mi/h, and 40 mi/h.</td>
<td>60</td>
</tr>
<tr>
<td>4-2</td>
<td>Selecting “Toll Plaza” as the input segment type in FREEPLAN</td>
<td>61</td>
</tr>
<tr>
<td>4-3</td>
<td>The “Toll Plaza Data” pop-up menu, which contains specific toll plaza inputs for a toll plaza segment in FREEPLAN</td>
<td>62</td>
</tr>
<tr>
<td>4-4</td>
<td>The LOS Results tab, which now contains results for a toll plaza segment in FREEPLAN</td>
<td>63</td>
</tr>
<tr>
<td>4-5</td>
<td>Additional toll plaza results screen.</td>
<td>64</td>
</tr>
<tr>
<td>A-1</td>
<td>Example 1 segment data input screen</td>
<td>73</td>
</tr>
<tr>
<td>A-2</td>
<td>Example 1 toll plaza data input screen</td>
<td>74</td>
</tr>
<tr>
<td>A-3</td>
<td>Example 1 LOS results tab</td>
<td>75</td>
</tr>
<tr>
<td>A-4</td>
<td>Example 1 additional toll plaza results</td>
<td>76</td>
</tr>
<tr>
<td>A-5</td>
<td>Example 2 segment data input screen</td>
<td>77</td>
</tr>
</tbody>
</table>
The planning, design, construction and maintenance of roadways is an extremely expensive process. As funds become more and more difficult to obtain via conventional methods, tolling has become a popular way to pay for new roads. The money is collected by charging a fee for each vehicle that uses the road. However, facilitating roadway users with an efficient method by which to pay the toll is important so that traffic operations are not disrupted significantly. The necessary research and analysis of toll road operations has not kept pace with the growing number of toll plazas being constructed across the country.

While some other researchers have studied how to analyze toll plazas individually, it is also important to be able to incorporate them as segments in a freeway facilities analysis. In the past this has been difficult to do because freeway segments use a performance measure of density, while toll plazas are a form of stop control, and therefore are analyzed using delay, thus making it difficult to define a level of service (LOS) that corresponds with freeway segments. This research incorporates toll plaza analysis into undersaturated freeway facility analysis.
One method by which to analyze toll plaza operations is through the use of traffic simulation tools, such as CORSIM, for which the capability of toll plaza modeling has recently added. In this research, CORSIM was used to gather toll plaza operations data from simulation outputs, which were the basis for the analytical methodology developed. The three payment types considered in this research are automated coin collection, manual payment, and electronic toll collection. The methodology was developed to provide a way to calculate capacity, the demand to capacity ratio, the density, the delay, and the level of service of a toll plaza. The methodology was then implemented into FREEPLAN, an undersaturated freeway facilities analysis computer program. The research approach, analysis and findings are presented in this thesis.
CHAPTER 1
INTRODUCTION

Background

The demand for quick, easy and inexpensive transportation will always be present. However, funds to provide such a service are often difficult to obtain. Therefore, an increasingly popular method to collect these funds is by building toll roads where drivers pay per usage instead of allowing free access to the facility. The collection of these tolls is important from a financial standpoint, but disruptive from a traffic operations standpoint. While toll roads have been and continue to be constructed across the country, the corresponding research and analysis of their effects on traffic have not kept pace.

Besides the significant financial benefit, toll roads can also be used to help route traffic more efficiently. By charging vehicles for each use of a toll road, some drivers will avoid paying the fee by choosing a different route, even though that route change may not correspond to the fastest path. These diversions significantly improve traffic conditions on the toll roads, which operate at higher flows and speeds. Therefore, while users are typically against paying tolls, they generate a constant and direct source of funding for costly facilities and provide users with a more efficient option in peak travel periods.

Problem Statement

The Highway Capacity Manual (HCM) is one of the most important analytical resources for traffic analysis, including chapters that detail the procedures for analyzing a variety of freeway segments (basic, weaving, ramp junction), or entire freeway facilities (a combination of multiple segments). However, the HCM currently does not
include any guidance for analyzing a toll plaza, either as an individual segment or within the context of a larger facility. Therefore, there is no standardized analytical method to evaluate toll plaza performance.

All analysis methods in the HCM use density as a service measure for freeway segments, and for the overall freeway facility. However, roadway facilities that include forms of yield or stop control typically use delay as the service measure. Previous research on toll plazas has mostly focused on delay as the primary performance measure as well. For a toll plaza analysis procedure to be useful in the context of a freeway facility analysis, it must provide a density output in addition to delay.

**Research Objective and Tasks**

The objective of this research is to develop a toll plaza analysis methodology at the segment and facility level and incorporate it into the FREEPLAN software program. FREEPLAN is the freeway facility analysis program prescribed by the Florida Department of Transportation for the analysis of freeway facilities in Florida, for undersaturated traffic conditions. The freeway facility analysis procedure implemented in FREEPLAN conforms to the Highway Capacity Manual freeway facility analysis procedure for undersaturated conditions. Therefore, the outputs from the methodology must be useful not only for toll plaza analysis, but must also be compatible with the current freeway facility analysis procedure. The tasks that will be conducted to achieve these objectives include:

- Validate simulation run outputs from field data collected from the Florida Turnpike
- Develop a simulation experimental design
- Execute the experimental design
• Perform statistical analysis on the simulation data collected to determine a relationship between toll plaza capacity and the variables that most significantly affect traffic conditions at a toll plaza

• Develop of an analytical method to evaluate toll plaza performance within a freeway facility.

• Define criteria for a standardized level of service for toll plaza freeway segments.

• Incorporate the various toll plaza analysis equations into FREEPLAN and develop/revise the input and output mechanisms of FREEPLAN as necessary.
The summaries of the first twelve studies (references 2 – 13) discussed in this chapter were obtained from Fuller (1).

Some of the first research done on toll plazas by Woo and Hoel (2) was aimed toward developing a method to analyze toll plaza capacity and determining a corresponding LOS. Equations 2-1 and 2-2 were developed to calculate capacity and density.

Equation for capacity of entire toll plaza:

\[
C = \sum_{j=1}^{j} n_j c_j = n_1 \frac{3600}{t_{i1}} + n_2 \frac{3600}{t_{i2}} + \cdots + n_j \frac{3600}{t_{ij}} = \sum_{j} n_j \frac{3600}{t_{ij}} 
\] (2-1)

where,

\[
C = \text{capacity of toll plaza (veh/h)},
\]
\[
n_j = \text{toll booth with collection type } j,
\]
\[
c_j = \text{capacity of toll booth with collection type } j \text{ (veh/h)},
\]
\[
t_{ij} = \text{service time for vehicle type } i \text{ and toll collection type } j \text{ (s)}.
\]

Equation for the density of a toll plaza:

\[
K = \frac{\sum Q_i T_i}{A} = \frac{2(Q_a T_a + Q_t T_t)}{(n_1 + n_2) L_1 + (n_2 + n_3) L_2}
\] (2-2)

where,

\[
K = \text{density of toll plaza (veh/mi/ln)},
\]
\[
Q = \text{flow rate, } a \text{ for automobiles, } t \text{ for trucks (veh/h)},
\]
\[
T = \text{average total time to travel through the toll plaza area, } a \text{ for automobiles, } t \text{ for trucks (hours)},
\]
\[
A = \text{Area of toll plaza segment (mi}^2\text{)},
\]
In order to allow these equations to undergo validation testing, field data were collected from eight toll plazas. Regression analysis was also performed on the data, which produced a distinct relationship between the volume-to-capacity ratio (v/c) and density. Also produced in their research was an LOS scale for toll plazas based on v/c and density, average service times for cars and trucks, and capacity values by payment type (3). A questionnaire was also given to the toll plaza operators to obtain plaza capacity values.

The presence of ETC-only lanes can greatly improve the capacity of a toll plaza (4). However, ETC-only lanes also make capacity very difficult to accurately measure because the percentage of vehicles that use ETC-only lanes can vary greatly between time periods and locations. The posted speed limit also has a significant effect on the capacity of the toll plaza. From data collected from Holland East Plaza in Orlando, Florida, a change in the posted speed limit of the ETC-only lane from 55 mi/h down to 35 mi/h resulted in a decrease in processing rate of the plaza from 32 veh/min down to 23 veh/min, which converts to a decrease of 540 veh/h (5). Zarrillo proposed Equations 2-3 and 2-4 to determine capacity of a toll plaza:

$$ C = J + K $$  

(2-3)

where,

$$ C = \text{toll plaza capacity (veh/h)}, $$
$J$ = capacity of single service lanes (veh/h),

$K$ = capacity of mixed use lanes (veh/h),

$$K_{MTE} = N_{MTE}S_{MTE} = N_{MTE}\frac{100\%}{\frac{P_M}{S_M} + \frac{P_T}{S_T} + \frac{P_E}{S_E}}$$

(2-4)

where,

$K$ = capacity of mixed use lanes (veh/h),

$N$ = number of lanes of mixed use,

$S_i$ = vehicle processing rate for payment type $i$ (veh/h),

$P_i$ = percentage of vehicles utilizing payment method $i$.

The processing rate $S$ can be found in Table 2-1.

Zarrillo evaluated the capacity of toll roads based on Equations 2-3 and 2-4 and the data collected from the Holland East Plaza in Orlando, Florida, along with Interchange 11A in Westborough, Massachusetts. The following notions were then deduced:

- Processing time and lane types of the toll plaza are two important components in determining toll plaza capacity.
- ETC lanes that are utilized sufficiently will improve toll plaza capacity over a similar booth without ETC lanes.
- Trucks that use non-ETC-only lanes decrease the capacity of a toll plaza.

One of the most difficult obstacles when comparing a simulation to an actual facility is that extensive field data are needed before any significant comparisons can be done. A methodology could be used to calculate the capacity, queuing, and delay manually to solve this problem (6). One important design characteristic of toll plazas is that they have a higher capacity than the upstream segment that feeds into the plaza. If the capacity of the upstream segment is higher than the capacity of the toll plaza, and a
queue forms at the toll plaza, the upstream segment could be affected because the toll plaza is acting as a bottleneck. If the toll plaza has a smaller capacity than the upstream segment, then it is decreasing the capacity of the overall facility. Aycin (6) proposed Equations 2-5, 2-6, 2-7, and 2-8 for capacity, plaza queue, and delay for different toll booth payment options.

Equation for capacity:

\[
C_{ETC} = \frac{3600 \cdot V_{ETC}}{S} 
\]  \hspace{1cm} (2-5) 

\[
C_{cash} = \frac{3600}{t_{service} + t_{moveup}} 
\]  \hspace{1cm} (2-6) 

\[
C_{cash-ETC} = \frac{3600}{\sum \Delta t_j P_j} 
\]  \hspace{1cm} (2-7) 

\[
C_{plaza} = N_{cash} \times C_{cash} + N_{ETC} \times C_{ETC} + N_{cash-ETC} \times C_{cash-ETC} 
\]  \hspace{1cm} (2-8) 

where,

\[C_i\] = capacity of toll booth for payment type \(i\) (veh/h),

\[V_{ETC}\] = average ETC vehicle speed (ft/s),

\[S\] = average distance headway (ft/veh),

\[t_{service}\] = vehicle service time (s),

\[t_{moveup}\] = time for next vehicle in queue to move to booth (s),

\[\Delta t_j\] = transaction time of pair \(j\),

\[P_j\] = probabilities of possible leader-follower pairs given the percentage of ETC vehicles using the mixed lane.

Now, to find the upstream segment capacity, Aycin used the established basic freeway segment equation (Equation 2-9) from the 2000 Highway Capacity Manual (7):

\[
C_{road} = v_p \times N \times f_{HV} \times f_p 
\]  \hspace{1cm} (2-9) 

where,
$C_{road}$ = capacity of upstream segment (veh/h),

$v_p$ = 15-min peak passenger car equivalent flow rate (pc/h/ln),

$N$ = number of lanes,

$f_{HV}$ = heavy vehicle factor,

$f_p$ = driver population factor.

Equation for queue:

$$Q_i = \Delta M_i - \frac{F_i}{V_{section}} \times X$$  \hspace{1cm} (2-10)

where,

$Q_i$ = number vehicles in plaza queue at time $i$,

$\Delta M_i$ = cumulative vehicle demand ($C_{plaza} - C$) at time $i$ (veh),

$F_i$ = flow rate (veh/h),

$V_{section}$ = average section speed (mi/h),

$X$ = distance between end of queue and automatic traffic recorder (mi).

Equation for delay:

$$D = \frac{X_j}{S} \times \Delta t_j + \frac{(X_{k joined}) \times n}{S} \times \frac{\Delta t_j}{B}$$  \hspace{1cm} (2-11)

where,

$D$ = queue delay (sec),

$X_j$ = length of individual queue section for booth $j$ (ft),

$\Delta t_j$ = average headway time between completing transactions of successive cars (sec),

$(X_{k joining})$ = length of joined queue section for vehicle $k$ in queue (ft),

$S$ = average distance headway (ft),

$n$ = number of queues in the joined area,
\[ B = \text{number of available booths.} \]

Certain assumptions were made about factors that can affect capacity. One of these assumptions was that queues of different payment types did not affect the arrival time of other vehicles. Separation distance and acceleration rates accounted for the lost time from perception-reaction. Simulation results were comparable to the manual calculations for capacity, queuing, and delay, even with these assumptions included.

**Simulation Approach**

Research with simulation has been done on toll plazas in Florida using two computer programs: TPSIM and PARAMICS. The research efforts with these two programs are detailed below.

**TPSIM**

Klodzinski and Al-Deek used TPSIM to look into different methodologies of analyzing toll plazas (8). TPSIM is a microscopic simulation program written in Visual Basic 6 that produces stochastic results and has been employed significantly to research toll plaza operations in Orlando, FL. The three measures of effectiveness for the methodologies that they investigated were traffic density, the volume to capacity ratio, and vehicle delay. They attempted to find the best measure of effectiveness and methodology so that they could properly define a level of service for toll plaza operations.

The three methodologies based on different measures of effectiveness were evaluated by comparing TPSIM simulations and field data. When studying density as a good measure of effectiveness, they determined that density was not good at representing the operations of a toll plaza. The capacity of a toll booth is dependent on
the average service time of that booth, which is theoretically independent of the density of the upstream segment. Also, the presence of ETC-only lanes can increase the density, while also increasing the capacity. For these two reasons, the researchers decided that density was not a good measure of effectiveness for analyzing toll plazas.

Klodzinski and Al-Deek then looked at the volume to capacity ratio ($v/c$), but concluded that it was a poor indicator of LOS. This is because toll plazas can operate close to capacity without having a negative effect on the operations. Because $v/c$ and LOS do not correlate well, it was decided that $v/c$ was not a good measure of effectiveness for toll plaza analysis.

Lastly, they investigated delay as a good measure of effectiveness for toll plaza operations (9). They concluded that delay was very representative of a driver's perception of the operations of a toll plaza. Delay accounts for many aspects of the toll plaza as a whole, such as the geometry, upstream and downstream conditions, and the presence of ETC-only lanes. After comparing the simulation data with the field data, Klodzinski and Al-Deek also concluded that cumulative delay was more representative than average delay because the variation of delay within the peak hour of operation at a toll plaza. Klodzinski and Al-Deek then used the cumulative delay values to define an LOS for toll plazas. After LOS A was determined, the next thresholds were found by using a percent increase that is discussed in the HCM 2000 for signalized intersection delay. The LOS results can be found in Table 2-2.

**PARAMICS**

QUADSTONE PARAMICS is a comprehensive microsimulation program that contains an application programing interface (API) that allows users to modify the
behavior of the simulation (10). By creating user based algorithms that are not built into the program, the simulation capabilities of PARAMICS are increased. Nezamuddin and Al-Deek wrote an API for integration into PARAMICS that allowed the program to simulate toll plazas.

Operations for individual toll plazas and for entire networks that included multiple toll plazas in Florida were simulated by PARAMICS. In order to calibrate the toll road corridor model built, Nezamuddin and Al-Deek used traffic data from the Orlando-Orange County Expressway Authority toll road corridor and GEH statistic, a statistical value similar to the chi-squared test that compares hourly traffic volume of a model to the hourly traffic volume of field data (11). Next, the validity of the model was tested by running eight hypothetical scenarios, to all of which the model acted as expected. The creation of this simulation model can therefore help properly analyze toll road corridors.

**ETC-Only Lanes**

Dedicated ETC-only lanes are lanes at a toll booth that do not require the user to stop to pay the toll. Instead the toll is collected electronically as the car is still in motion. Some versions of ETC-only lanes require vehicles to slow down significantly, to as low as 15 mi/h, whereas others capture the tolling information while vehicles are permitted to maintain free flow speed on the freeway. ETC-only lanes are one of the biggest factors in determining the level of service of a toll plaza, yet the characteristics of an individual ETC-only lane are the reason that it is difficult to accurately define an LOS for toll plazas. With ETC-only lanes, density and v/c may not be good indicators of when the operations at a toll plaza are poor. Table 2-3 shows that for similar levels of v/c, but drastically different levels of ETC-vehicle percentages, the level of delay can be very
different. Zarrillo also investigated the effect that ETC-only lanes can have on toll plaza capacity. The results in Table 2-4 show that the presence of ETC-only lanes can have a significant impact by increasing the capacity of the toll plaza. A methodology that analyzes toll plazas would greatly benefit from inclusion of an understanding of the effect of ETC-only lanes.

One solution to increasing the capacity of a toll plaza is to convert manual booth lanes and automated coin machine lanes to ETC-only lanes. However, to do this would decrease the capacity of the payment types that require vehicles to stop. If the demand for non-ETC-only payment types is too high, then this reduction in capacity could result in worse operations at the plaza. It is therefore, important to make sure that the percentage of vehicles that can use ETC-only lanes, known as the ETC penetration, corresponds to the number of ETC lanes. Also, the number of non-ETC-only lanes needs to be able to sufficiently handle the demand of vehicles that require a stopped payment type. This idea was demonstrated by Al-Deek, who used simulation software to confirm this (13).

A flowchart was created to estimate density through a toll plaza segment by Velasquez, Rae, and Prassas (14). This flowchart (Figure 2-1 and Figure 2-2) calculates equivalent lane density for the toll plaza segment based on number of lanes of each payment type, percent heavy vehicles, peak hour factor, and portion of non-ETC demand. The model begins by calculating the capacity of the non-ETC part of the plaza by assigning individual lanes a capacity based on payment type. Manual booths (MB) are assigned 450 passenger cars per hour (pc/h) and automated coin machine (ACM) lanes are assigned 550 pc/h. These individual lane capacity values were calibrated
using field data. Next, the heavy vehicle factor ($f_{HV}$) is calculated to account for the percentage of trucks. According to field data, a passenger car equivalent of 6 is used because of the deceleration into and acceleration away from the plaza. Then the demand volume is converted from veh/h to pc/h using the heavy vehicle factor and the peak hour factor.

Next, any volume for the ETC-only lanes that exceeds the capacity (1800 pc/h/ln, calibrated from field data) is applied to the non-ETC-only lanes. Then, the volume-to-capacity ratio ($v/c$) for non-ETC-only lanes is computed and used to calculate the density of non-ETC traffic, based on a graph (Figure 2-3) developed from field data. Then, the density of the ETC-only lanes are calculated based on whether or not the ETC-only lanes are oversaturated or undersaturated and the speed of the ETC-only lanes. The final equivalent density is calculated by adding the non-ETC and the ETC density values, then dividing by the number of lanes that approach the plaza.

The segment length of the plaza is then discussed, saying that observations in the field saw large variation in approach distances, from 875 ft to 3,300 ft, with an average of 2000 ft. However, speed changes were observed even further away from where the approach begins to widen for an upcoming toll plaza. A distance of 1 mile is suggested to account for this. There is some room for adjustment to local conditions, but an adjustment would then occur to the equivalent lane density.

The effect of toll plazas and their operations have been and will continue to be researched. Based on the previous research reviewed in this chapter, analytical methodologies have been developed to estimate capacity, queuing, density and delay. However, some of these studies are still limited in either the completeness or depth of
their methodology. The quantity, location and recency of data that have been collected relating to toll plazas could always improve. Specifically, efforts could be made toward improving an analytical methodology for analyzing toll plazas within a larger freeway facility.
### Table 2-1. Processing rate at toll facilities by customer group

<table>
<thead>
<tr>
<th>Customer Group</th>
<th>Processing Rates (veh/h/ln)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>498 ± 48</td>
</tr>
<tr>
<td>ACM</td>
<td>618 ± 30</td>
</tr>
<tr>
<td>Trucks</td>
<td>138 ± 78</td>
</tr>
<tr>
<td>ETC 15 mi/h</td>
<td>900 ± 120</td>
</tr>
<tr>
<td>ETC 35 mi/h</td>
<td>1380 ± 120</td>
</tr>
<tr>
<td>ETC 55 mi/h</td>
<td>1920 ± 120</td>
</tr>
</tbody>
</table>

### Table 2-2. LOS ranges based on delay.

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>85th-percentile delay (s/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤ 14</td>
</tr>
<tr>
<td>B</td>
<td>&gt; 14 - 28</td>
</tr>
<tr>
<td>C</td>
<td>&gt; 28 - 49</td>
</tr>
<tr>
<td>D</td>
<td>&gt; 49 - 77</td>
</tr>
<tr>
<td>E</td>
<td>&gt; 77 - 112</td>
</tr>
<tr>
<td>F</td>
<td>&gt; 112</td>
</tr>
</tbody>
</table>

### Table 2-3. Delay and \( v/c \) ratio scenarios

<table>
<thead>
<tr>
<th>Volume</th>
<th>% of ETC vehicle</th>
<th>% of ACM vehicle</th>
<th>% of manual vehicle</th>
<th># of ETC lanes</th>
<th># of ACM lanes</th>
<th># of manual lanes</th>
<th>( v/c ) ratio</th>
<th>Minimum % vehicles that have no delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>0%</td>
<td>20%</td>
<td>80%</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>1.00</td>
<td>0%</td>
</tr>
<tr>
<td>5000</td>
<td>36%</td>
<td>20%</td>
<td>44%</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>0.96</td>
<td>36%</td>
</tr>
<tr>
<td>5000</td>
<td>72%</td>
<td>10%</td>
<td>18%</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>0.94</td>
<td>72%</td>
</tr>
<tr>
<td>5000</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0.93</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Table 2-4. Capacity evaluation of interchange 11A in Westborough, Massachusetts

<table>
<thead>
<tr>
<th>Stage</th>
<th>For entire Plaza (%)</th>
<th>Entry to Turnpike</th>
<th>( v/c ) ratio</th>
<th>MSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before ETC</td>
<td>0 8.6 0 1440 1131 2571 2220</td>
<td>0.864 1900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After SE = 15 veh/min</td>
<td>5 8.0 1 1542 492 2034 2200</td>
<td>&gt;1.00 &gt;2200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After SE = 15 veh/min</td>
<td>25 6.0 1 2088 502 2590 2200</td>
<td>0.849 1870</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After SE = 23 veh/min</td>
<td>45 4.0 1 2820 606 3426 2200</td>
<td>0.642 1410</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2-1. Flowchart for estimating density through a toll plaza segment (part 1) [From Velasquez, A., and D. Rae. FREEPLAN Software - Toll Plaza Module. Memorandum to Elena Prassas. 12 July 2000. MS. (Page 1)]
Figure 2-2. Flowchart for estimating density through a toll plaza segment (part 2) [From Velasquez, A., and D. Rae. FREEPLAN Software - Toll Plaza Module. Memorandum to Elena Prassas. 12 July 2000. MS. (Page 2)]
Figure 2-3. Graph of v/c ratio vs. density used to calculate density for non-ETC traffic [From Velasquez, A., and D. Rae. FREEPLAN Software - Toll Plaza Module. Memorandum to Elena Prassas. 12 July 2000. MS. (Page 1)]
CHAPTER 3
RESEARCH APPROACH

The intent of this research was to develop an analytical procedure for determining density and delay of a toll plaza segment. Data were collected from outputs of simulation runs in CORSIM and field data were used to verify the general accuracy of the toll plaza simulation modeling in CORSIM. The scenarios simulated varied by geometric configuration and traffic input conditions. The data were then used to develop models that use relevant inputs, such as the average service time, the number of lanes, the percentage of trucks, and percentage of demand for each payment type to estimate important performance measures, such as capacity, density, and delay of a toll plaza segment. These models make up a methodology that incorporates toll plaza segments in the analysis of undersaturated freeway facilities.

Outlined in the following sections of this chapter is the research approach, which consisted of the following steps:

- Perform preliminary testing to identify key variables as well as confirm key variables identified in the literature.
- Determine simulation setup parameters and the geometric configuration(s) to utilize in the simulation.
- Develop and run simulation experimental design for capacity model.
- Develop and run simulation experimental design for density and delay model.
- Consider effect of ETC-only lanes.
- Develop methodology for calculating density and delay from toll plaza geometric and traffic inputs.
- Implement toll plaza findings into FREEPLAN.
Preliminary Research

In order to gather information about typical geometric configurations of toll plazas, Florida’s toll plazas were examined using Google Earth. One of the pieces of data that was gathered was the approach and the departure distances for each toll plaza. The approach distances were measured from the point upstream from the plaza at which the mainline started to widen to accommodate the toll booths. The departure distance was measured from the toll booths to the point downstream of the plaza where the mainline had returned to its original lane count and width. Of the twenty four toll plazas cataloged, the average distances for both the approach and the departure were about 1500 ft and 1400 ft, respectively. Therefore, 1500 ft was used for both the approach and the departure distances in the simulation file for data collection.

Each specific scenario examined to collect data was composed of a unique combination of geometric configurations and traffic inputs, which are based on the following variables that were found to be significant from the literature review and preliminary testing:

- The percentage of trucks present in the traffic stream
- The average service time for each open booth
  - A function of the payment types allowed at a booth and the percentage of vehicles using each allowed payment type at the booth
- The number of booths open
- For plazas that accept multiple payment types, the percentage of vehicles that required each payment type

The field data that were compared to the simulation results were collected from the FDOT Turnpike district, specifically, Leesburg plaza, located on the Florida Turnpike.
just north of Orlando, Florida, and Beach Line plaza, located on State Road 528, also in Orlando, FL.

**Determine Simulation Setup Parameters**

Data for this research were collected by running thousands of simulations and recording the corresponding outputs. The simulation software used was CORSIM in TSIS 6.3. The driver type distribution was left at CORSIM’s default values throughout the data collection process, which is 10% of each of the driver types 1-10. Similarly, the vehicle type distribution was left at CORSIM’s default values, with the exception of the percentage of trucks that entered the facility, which was a variable considered in the research. The parameter values for fundamental car-movement models (car following, gap acceptance, lane changing) were also left at default values. Each simulation was performed over one 15-minute analysis time period. Before this analysis period begins, there is a warm-up period where traffic conditions are set up to ensure that the simulation has reached equilibrium. This is done so that the analysis period does not include the time required to initiate the traffic conditions being simulated. Except for the variables mentioned in the previous section, the geometric configuration and traffic inputs remained constant throughout the data collection process.

**Geometric Configurations for Simulation**

The facility used to simulate the scenarios consisted of six straight segments, each 500 ft long, with all lanes 12 ft wide. The first segment was two lanes and at the beginning of the second segment, a third lane was added. The fifth segment was three lanes and the sixth and last segment returned to the original two lanes. Depending on the specific scenario being considered, the two middle segments (third and fourth
segments) varied between three, four, or five lanes. The adding of lanes before the toll plaza, followed by the dropping of lanes after the plaza intended to replicate the scenario of a two-lane directional highway that expands to accommodate a toll plaza, then narrows back to the original number of lanes after the plaza (Figure 3-1, Figure 3-2, and Figure 3-3).

For the simulation file used to collect data, the input parameters that were modified for each scenario included the geometric configuration of the freeway and traffic conditions. Once the simulation input file was constructed with a specific geometric configuration, simulations were run and data were collected. The percentage of trucks, average service time, and number of booths open were set and the entry volume for the facility was initiated at a volume much less than the estimated capacity. The simulation was then run and output data were recorded for the given inputs. These outputs included the total vehicles that entered the toll plaza link, total vehicles discharged from the toll plaza link, current content of the toll plaza link, density of the facility, and delay of the facility. To reduce variation from a single run in the output data, ten CORSIM runs were conducted for each specific scenario and the average over these runs was recorded as the output data for a given scenario.

After the outputs were recorded, the entry volume for the facility was increased by 100 veh/h, while holding the rest of the variables constant. This process of incrementally increasing the entry volume by 100 veh/h and recording of the corresponding output data was repeated with the same simulation file until the plaza reached capacity. Capacity can be marked by the stabilization of total vehicles
discharged from the toll plaza; that is, additional increases in entry volume do not result in an increase in total vehicles discharged from the toll plaza.

The next step in the data collection process was to increase one of the variables by the interval in Table 3-1, holding all other variables constant. Once this modification was made to the simulation file, and the entry volume was reinitiated to a volume much less than the estimated capacity, the process described above was repeated for this specific geometric scenario. Once capacity was reached for that scenario, the same variable that was increased above was increased again by the interval in Table 3-1, and data were collected for that geometric scenario. After output data were recorded for the variable being increased at its maximum value, that variable was reset to its minimum value and one of the other variables was increased by its prescribed interval in Table 3-1. In this way, incremental variations of the variables are nested within one another. This was done for each variable, achieved by doing three different lane configurations, four different truck percentages, and four different average service times, until approximately all 48 possible combinations of the variables have been simulated and the corresponding output data have been recorded.

The ranges through which the other inputs were varied include the lane count (3, 4, or 5 lanes), the truck percentage (0 % though 30%, by 10% intervals), and the average service time (5.5 s – 14.5 s by 3 s intervals). For every possible combination of these three variables, the process in the preceding paragraph was conducted until all the data were recorded. Because the analysis time period was 15 minutes, any output data in terms of vehicles were multiplied by 4 to convert to hourly flow volumes.
The same process described above was repeated to collect data for scenarios with plazas that accept multiple payment types. However, the range of input variables was different for these simulations. The entry link volume and the truck percentages considered were the same as in the process above. However, only two lane configurations were considered: four lanes, with two lanes for each payment type, and six lanes, with three for each payment type (Figure 3-4 and Figure 3-5, respectively). Another input variable was the percentage of the total demand of vehicles that desired to use each of the payment types. The two payment types considered were automated coin machine lanes (average service time of 2.5 s) and manual payment booths (average service time of 5.5 s). The five payment type distribution splits considered were:

- 34% MB, 66% ACM
- 42% MB, 58% ACM
- 50% MB, 50% ACM
- 58% MB, 42% ACM
- 66% MB, 34% ACM

The payment type demand distributions above were collected to account for the interaction between booths that accept different payment types. These data were collected to analyze capacity, density, and delay for each of the scenarios. All of the data collection process that is described above was collected without the presence of ETC-only lanes.

**Capacity**

The average service time for a booth at a toll plaza is inversely related to capacity; that is, the higher the service time, the lower the capacity. This is because the capacity is measured in vehicles per hour, so as each vehicle takes longer to pay the
toll at the booth, the fewer number of vehicles that will be able to be processed. The number of service booths open affects toll plaza capacity because as more lanes are open, more vehicles can be processed simultaneously instead of waiting in a queue.

Of all the major components that affect plaza capacity, the presence of heavy vehicles is one of the most complex variables to analytically quantify. In the data gathered, a higher truck percentage has consistently resulted in a lower plaza capacity. There are a couple reasons why this relationship exists. First, trucks have much lower acceleration and deceleration rates than passenger cars. Therefore, their pull-up time (time required for a stopped vehicle that is first in queue to move up to the payment booth and completely stop) is increased, which directly increases the processing time, and results in a fewer number of vehicles that can be discharged by the plaza. Secondly, they cannot accelerate away from the plaza and get back up to operating speed as quickly as smaller vehicles, causing a drop in capacity. Finally, trucks require a much greater acceptable critical gap when making a lane change. Vehicles approaching a plaza usually make lane changes more frequently than vehicles on a basic freeway segment, so heavy vehicles making lane changes could cause additional congestion at the plaza approach.

As mentioned in the previous section, data were collected for each scenario until the capacity of that scenario had been reached. The capacities of each scenario were recorded, along with other important variables, such as average service time, number of booths open for each payment type, and the percentage of trucks. All of these variables were relevant in the development of a capacity equation.
Density and Delay

Obtaining density and delay data was done similarly to the obtaining capacity. However, each scenario only has one capacity value. Density and delay data were gathered as outputs for each of the simulation runs discussed above, hence, there were many more data collected for density and delay for each scenario. The density and delay data were collected for analyzing the performance of the toll plazas. Therefore, it was important to obtain data for all amounts of traffic demand and all types of geometric configurations. There are also many more individual factors that can determine the density or delay of a segment, especially toll plaza, so collecting a significant amount of data was crucial.

ETC-Only Lanes

For the discussion in this chapter, it should be noted that the use of the term 'ETC-only lanes' refers to lanes where drives can pay the toll without having to bring their vehicle. ETC-only lanes can require vehicles to a complete stop, but still travel through the plaza at a speed well below the free-flow speed of the adjacent freeway segments. For situations in which electronic toll collection is performed at regular freeway speeds, and without any physical toll plaza infrastructure (other than possibly an unobtrusive overhead gantry), this is referred to as 'Open Road Tolling' (ORT). Accommodating ORT analysis in the FREEPLAN software is discussed in the Appendix.

While the speed of traffic passing through the plaza in an ETC-only lane is usually considerably lower than the free-flow speed of the adjacent freeway segments, it does not have to stop; thus, the traffic flow in these lanes can generally be analyzed according to uninterrupted traffic flow theory. To apply uninterrupted traffic flow theory,
at a macroscopic level, it is essential to have knowledge of the underlying speed-flow-density relationship. Knowledge of the values of any two of these variables allows the third to be obtained directly from Equation 3-1.

\[ q = uk \]  

(3-1)

where,

- \( q \) = flow (veh/h),
- \( u \) = speed (mi/h),
- \( k \) = density (veh/mi).

Although a speed-flow relationship for uninterrupted flow is given in the HCM for basic freeway segments, it is generally only applicable at free-flow speeds higher than those experienced in ETC-only lanes. Thus, ideally, the speed-flow relationship for ETC-only lanes should be determined empirically from toll plaza sites. Unfortunately, field data of this type were not available. Thus, a speed-flow relationship for this situation was determined from CORSIM simulation output. While it is known that the underlying car-following model used in CORSIM does not lead to the speed-flow relationship given in the HCM for freeway segments, and thus, may not be accurate for ETC-only lanes, it is likely a reasonable enough approximation to use until a more accurate one can be determined from field data. For the development of the speed-flow relationship, free-flow speeds from 20 mi/h to 40 mi/h in increments of 10 mi/h were used. In all, 82 data points were collected, which was achieved by using three truck percentage values (0, 10, and 20%), three different free-flow speed values (20, 30, and 40 mi/h), and nine demand volume values (500 veh/h – 4500 veh/h, by increments of 500 veh/h except for one scenario ranged from 500 veh/h – 5000 veh/h). Capacity was also achieved from these simulation runs for each of the free-flow speeds, but only considering passenger
cars (no heavy vehicles). The development of the speed-flow relationship and its application is discussed in Chapter 4.

Data about ETC-only lanes were collected using a different CORSIM simulation file. This file began with two FRESIM lanes, which added a lane to become three lanes. Then, a two-lane exit link led to the non-ETC-only plaza with three toll booths while the one-lane ETC-only link bypassed the plaza. Starting from the beginning of the facility until the ETC-only link passes the plaza, the link speeds were incrementally decreased until the desired free flow speed to be studied was achieved. After the vehicles pass the plaza, the link free flow speed is increased again so that they regain freeway free-flow speed. Figure 3-6 shows the setup of the simulation file for collecting data on the scenarios with an ETC-only lane. Only one ETC-only lane was studied because no example of multiple ETC-only lanes could be found in Florida, except in the case of open road tolling.

**Model Development**

Once all the data were recorded, they were analyzed with a statistical analysis program in an attempt to create equations that can relate the variables described above with the capacity of a particular toll plaza. Separate equations were developed for certain scenarios, based on the payment type, and demand percentages for each payment type for plazas that accept multiple payment types.

Once the experimental design for toll plaza capacity was achieved, statistical analysis was conducted in a similar manner as described above to develop relationships between demand-to-capacity ratio \((d/c)\) to density, and \(d/c\) to delay. These relationships allow a toll plaza to be analyzed within a freeway facility, given the
demand, percentage of trucks, number of booths open, and the average service time of the plaza. Ranges for a LOS scale were also defined once the statistical analysis on the data was completed.

Implementation into FREEPLAN

Not only did this research develop the analysis methodology described in Chapter 4, but it also implemented the methodology into FREEPLAN. Once the methodology was developed on paper, it needed to be constructed in a way that could be turned into programing code. The logic and framework behind the code were developed and put into the FREEPLAN code, which was written in C#. Then the new features were tested by inputting a combination of geometric inputs and different traffic conditions. Input validation was also required to keep the user from inputting physically impossible scenarios.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry volume</td>
<td>100 veh/h</td>
<td>Capacity</td>
<td>100 veh/h</td>
</tr>
<tr>
<td>Truck percentage</td>
<td>0%</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>Number of booths open</td>
<td>3 booths</td>
<td>5 booths</td>
<td>1 booth</td>
</tr>
<tr>
<td>Average plaza service time</td>
<td>5.5 s</td>
<td>14.5 s</td>
<td>3 s</td>
</tr>
</tbody>
</table>
Figure 3-1. Diagram of 3-lane, single payment type simulation geometry

Figure 3-2. Diagram of 4-lane, single payment type simulation geometry

Figure 3-3. Diagram of 5-lane, single payment type simulation geometry

Figure 3-4. Diagram of 4-lane, multiple payment type simulation geometry

Figure 3-5. Diagram of 6-lane, multiple payment type simulation geometry
Figure 3-6. Diagram of 4-lane (1 ETC-only lane, 3 manual payment lanes), multiple payment type simulation geometry
CHAPTER 4
RESULTS AND ANALYSIS

This chapter discusses the overall analysis methodology and models that have been developed from the simulation output data generated from the research approach discussed in the previous chapter.

**Methodology Development**

The first three steps of the methodology discussion initially focus on toll plazas without ETC-lanes. Once all the non-ETC-only lanes have been addressed, ETC-only lanes are incorporated into the methodology, as discussed in a later section.

**Step One**

**One payment type**

The developed methodology is a three-step process. The first step is to calculate an average processing rate for the plaza. For plazas with only one type of payment accepted, the average is the same for the whole plaza as it is for each individual booth. The average service time can be obtained by collecting field data for a specific plaza, or by using the defaults of 2.5 s for automated coin machine, 5.5 s for manual booths, and 2.5 s for a ticketed booth, which are values consistent with data obtained from the Florida Department of Transportation. Next, the average pull-up time (1) (Aycin refers to the pull-up time as the move-up time) should be added to the average service time to get the average processing rate. This approach is consistent with the methodologies in Chapter 2 proposed by Zarrillo (5) and Aycin (6). This value will be used in the capacity calculation in **Step Two**.

**Multiple payment types**
Just as for one payment type, for booths that accept multiple payment types, an average of each payment types’ average service time can be taken. However, for the most part, individual toll booths do not mix the payment types they accept. One exception that is common is for electronic toll collection (ETC) to be paired with either manual booth payment (MB), automated coin machine (ACM), or ticketed payment. ETC is usually accepted at most booths, but is rarely used at booths that accept other payment types because there is often at least one dedicated ETC-only lane at which vehicles do not have to stop to pay. Therefore, this research does not consider booths that accept multiple payment types, only plazas that accept multiple payment types, each at a different booth.

For plazas that accept multiple payment types, a simple average of individual booth service times is not an accurate calculation for the average plaza service time. Because different payment types will have different service times, booths will process vehicles at different rates and consequently have different capacities. Therefore, the capacity for each payment type must be calculated separately. Once the average service time is calculated for each payment type, the pull-up time must be added to get the processing time for each payment type.

**Step Two**

Once an average plaza processing time has been calculated, the next step is to calculate the capacity for the plaza. As discussed above, the plaza capacity is based on the average processing time, the number of lanes that accept payment, and the percentage of trucks present. This calculation will yield the demand-to-capacity ($d/c$) ratio, which determines if traffic conditions are undersaturated or oversaturated.
One payment type

The capacity data collection method discussed in the previous chapter provided 480 runs (10 runs per scenario) resulting in 48 data points for scenarios with one payment type. Then, statistical analysis was performed on the data. From non-linear regression analysis, Equation 4-1 was developed for calculating the capacity of a toll plaza that only accepts one payment type:

Single payment type capacity model:

\[
\text{Cap} = \frac{3643.564 \times N}{\bar{t}_{\text{process}}} - 1.313 \times \text{PctTrucks} \\
\text{(4-1)}
\]

where,

- \(\text{Cap}\) = the maximum number of vehicles a toll plaza can discharge per hour (veh/h),
- \(\bar{t}_{\text{process}}\) = average processing time for the plaza (s),
- \(N\) = number of open toll lanes,
- \(\text{PctTrucks}\) = the percentage of trucks present.

The R-squared value for this capacity model is 0.9970. The form of this model for capacity is very close to that used by Aycin (6). The first term in the equation is the theoretical capacity of a toll plaza, but with a slight difference in the coefficient. In the theoretical version, 3600 sec/h is multiplied by the number of lanes and then divided by the processing time. The coefficient in the first term of Equation 4-1 above is very close to the theoretical coefficient of 3600, but slightly different due to the second term, which adjusts for the presence of trucks in the traffic stream.

Multiple payment types
When multiple payment types are accepted, their respective capacities must be calculated separately so that the d/c ratio for each payment type can be found for use in Step Three. To do this, the ideal payment type distribution percentage must be calculated for each payment type based on the number of booths accepting each payment type. This calculation is done by finding the percentage of demand for each payment type that should enter the plaza that would result in the maximum total discharge from the plaza. The ideal percentages for each payment type are calculated in Equation 4-2:

Ideal percentage of payment type $i$:

$$\text{Percent of } PT_i = \frac{N_{PTi}}{\sum_{j=1}^{m} \frac{N_{PTj}}{t_{process_{PTj}}}} \times 100\%$$  \hspace{1cm} (4-2)$$

where,

$PT_i$ = Payment type $i$,

$N_{PTi}$ = Number of open booths that accept payment type $i$,

$\bar{t}_{process, PT_i}$ = average processing time for the booths of payment type $i$,

$m$ = number of non-ETC payment types accepted at the plaza.

Next, the ideal payment type distribution percentage for each payment type can be compared to the actual payment type distribution percentage for that payment type. If the actual distribution is greater than the ideal distribution, then that payment type will be considered to be over-utilized and will use a certain equation, detailed in Step Three. If the actual distribution is less than the ideal distribution, the payment type will be
considered underutilized and will therefore use a different equation, also detailed in
Step Three.

The capacity data collection method discussed in the previous chapter provided
360 runs (10 runs per scenario) resulting in 36 data points for scenarios with multiple
payment types. Then, statistical analysis was performed on the data. From non-linear
regression analysis, Equations 4-3, 4-4, 4-5, and 4-6 were developed for calculating the
capacity of a toll plaza:

ACM capacity model if actual distribution is greater than or equal to ideal distribution:

\[
\text{Cap}_{\text{ACM}} = \frac{3672.266 \times N_{\text{ACM}}}{t_{\text{process, ACM}}} - 3.255 \times N_{\text{ACM}} \times \sqrt{PctTrucks}
\] (4-3)

where,

\( \text{Cap}_{\text{ACM}} \) = the maximum number of vehicles the ACM lanes can discharge per hour,

\( t_{\text{process, ACM}} \) = average processing time for the ACM booths,

\( N_{\text{ACM}} \) = number of open ACM toll lanes,

*Note: All other variables as previously defined.*

ACM capacity model if actual distribution is less than ideal distribution:

\[
\text{Cap}_{\text{ACM}} = \frac{3803.336 \times N_{\text{ACM}}}{t_{\text{process, ACM}}} \times \left( 1 - \frac{\text{IdealPct}_{\text{ACM}} - \text{ActPct}_{\text{ACM}}}{44.859} \right) - 3.255 \times N_{\text{ACM}} \times \sqrt{PctTrucks}
\] (4-4)

where,

\( \text{IdealPct}_{\text{ACM}} \) = the ideal percentage of distribution for ACM booths,

\( \text{ActPct}_{\text{ACM}} \) = the actual percentage of distribution for ACM booths,

*Note: All other variables as previously defined.*

MB Capacity model if actual distribution is greater than or equal to ideal distribution:
\[ \text{Cap}_{MB} = \frac{3678.417 \times N_{MB}}{t_{\text{process,MB}}} - 2.357 \times N_{MB} \times \sqrt{\text{PctTrucks}} \quad (4-5) \]

where,

- \( \text{Cap}_{MB} \) = the maximum number of vehicles the manual booth lanes can discharge per hour,
- \( \bar{t}_{\text{process,MB}} \) = average processing time for the manual booths,
- \( N_{MB} \) = number of open manual booth lanes,

**Note:** All other variables as previously defined.

MB Capacity model if actual distribution is less than ideal distribution:

\[ \text{Cap}_{MB} = \frac{3630.240 \times N_{MB}}{t_{\text{process,MB}}} \times (1 - \frac{\text{IdealPct}_{MB} - \text{ActPct}_{MB}}{33}) - 2.357 \times N_{MB} \times \sqrt{\text{PctTrucks}} \quad (4-6) \]

where,

- \( \text{IdealPct}_{MB} \) = the ideal percentage of distribution for manual booths,
- \( \text{ActPct}_{MB} \) = the actual percentage of distribution for manual booths,

**Note:** All other variables as previously defined.

The R-squared value for the ACM capacity model is 0.9963. The R-squared value for the MB capacity model is 0.9977. Once again, part of the form of these models for capacity is very close to that used by Aycin (6). Theoretically, to calculate toll plaza capacity, 3600 sec/h is multiplied by the number of lanes and then divided by the processing time. The first term in the equation is the theoretical capacity of a toll plaza, but with a slight difference in the coefficient, again because of the term accounting for truck percentage. For the equations where actual distribution percentage is greater than the ideal distribution percentage, the modifying term multiplied with the first term
accounts for the fact that the payment type is underutilized because the other payment type is over utilized.

**Step Three**

First, the deceleration delay for slowing from free-flow speed to pay the toll must be calculated. This delay represents the difference in travel times between a vehicle stopping to pay the toll, and a vehicle that is traveling at free-flow speed of the freeway. Equation 4-7 is for calculating deceleration delay:

\[
Decel\ Delay = \frac{(FFS-v_{final}) \times 1.467}{10\ ft/s^2}
\]  

(4-7)

where,

- \( Decel\ Delay \) = the time it takes to go from the free flow speed of the freeway to the final speed at which the toll is paid (s),
- \( FFS \) = the free flow speed of the freeway upstream of the toll plaza before speed reductions (mi/h)
- \( v_{final} \) = the speed at which the vehicle is traveling as the toll is paid (mi/h)

For non-ETC payment types, \( v_{final} \) will be 0 mi/h and for ETC-only lanes, it will be the free-flow speed at which vehicles pass the plaza. Deceleration delay should be added to any of the delay values calculated with equations from *Step Three*. These equations are calculating the time spent in queue at the plaza, along with the reacceleration back to free-flow speed done after a driver has paid the toll.

The next step in the methodology is to calculate density and delay based on the information obtained from *Step One* and *Step Two*. Given the demand and the capacity for each payment type, a \( d/c \) ratio can be calculated for each payment type, which will be used to calculate the density and delay.
One payment type

For toll plazas that only have ACM lanes, Equations 4-8 and 4-9 should be used for calculating density and delay:

Equation for the density of a plaza with only ACM lanes:

\[
Density = \exp \left( 3.9198 \times \left( \frac{d}{c_{ACM}} \right) \right) + 18.2248 \times \left( \frac{d}{c_{ACM}} \right) - 27.5647 \times \left( \frac{d}{c_{ACM}} \right)^3 - 0.0188 \times N \times PctTrucks \tag{4-8}
\]

Equation for the delay of a plaza with only ACM lanes:

\[
Delay = 14.0362 + \exp \left( 3.8156 \times \left( \frac{d}{c_{ACM}} \right) \right) + 5.2976 \times \left( \frac{d}{c_{ACM}} \right) - 30.2847 \times \left( \frac{d}{c_{ACM}} \right)^3 + 0.098 \times N \times PctTrucks \tag{4-9}
\]

where,

\[
Density = \text{the density of the toll plaza segment (veh/mi/ln)},
\]

\[
Delay = \text{the difference in actual travel time and the travel time at free-flow speed (s)},
\]

\[
\frac{d}{c_{ACM}} = \text{the demand to capacity ratio for ACM lanes},
\]

\[
N = \text{the number of open toll lanes},
\]

\[
PctTrucks = \text{the percentage of trucks present}.
\]

The \( R^2 \) value of the density equation is 0.9886 and the \( R^2 \) value for the delay equation is 0.9504. The data used in the development of these equations were produced by 2120 CORSIM runs (10 runs per scenario) providing 212 data points. For toll plazas that only have manual booth lanes, Equations 4-10 and 4-11 should be used for density and delay:

Equation for the density of a plaza with only MB lanes:
\[ \text{Density} = \exp \left( 3.9041 \times \left( \frac{d}{c_{MB}} \right) \right) + 13.0301 \times \left( \frac{d}{c_{MB}} \right) - 26.1173 \times \left( \frac{d}{c_{MB}} \right)^3 - 0.0128 \times N \times \text{PctTrucks} \] \tag{4-10}

Equation for the delay of a plaza with only MB lanes:

\[ \text{Delay} = 15.7208 + \exp \left( 4.0232 \times \left( \frac{d}{c_{MB}} \right) \right) + 7.8286 \times \left( \frac{d}{c_{MB}} \right) - 39.5006 \times \left( \frac{d}{c_{MB}} \right)^3 + 0.0105 \times N \times \text{PctTrucks} \] \tag{4-11}

where,

\[ \frac{d}{c_{MB}} = \text{the demand to capacity ratio for MB lanes}, \]

Note: All other variables as previously defined.

The \( R^2 \) value of the density equation for manual payment booths is 0.9918 and the \( R^2 \) value for the delay equation is 0.9822. The data used in the development of these equations were produced by 1300 CORSIM runs (10 runs per scenario) providing 130 data points.

Multiple payment types

The first step in calculating density and delay for plazas that accept multiple payment types depends on the percentage split for each of the payment types. If the payment type distribution percentage for one non-ETC payment type is greater than 3 times the payment type distribution percentage of the other non-ETC payment type, then the equations from the Step Three, One payment type section should be used, respectively. For example, if 80% of the demand is for ACM lanes, and 20% is for the manual booths, then the equations for the single payment type should be used for each respective payment type. Once the individual density for each payment type is calculated, to obtain the overall plaza density, an average, weighted by lane, should be done for the density, as shown in Equation 4-12:
Overall plaza density:

\[
\text{Overall Density} = \frac{\left(\text{Den}_{\text{ACM}} \times N_{\text{ACM}} + \text{Den}_{\text{MB}} \times N_{\text{MB}}\right)}{N} \tag{4-12}
\]

where,

\text{Overall Plaza Density} = \text{average density, weighted by lane, of the all the lanes at the plaza},

\text{Den}_{\text{ACM}} = \text{average density of the ACM lanes},

N_{\text{ACM}} = \text{number of ACM lanes},

\text{Den}_{\text{MB}} = \text{average density of the MB lanes},

N_{\text{MB}} = \text{number of manual payment lanes},

N = \text{the total number of non-ETC-only lanes at the plaza}.

For the overall delay of the plaza, a vehicle-weighted average should be taken, as shown in Equation 4-13:

Overall plaza delay:

\[
\text{Overall Delay} = \frac{\left(\text{Del}_{\text{ACM}} \times \text{TotVol} \times \text{Pct}_{\text{ACM}} + \text{Del}_{\text{MB}} \times \text{TotVol} \times \text{Pct}_{\text{MB}}\right)}{\text{TotVol}} \tag{4-13}
\]

where,

\text{Overall Plaza Delay} = \text{average delay, weighted by vehicle, at the plaza (s)},

\text{Del}_{\text{ACM}} = \text{average delay of the ACM lanes (s)},

\text{Pct}_{\text{ACM}} = \text{percentage of the total non-ETC-only volume that chooses ACM lanes},

\text{Del}_{\text{MB}} = \text{average delay of the MB lanes (s)},

\text{Pct}_{\text{MB}} = \text{percentage of the total non-ETC-only volume that chooses MB lanes},

\text{TotVol} = \text{the total demand volume entering the toll plaza segment (veh/h)}. 

53
For plazas that have multiple payment types where either of the payment type
distribution percentages is less than 3 times the other, then the $d/c$ ratio will be used in
the Equations 4-14 and 4-15 to calculate density and delay for the plaza:

Equation for density:

$$Density = \exp \left( 4.1402 \times \left( \frac{d}{c_{MB}} \right) \right) + \exp \left( 3.3952 \times \left( \frac{d}{c_{ACM}} \right) \right) - 49.2126 \times \left( \frac{d}{c_{MB}} \right)^3 + 4.5947 \times \left( \frac{d}{c_{ACM}} \right)$$

(4-14)

Equation for delay:

$$Delay = 16.3418 + \exp \left( 4.8055 \times \left( \frac{d}{c_{MB}} \right) \right) + \exp \left( 3.0160 \times \left( \frac{d}{c_{ACM}} \right) \right) - 99.2775 \times \left( \frac{d}{c_{MB}} \right)^4 - 4.8725 \times \left( \frac{d}{c_{ACM}} \right)$$

(4-15)

where,

$Density = \text{the number of vehicles per lane per mile of the toll plaza segment}$

(veh/mi/ln),

$Delay = \text{the difference in the actual trip time for a vehicle and its free flow travel time (s)},$

$d/c_{MB} = \text{the } d/c \text{ ratio of manual booth lanes},$

$d/c_{ACM} = \text{the } d/c \text{ ratio of ACM lanes}.$

The $R^2$ value of the density equation is 0.9255 and the $R^2$ value for the delay equation is 0.9292. The data used in the development of these equations were produced by 620 CORSIM runs (10 runs per scenario) providing 62 data points.

**ETC-Only Lanes**

This section discusses the necessary additions to the analysis methodology to account for the presence of one or more ETC-only lanes at a toll plaza. As discussed in
the previous chapter, uninterrupted traffic flow theory was applied to the analysis of ETC-only lanes.

The resulting speed-flow curves from CORSIM are shown in Figure 4-1. From a software implementation perspective, it is easier to deal with a single equation than multiple ones. Thus, given that the equations for each free-flow speed were extremely similar in slope, an average slope across the three equations was used in a single equation, as given below in Equation 4-16:

Speed-flow relationship for an ETC-only lane:

$$\text{Average Speed} = \text{FFS}_{ETC} - 0.00254 \times \text{FlowRate}_{ETC}$$

where,

- $\text{Average Speed}$ = the average speed of the vehicles in the ETC-only lane as they pass through the toll plaza (mi/h),
- $\text{FFS}_{ETC}$ = free-flow speed of the vehicles in the ETC-only lane through the plaza,
- $\text{FlowRate}_{ETC}$ = the hourly volume per lane of vehicles that pass through the toll plaza (veh/h/ln).

The $R^2$ value for the speed-flow equation is 0.9783, and the data used in the development of this equation were produced by 820 CORSIM runs (10 runs per scenario) providing 82 data points.

The average speed obtained from Equation 4-16 can be used with the corresponding flow rate in Equation 3-1 to obtain the density. For situations where there are multiple adjacent ETC-only lanes, lane changing, if allowed, would be minimal. Therefore, while Equation 4-16 is applicable to situations with multiple adjacent ETC-only lanes, if significant lane changes are determined to exist, caution should be used when applying Equation 4-16. Additionally, Equation 4-16 is not valid in saturated...
conditions when the $d/c$ ratio is greater than 1.0. Neither of the two scenarios mentioned in this paragraph, oversaturated conditions or adjacent ETC-only lanes, have been tested.

While Table 2-1 provides some capacity values for ETC-only lanes, these are based on older research. And since recent field data were not available to use for determining capacity values in ETC-only lanes, CORSIM was used once again in this area. While it is certainly debatable whether capacity values determined through CORSIM output are realistic, it does have the advantage of providing some consistency with the speed-flow curves as determined through CORSIM and used in this study. Based on simulation runs in CORSIM, the capacity for some common free-flow speeds of ETC-only lanes are listed in Table 4-2. From Table 4-2, it can be seen that when the free-flow speed goes up, the capacity increases. This is expected, as capacity for freeway segments generally occurs in the range of 50-53 mi/h. Free-flow speeds above 40 mi/h are typically going to be limited to open-road tolling situations, in which case the methodology relies on the speed-flow relationship and capacity values as provided in the basic freeway segment chapter of the Highway Capacity Manual (7).

**Level of Service**

Once the toll plaza has been fully evaluated for all payment types, the segment operations must be categorized with LOS criteria. A new LOS scale was defined (Table 4-1). From Table 4-1, it can be seen that delay is the performance measure chosen to define the LOS ranges. This was done because it represents the inconvenience a toll plaza driver experiences. The intervals increase as the LOS
worsens in order to generally reflect the exponential nature of the flow rate versus delay relationship.

The lower bound of 32 s for LOS A was chosen because under extremely low demand, delay values a little less than this value are obtained, which primarily correspond to deceleration delay, service time, and acceleration delay. The upper bound of 60 s for LOS F generally corresponds to the point at which the $d/c$ ratio equals 1.0.

The LOS for individual toll plazas is different than the LOS for the segment when considered in a freeway. In order to incorporate a toll plaza segment into the freeway facilities analysis, it must use density as a service measure, as do the other segment types. Therefore, when the segment is considered as part of the facility, its density is used on the same scale as other freeway facility segments to define the level of service of the toll plaza segment.

**Implementation into FREEPLAN**

The methodology discussed above was implemented into FREEPLAN (15). A toll plaza can be modeled as a segment (Figure 4-2). The other parameters of the toll plaza segment, such as segment length, posted speed limit, and terrain, can be modified normally. New inputs such as the number of lanes for each payment type, the percentage of demand for each payment type, the average service time for each payment type, the portion of ORT utilization, and the number of ORT lanes can be modified (Figure 4-3). An isolated toll plaza, an isolated ORT segment, and the combination of these two scenarios can be modeled. Finally, the LOS Results tab (Figure 4-4) shows the results of the analysis, including the adjusted capacity, $d/c$ ratio,
average speed, density, delay, and segment LOS. Special toll plaza results have been added as well, including speed, density, delay and LOS for the non-ETC-only lanes, the ETC-only lanes, and the overall plaza (Figure 4-5).

Input validation has been incorporated into the input screens to ensure that a user cannot attempt to create physically impossible scenarios. Some testing has been done on the new implementation to verify that the inputs give reasonable results. Unique geometric scenarios with traffic demand conditions that were not simulated during the data collection process were tested in the updated FREEPLAN software. The results are generally reasonable, based on the scenarios that have been tested.
Table 4-1. Level of service criteria for toll plaza segments

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>Average travel delay (s/veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤ 32</td>
</tr>
<tr>
<td>B</td>
<td>&gt; 32 - 36</td>
</tr>
<tr>
<td>C</td>
<td>&gt; 36 - 42</td>
</tr>
<tr>
<td>D</td>
<td>&gt; 42 - 50</td>
</tr>
<tr>
<td>E</td>
<td>&gt; 50 - 60</td>
</tr>
<tr>
<td>F</td>
<td>&gt; 60</td>
</tr>
</tbody>
</table>

Table 4-2. Capacity of ETC-only lanes based on free-flow speed

<table>
<thead>
<tr>
<th>Free-flow Speed (mi/h)</th>
<th>Capacity (veh/h/ln)</th>
<th>Rounded Capacity Values (veh/h/ln)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1934</td>
<td>1950</td>
</tr>
<tr>
<td>30</td>
<td>2156</td>
<td>2150</td>
</tr>
<tr>
<td>40</td>
<td>2183</td>
<td>2200</td>
</tr>
</tbody>
</table>
Figure 4-1. Average speed of ETC-only lanes versus discharge for free-flow speeds of 20 mi/h, 30 mi/h, and 40 mi/h.
Figure 4-2. Selecting “Toll Plaza” as the input segment type in FREEPLAN
Figure 4-3. The “Toll Plaza Data” pop-up menu, which contains specific toll plaza inputs for a toll plaza segment in FREEPLAN
Figure 4-4. The LOS Results tab, which now contains results for a toll plaza segment in FREEPLAN.
Figure 4-5. Additional toll plaza results screen.
Data collected from simulations in CORSIM were used to develop a methodology for analyzing toll plazas for both single-payment plazas and multiple-payment plazas. First, the processing rate is calculated by adding the service time and the pull-up time. Next, the ideal portion of the total demand for each payment type must be determined. Then, the capacity of each payment type is calculated based on the number of booths, the processing time, and the percentage of trucks. Finally, the demand to capacity ratio is used to determine the density and delay of the toll plaza segment. The level of service for the toll plaza segment is based on delay, while the density of the toll plaza segment is used in the calculation for overall freeway facility LOS.

ETC-only lanes were also considered in the analysis. Availability of ETC-only lanes can significantly increase the capacity of a toll plaza. They are analyzed based on macroscopic uninterrupted traffic flow theory. The developed speed-flow relationship is used to determine density. The free-flow speed of ETC-only lanes is an important factor in determining their capacity. A low free-flow speed yields a lower capacity than a high free-flow speed. As the free-flow speed approaches regular freeway and ORT segment free-flow speeds, it is expected that the capacity will be similar to the values identified in the HCM for basic freeway segments, where capacity generally occurs around average speeds of 50 to 53 mi/h.

The methodology briefly described above for analyzing toll plazas was implemented into a freeway facility analysis program named FREEPLAN. Once a segment type is identified as “Toll Plaza”, the details, such as payment type distribution,
number of lanes, average service time, length of the segment, etc., are inputted on the Segment Data tab and under the “Edit” pop-up input dialog. The LOS Results tab provides the outputs from the facility analysis, including density, speed, and LOS. There is also an additional toll plaza outputs screen that provides speed, density, delay, and LOS for non-ETC-only lanes, ETC-only lanes, and the overall plaza.

**Recommendations**

Although the research presented in this thesis made significant advances in the ability to accommodate toll plaza analysis within the broader context of freeway facility analysis, there is still additional work to be done in this area. The following are recommendations based on the results or limitations of this research.

**Oversaturated Analysis and Implementation into the Freeway Facilities Program**

This research was limited to undersaturated analysis. While undersaturated freeway facilities analysis is included in this research, this can be limiting for those that wish to model oversaturated conditions with multiple time periods. Additional research should be done that covers oversaturated scenarios. This will provide a more complete understanding of the effect toll plazas have on an extended length freeway, not just the immediate area upstream and downstream of a toll plaza.

**Implementation into the HCM**

It is recommended that the methodology developed in this research be included in the Highway Capacity Manual. There is currently no guidance on how to analyze toll plazas, either at the segment level or the facility level. With the methodology developed in this analysis, the capacity and level of service of toll plazas can be analyzed, both in isolation and in conjunction with other surrounding segments that form a facility. The
methodology presented in this thesis can be included in the HCM as a stand-alone chapter in the uninterrupted flow volume. The HCM chapter on freeway facility analysis can be modified to include guidance on incorporating toll plaza segments into a facility analysis for undersaturated conditions. When future research on oversaturated analysis of toll plazas is completed, the HCM chapters can be further updated as appropriate.

Simulation with ETC-Only Lanes

To keep the experimental design and subsequent computational time manageable, the simulation and analysis of ETC-only lanes was done independent of the manual and ACM lanes. Thus, the analysis methodology presented in this thesis reflects separate equations for these two types of lanes, for which the results are aggregated to arrive at overall toll plaza measures. While these two groups of lanes generally operate independently of one another, it is possible that some interactions may occur during the upstream diverging and downstream merging process, which might lead to slightly different results than those estimated by the approach given here. Thus, future research should explore simulation scenarios that consider ETC-only and manual/ACM lanes in the same plaza, particularly for oversaturated conditions.

Density, Delay and LOS by Payment Type

As described in Chapter 3, some of the data collected for this research were from scenarios with multiple payment types accepted at the plaza. The resulting equations in the methodology in Chapter 4 use a single equation to calculate density and a single equation to calculate delay. Therefore, the density and delay values are for the plaza as a whole, and are not split specifically by payment type. However, the density, delay, and LOS are reported for non-ETC-only lanes and ETC-only lanes separately.
While, in general, this combined output is sufficient to analyze the plaza, occasionally, it could be useful to know the density, delay, and LOS of a single payment type. Because different payment types have different average service times at the plaza, they are likely to have different typical delay values. It is also possible that the driver perspective can change for different payment types; for example, a driver might expect to have a shorter delay at an ACM lane than at a manual lane where change is required. Just as ETC-only lanes have a different LOS scale, so should each of the non-ETC-only payment types accepted at a plaza.

Future research should consider determining whether separate LOS scales should be used for different payment types, especially for non-ETC-only lanes. Also, the appropriate service measure(s) and threshold values should be properly identified and confirmed with research.
This appendix serves as a guide for modeling toll plazas in FREEPLAN. It specifically covers three types of toll plazas: traditional, open road tolling (ORT) only plazas, and the combination of a traditional plaza and the open road tolling segments in parallel. These scenarios, as well as the corresponding options that can be modified, are discussed in detail.

**Traditional Toll Plaza Only on Mainline**

A traditional toll plaza is one that consists of payment types that require the vehicle to slow or stop completely to pay the toll. These payment types include automated coin machines (ACM), manual booths (MB) and electronic toll collection lanes (ETC) that require the driver to slow to a speed of at most 45 mi/h.

To model this type of toll plaza in FREEPLAN, make a new segment, and select “Toll Plaza” as the segment type. This segment cannot be either the first or last segment of the facility. Selecting the corresponding highlighted “Edit” option will produce the “Toll Plaza Data” popup window. Here, options can be changed for the toll plaza segment. First, confirm the radial option for “Traditional Plaza only on mainline” is selected. Secondly, in the “Number of Lanes” section, indicate the number of booths for each payment type. Next, if any ETC-only lanes exist, input the free flow speed of these lanes. Then, in the “Payment Type Composition” section, edit the percentage of the total demand volume that will use each of the payment types. These values must sum to 100%. Finally, if necessary, modify the average service times for the two stop required payment types in the “Average Service Times” section.
Click “OK” to close the “Toll Plaza Data” popup window. Next modify the rest of the input data in the “Segment Data” tab. Once the input data for all other segments in the facility have been set up, the individual segment results along with the facility results can be viewed on the “LOS Results” tab. On the results tab under the “Additional Off-Ramp/Toll Outputs” column, additional results for the toll plaza can be viewed. These results show specific outputs, such as average speed, density, delay, and LOS, for the non-ETC-only lanes, the ETC-only lanes, and the overall toll plaza.

**Open Road Tolling Only on Mainline**

Another toll plaza scenario that can be modeled is open road tolling (ORT) with no traditional payment options. In this situation, the toll is collected via ETC, but without requiring vehicles to stop or slow down at all. In some situations, the toll is collected by recording license plates and mailing a bill to the registered owner of the vehicle. Typically, there is no change in the roadway geometry of an ORT segment; therefore, the segment is analyzed as a basic segment.

To input this scenario into FREEPLAN, add a new segment, select “Toll Plaza” as the segment input type, and click the “Edit” button to bring up the “Toll Plaza Data” popup window. After the radial option for “Open Road Tolling only on mainline” is selected and the number of ORT lanes are entered, no additional inputs are necessary. Click “OK” and modify any other segments inputs in the “Segment Data” tab. Then find the results of the analysis on the “LOS Results” tab. There are no additional results under the “Additional Off-Ramp/Toll Outputs” column because the segment is simply analyzed as a basic segment.
Open Road Tolling and Parallel Traditional Plaza

The last toll plaza scenario that can be modeled in FREEPLAN is one that combines the previous two scenarios by modeling an ORT section with a parallel traditional plaza. The ORT section includes multiple lanes by which vehicles are not required to slow down, while the parallel traditional toll plaza provides drivers with the option of using stop-required payment methods. In order to enter the traditional toll plaza area, vehicles can exit the freeway segment via an off-ramp, and, after having paid the toll, can re-enter using the connecting on-ramp. If drivers prefer ORT, they can simply continue on the freeway segment without exiting.

This scenario is inputted very similarly to the “Traditional Plaza only on mainline” except for one additional input: the proportion of the demand using the traditional toll plaza. This ratio can be inputted once the “Open Road Tolling + Parallel Traditional Plaza” option has been selected. After the rest of the details are inputted (as discussed in the Traditional Toll Plaza Only on Mainline section), click “OK” to close the “Toll Plaza Data” popup window. Find the results on the “LOS Results” tab. The results displayed in the toll plaza segment row describe the ORT segment. The traditional plaza results can be found under the “Additional Off-Ramp/Toll Outputs” column. Here, results are split into regular lanes, ETC-only lanes, and overall plaza results.

Examples

The following are examples for each of the scenarios listed above. They show the input data used, along with the results obtained from FREEPLAN.
Example 1: Traditional Toll Plaza Only on Mainline

Example 1 shows an example of how to set up a segment with only a traditional toll plaza. The “Segment Input” tab contains five segments, the third of which is a toll plaza segment (Figure A-1). The toll plaza contains two manual lanes (35% demand) with an average service time of 5.6 sec, two automated coin machine lanes (40% demand) with an average service time of 2.3 sec, and 1 ETC-only lane with a free-flow speed of 35 mi/h (Figure A-2). The results of Example 1 can be found in Figure A-3 and Figure A-4.

Example 2: Open Road Tolling Only on Mainline

Example 2 demonstrates the way an ORT only segment is modeled. The “Segment Data” tab contains the number of through mainline lanes (three) and the length of the toll plaza segment (2640 ft) (Figure A-5). Correspondingly, under the “Toll Plaza Data” input screen, three lanes were entered (Figure A-6). The results for the analysis can be found in Figure A-7.

Example 3: Open Road Tolling + Parallel Traditional Plaza

Example 3 shows an example of how an ORT segment and a parallel traditional toll plaza are set up in FREEPLAN. First, a Toll Plaza segment is created (Figure A-8), and the “Open Road Tolling + Parallel Traditional Plaza” option is selected. Three ORT lanes and a traditional toll plaza usage rate of 0.4 are inputted. The parallel traditional plaza is made up of three manual lanes, with average service times of 5.5 s (Figure A-9). After confirming the inputs, the off- and on-ramps are added to the list of segments (Figure A-10). Finally, the results can be viewed in Figure A-11, along with additional toll plaza results (Figure A-12).
Figure A-1. Example 1 segment data input screen
Figure A-2. Example 1 toll plaza data input screen
Figure A-3. Example 1 LOS results tab
Figure A-4. Example 1 additional toll plaza results
Figure A-5. Example 2 segment data input screen
Figure A-6. Example 2 toll plaza data input screen
Figure A-7. Example 2 LOS results tab
Figure A-8. Example 3 segment data input screen
Figure A-9. Example 3 toll plaza data input screen
Figure A-10. Example 3 segment data input screen with automatically added off- and on-ramps
Figure A-11. Example 3 LOS results tab
Figure A-12. Example 3 additional toll plaza results

<table>
<thead>
<tr>
<th></th>
<th>Regular Lanes</th>
<th>ETC-only Lanes</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (mi/h)</td>
<td>148.5</td>
<td>0.0</td>
<td>148.5</td>
</tr>
<tr>
<td>Density (veh/h/ln)</td>
<td>0.8</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Delay (s/veh)</td>
<td>27.1</td>
<td>0.0</td>
<td>27.1</td>
</tr>
<tr>
<td>LOS (based on delay)</td>
<td>A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: If one payment type is oversaturated, this can lead to LOS F for the entire plaza. Make sure there are a sufficient number of lanes for each payment type.
REFERENCES


15. LOS Plan Software, Downloads and Instructions Page. Florida Department of Transportation. 4/13/2012
   http://www.dot.state.fl.us/planning/systems/sm/los/los_sw2m2.shtm
BIOGRAPHICAL SKETCH

Robin Osborne was born and raised in Austin, Texas, where he attended the University of Texas at Austin and received a B.S. in civil engineering along with a minor in physics. He also held four summer internships with formerly PBS&J (now Atkins) working for the tolls group in the transportation division. In August 2010, he began working towards his Master of Engineering degree at the University of Florida in Gainesville and graduated in May 2012. Robin was also a Research Assistant under Dr. Scott Washburn studying toll plaza modeling and analysis and working to implement toll plaza simulation methods into CORSIM. Robin has been a member of ASCE and held an officer position in the UF chapter of ITE.