Operational Analyses of Varied Toll Plaza Configurations

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Introduction
Toll plaza operation is a critical component of roadway operations throughout the United States, as tolls provide both a means of revenue for expansion and opportunity for demand management. Efforts to maximize vehicle throughput and reduce delay has led to the emergence of electronic toll collection (ETC), a paramount solution to congestion reduction at these major highway bottlenecks. While new payment collection strategies have arisen, traditional cash payments are generally still accepted. In turn, ETC has introduced a new form of driver decision making at toll plazas due to payment choices.

Methodology
As documented previous, an impending need has developed to investigate the role of electronic tolling collection configuration on toll plazas. The overall objective of this research is to evaluate issues related to toll plaza configuration and driver decision making resulting from the introduction of ETC toll lanes.

The driver decision making objective strives to understand and model how motorists chose lanes on toll plaza approach. A clear understanding of this behavior may lead to improved designs and recommendations for placement of lanes and configurations to minimize risk and improve overall traffic flow. The role of electronic toll collection lane availability and in what form (dedicated or mixed-use) is believed to have a large role in this decision. Furthermore, the function of lane type may influence weaving movements and other potentially risky vehicle movements. The role of upstream traffic and queue length are believed to have a large influence on the frequency and nature of lane movements. Analysis from these studies aimed to understand how drivers analyze, and act upon information on the approach to a toll plaza.

The intent of the operations-based research objective is to model driver behavior at toll plazas with multiple forms of payments forcing decision making. The stochastic microsimulation software VISSIM by PTV America, Inc. (Planung Transport Verkehr AG, 2008) was selected for its depth of configuration and dynamic traffic assignment features. The model was calibrated based on field data from Exit 4 of the Massachusetts Turnpike and validated with data from the same plaza under a different lane configuration pattern from an earlier time. The operational performance of the toll plaza could subsequently be evaluated under a variety of lane configuration combinations.

Computer-Based Static Evaluation
Driver decision making was identified as a central factor in the design and configuration of toll plazas. A computer-based static evaluation was developed to help determine the decision process of drivers during an approach to a toll plaza. The evaluation provided participants with a photo from the driving perspective shown in Figure 1 and asked them to select one lane to use based on the information they could deduce from that one frame. The static evaluation was created using Adobe Captivate, a learning management software (LMS) with built-in quiz and multimedia capabilities. A within subject design randomly assigned participants as either cash or ETC customers as they approach an interchange and answer a series of lane choice questions based on static photographs from toll plaza scenarios. After fifteen scenarios the participants’ role changed to the other payment method and those same scenarios were administered again.

Fifteen scenarios were presented with varied queue lengths (number of vehicles) at each of the toll lanes, number of lanes, ETC lane placement (left, right, center), and combination of lane type (Manual, Automatic, ETC, Mixed). A total of 30 scenarios (2 of each 15 scenarios) were incorporated into the static evaluation in random order. Each scenario was created by manipulating photos taken from the four-lane toll plaza off Exit 4 of Interstate 90 in West Springfield, Massachusetts on December 20, 2012.

Participants did not know that scenario plaza had a downstream decision point nor were they told which direction they were going downstream of the plaza. Participants answered demographic questions following the evaluation indicating their age, gender, recent driving history, education, toll road experience, and payment method history.

The evaluation was shared with contacts and their acquaintances via a private email link, without a public or directory listing anywhere on the internet. The published evaluation was made available during a 3-week collection period during which 100 responses were gathered.

VISSIM Microsimulation
Based upon the safety and driver decision making analysis, an attempt was made to improve the operation modeling of toll plazas as a function of lane configuration. Unfortunately, VISSIM lacks a built-in toll plaza feature or module. As part of the development stage, steps were made to configure resources of VISSIM to act as control traffic as if a toll plaza were present. Stop signs were used to mimic cash transactions and reduced speed zones imitated ETC lanes. Massachusetts utilizes the interoperable E-ZPass tolling system with Mark IV Industries (now Kapsch TrafficCom) hardware. The West Springfield toll plaza was built in the microsimulation package. Video data was collected in January 2012 and

Figure 1: Static Evaluation Screenshot

Continued on Page 12
analyzed to serve as an input for the VISSIM model. After model development, parameters were calibrated to mimic observed behavior. A visual inspection during calibration looked for weaving, queuing, and minor amounts of unpredictable maneuvers expected at a toll plaza. Following calibration, another toll plaza configuration representing the configuration in January 2013 as seen in Table 2, which was different than the one of January 2012, was built into VISSIM using the calibrated model to compare to actual performance. The validation’s measure of effectiveness target was a 10% or less difference in total throughput of the observed field volumes.

**Model calibration**

The Federal Highway Administration’s Guidelines for Applying Traffic Microsimulation Modeling Software was referenced for guidance in model calibration (Downling et al., 2004). In order to highlight the decision making process explored in proposed models (Correa et al., 2004), origin and destination data were extracted. The interchange of Exit 4 has two entrances and two exits. Exits include one from the westbound direction of I-91 and one from the eastbound direction on the Turnpike. Destinations are the interchange with I-91 and US Route 5. While approaching the plaza, drivers may change their lane choice several times based on traffic demand and future destination. The origin-destination (O-D) information was collected with a two-camera setup as shown in Figure 2. Each vehicle was tracked from their entrance lane, through the toll plaza to their final destination from Camera 1 to Camera 2. Payment method, lane choice, and number of lane maneuvers were noted in addition to origin and destination. This process indicated how many customers of each toll payment method were originating from the east, from the west and their decision at the toll plaza to travel on to I-91 or US Route 5. These tracked vehicles formed an O-D volume matrix and served as the input volumes to the model.

The second calibration parameter was transaction time within the toll plaza boundaries. Transaction time was a form of the processing time at the plaza, but differed because it neglected time in queue and travel time to an exit point. Transaction time was calculated as the time differential between the time from when the front of the car passed the physical toll booth to the time when the rear bumper passed the end of the toll booth and passed the traffic signal displaying green. Transaction time allowed each payment method or lane type to be equitably compared. Brief transaction times commanded supreme time measurement accuracy. Therefore, video was analyzed on a frame-by-frame basis with an accuracy of 1/29th of a second. One hundred transaction times were randomly sampled from each lane from January 2012 video, and were recorded with transaction type and vehicle class.

Distributions and statistics were generated and cumulative distribution figures were plotted from raw data to serve as input for plaza dwell time in VISSIM. Figure 3 below shows the transaction time distributions and mean and standard deviation for cash transactions for both passenger vehicles and heavy vehicles for cash transactions.

The calibration model used 2012 data for volumes, O-D assignment and dwell times. Additionally, several car following model attributes and environmental settings used to tweak the base case model.

Based upon previous research, the 1999 Wiedemann car following model version was selected (Wiedemann, 1991; Russo, 2008). Each of these entities has several configurable parameters. Default values were used for the majority of driver behavior parameters. However, a couple values were tweaked during calibration. The Wiedemann 99 model has 10 parameters of which three were altered to best describe toll plaza activity. Standstill distance was changed to 4.92 feet from 2 feet to represent condensed queuing situations. Headway time was changed from 0.90 seconds to 0.50 seconds based on transaction time observations. Another car following related parameter change involved the number of observed vehicles. Observed vehicle count was raised from 2 to 4 vehicles; this change was consistent with other VISSIM toll plaza models.

Two lane changing parameters were tweaked to calibrate the model. The minimum front and rear headway was lowered from 1.64 feet to 0.5 feet. The waiting time before diffusion was decreased from 60 seconds to 10 seconds. This period of time is defined as the time a car sits waiting for a gap to change lanes in order to stay on its route before it is removed from the network. This parameter helped remove gridlock situations troubling the microsimulation tests.

**Model Validation**

For the process of validating the toll plaza model, video data throughput or collected volumes per lane were used. Individual sensors were placed on toll lanes 1-4 and configured to collect these data in the simulation model. Ten simulation runs were averaged together to obtain the throughput for each lane of the toll plaza, which was compared with the throughput obtained from the video data.

**Reduced Speed Limit Zones**

Reduced speed limit zones allowed the model to emulate ETC lanes. In VISSIM, established...
reduced speed zones override speeds set by vehicle class and link. Restricting speeds provided the natural effect of deceleration behavior of E-ZPass customers who decelerate at plazas. Cash customer vehicle classes were unaffected by these zones. Reduced speed limits used default-desired distributions based on toll plaza speed limits in Massachusetts. Heavy vehicles were assigned a speed distribution between 10 and 18 mph and cars were assigned 15-22 mph. In the case of a combination lane, the reduced speed zones would only apply to E-ZPass vehicles and cash customers would be unaffected by the zone.

**Stop Signs and Dwell Distributions**
Stop signs were used as a means to emulate cash toll transactions. This function of VISSIM was deemed suitable due to the majority of vehicles coming to a complete stop during a manual cash toll transaction. Field data generated empirical dwell distributions were designated by vehicle class to assign varying stop or transaction times randomly upon plaza arrival. Car and heavy vehicle dwell distributions that were used as input in this model are shown below in Figure 4.

**Dynamic Assignment & Discrete Choice Modeling**
VISSIM’s dynamic assignment feature was employed to capture driver decision making based on traffic conditions. Using zones of origin and destination called “parking lots” a discrete choice model can be made to evaluate the shortest paths in real time (Planung Transport Verkehr AG, 2008). VISSIM solves a modified version of the shortest path algorithm and distributes traffic demand based on a logit model.

Prior to route choice analysis, edges in the network were established. VISSIM utilizes nodes to recognize decision points within the network. Each possible combination of edges creates an array of paths from origin to destination zones.

Trips are inputted from a text file containing an O-D matrix. Figure 5 indicates the layout of entrance zones numbered 1, 2 and exiting zones numbered 3, 4 in green font. Nodes are labeled in red in this same figure. Zone connector “parking lots” simply allow vehicles to appear and disappear when they enter or exit the middle of the parking lot. These virtual parking lots have no capacity and take no physical spaces (Planung Transport Verkehr AG, 2008).

The shortest path algorithm iterative process transpires on a user-selected simulation evaluation interval. However, in an attempt to highlight driver decision making on toll plaza approaches where lane choice reevaluation occurs frequently, the lowest value of 10 seconds was used. At the end of each dynamic assignment iteration all travel times of vehicles that exited within the previous simulation interval were successively averaged. The simulation model did not use route tolls or link costs and other parameters of the utility function were not assessed.

**Results**
Initial static evaluation results provided feedback on the most interesting lane configurations that were chosen to be tested with the microsimulation model. Scenarios with distributed lane choices were seen as ideal. Additional alternatives were derived from the review of the literature.

The static evaluation was administered over the course of 3 weeks in spring 2013. One hundred evaluation responses were collected and tabulated. The region of participants was concentrated in the Northeast region of the United States and was solicited in a controlled manner to prevent falsified submissions. Participants ranged in age from 16 to 70 years old, with an equal 50% split of male and female respondents. Educational background of the evaluation pool was 74% college educated, 16% some college, 8% high school degree and 2% no degree. Fifteen percent of evaluation results indicated over 10,000 miles of driving per year, 45% selected 1 to 10,000 miles per year and 40% did not drive at all. Fifty seven percent of participants indicated they are typically ETC users, 33% were cash users and 10% used a mix of both. Eleven percent of the participants were daily toll users, 12% were weekly users, 44% were monthly users and 33% used toll lanes less than 10 times per year.

Results from the static evaluation yielded several lane choice trends. In one scenario, a one-car queue was enough to motivate the majority of cash payment respondents to make lane changes across three lanes. This lane change created a “buffer” or region of safety between the faster moving E-ZPass customers and slower moving cash customers.

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*Figure 4: VISSIM Node and Parking Lot Schematic.*

*Figure 4: Vehicle Dwell Distributions*
In another scenario with dedicated lanes and combination lanes available to E-ZPass customers, preference was given to dedicated lanes. Drivers may be considering the relative transaction time of one E-ZPass customer versus one cash customer. When approaching the toll plaza, combination lanes are enticing but require a second round of decision making that involves weighing the risk of waiting behind a cash customer versus waiting in a queue of slowly moving vehicle(s) such as a tractor trailer in a dedicated ETC lane. While a driver may only wait 5-6 seconds behind a queue on the dedicated ETC lane, he could potentially remain behind a cash transaction for 20-60 seconds. This weighing of travel time benefit to cost is a cyclical evaluation that drivers must make on toll plaza approaches where combination lanes are present. While combination lanes may provide an outlet for vehicles who become trapped in a toll plaza away from their section of payment type lanes, these lanes may be invoking driver inattention.

West Springfield’s Exit 4 of the Massachusetts Turnpike provided the base case for the microsimulation model development and testing of different lane configurations. The base case scenario used December 2012 volumes, O-D data and lane configuration of the plaza. Lane configuration offered two cash lanes on the outside, and two inner dedicated ETC lanes. Average volumes were calculated from 10 simulation runs with different random seeds starting at 1 and increasing by 10 per iteration. The simulation had a 2 minute or 120 second warm up period where no results were recorded, followed by a period of 15 minutes of data collection. Volume throughputs are collected for 15 minutes from the 120 second mark up to 1020 seconds. Fifteen minute values were multiplied by a factor of 4 to compare to industry toll standards for hourly flows. The results from the calibration can be located in Table 1. The microsimulation model resulted in a similar distribution of lane choices. Parameter tweaking resulted in a throughput of 8% lower than the observed.

**West Springfield Prior Configuration Validation**

The toll plaza model validation began by examining the configuration that existed when the first round of video data was collected back in January 2012. During 2012 the plaza’s configuration was modified by the Massachusetts Department of Transportation to remove two combination lanes, and transition to the current configuration of Cash, E-ZPass, E-ZPass, and Cash. Using traffic flow volumes from the base case, the model was retested for performance and operations. The comparison of this configuration to the base case served as validation of the model’s effectiveness. The validation was successful in terms of total throughput volumes with only a 3% difference in throughput as seen in Table 2 below. The distribution of lane choices were different in the simulated case, but overall plaza throughput was within tolerance. The model’s dynamic assignment may have shifted volumes to combination lanes 1 and 4 due to their lower average travel time when cash and ETC vehicle classes are combined in iterative link cost analysis.

**New Configurations**

The research goals outlined the practicality of this research as a tool for toll plaza operational performance prediction. Building off prior configuration scenario results of the static evaluation, configurations of interest were pinpointed for analysis. Stemming from the analysis of static evaluation feedback, several driver decision making concepts were introduced that may be at work in the plaza environment. Among these ideas were the addition of a buffer of one or more lanes between ETC lanes may improve operations as drivers choose to use separated lanes was prevalent. Lane grouping was the second strategy employed in the new configuration development. Moving lanes next to one another may minimize dangerous merging maneuvers. A third strategy aimed to remove driver confusion by allowing ETC and cash payments at every lane. Previous conceptualizations reason that the consequence of opening up these possibilities will be drivers ignoring lane choices based on payment method and will look to queues and preference alone. These cases along with the throughput outcomes of the simulation tests are summarized in Table 3 below. Combination lanes are abbreviated “combo”

<table>
<thead>
<tr>
<th>Case</th>
<th>Lane Configuration</th>
<th>Volume (Vehicles per hour)</th>
<th>Total</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lane 1</td>
<td>Lane 2</td>
<td>Lane 3</td>
</tr>
<tr>
<td>2013</td>
<td>Observed Data</td>
<td>270</td>
<td>390</td>
<td>503</td>
</tr>
<tr>
<td>2013</td>
<td>Configuration</td>
<td>220</td>
<td>368</td>
<td>496</td>
</tr>
</tbody>
</table>

**Table 1: Model Calibration Volumes**

<table>
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<th>Case</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lane 1</td>
<td>Lane 2</td>
<td>Lane 3</td>
</tr>
<tr>
<td>2012</td>
<td>Observed Data</td>
<td>149</td>
<td>189</td>
<td>455</td>
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<tr>
<td>2012</td>
<td>Simulated Data</td>
<td>400</td>
<td>84</td>
<td>212</td>
</tr>
</tbody>
</table>

**Table 2: Model Validation Volumes**

<table>
<thead>
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<th>Case</th>
<th>Lane Configuration</th>
<th>Volume (Vehicles per hour)</th>
<th>Total</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lane 1</td>
<td>Lane 2</td>
<td>Lane 3</td>
</tr>
<tr>
<td>2013 Simulation</td>
<td>Cash-E-ZPass-E-ZPass-Cash</td>
<td>220</td>
<td>368</td>
<td>496</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>E-ZPass-Cash-Cash-E-ZPass</td>
<td>284</td>
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<td>240</td>
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<tr>
<td>Scenario 2</td>
<td>E-ZPass-Cash-E-ZPass-Cash</td>
<td>156</td>
<td>220</td>
<td>324</td>
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<tr>
<td>Scenario 3</td>
<td>E-ZPass-E-ZPass-Cash-Cash</td>
<td>576</td>
<td>304</td>
<td>200</td>
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<tr>
<td>Scenario 4</td>
<td>E-ZPass-Cash-E-ZPass-Cash</td>
<td>188</td>
<td>228</td>
<td>160</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>E-ZPass-E-ZPass-Cash-Cash</td>
<td>368</td>
<td>108</td>
<td>164</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>E-ZPass-Cash-Cash-E-ZPass</td>
<td>364</td>
<td>208</td>
<td>336</td>
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</table>

**Table 3: Microsimulation Alternate Configuration Results**
in the scenario comparison table. Percent change as referred in the table, highlights the difference in percentage of total throughput of each scenario as compared to the base 2013 simulation case.

Scenario 2 configuration provided the lowest plaza throughput as a whole, while the all combination lane configuration, scenario 6, provided the highest throughput of all alternatives. The current configuration remained the one with the highest throughput result compared to all other configurations tested.

Conclusions
Toll plazas, while designed to be an undemanding and forthright revenue generator, are often times vastly unpredictable and make driver behavior difficult to understand. Driver decision making scenarios were designed and tested with a static evaluation to gain insight into how drivers react to alternate configurations. Observations from the static evaluation scenarios indicated drivers took efforts to minimize their time in the plaza and their overall travel times. Even a small queue of one car can provide motivation to maneuver to open lanes. Combination lanes that accept multiple forms of payment help disperse demand in peak hour situations. Additionally, they provide opportunities for unfamiliar drivers to utilize any lane for their transaction. However, added ETC payment users to lanes that serve cash customers degrade the level of service and increase delays for both types of drivers. Motorist mental workload may increase as they scan more lanes for the shortest path. ETC customers may be calculating the risks of falling behind a cash customer by choosing a combination lane with a queue versus a several cars in an ETC lane. The type of vehicles queued may also be guiding driver decision making. In more than one occasion drivers avoided queued heavy vehicles in both cash and E-ZPass exclusive lanes. Drivers seem sensitive to these slower moving vehicles and anticipate a longer transaction time. Consequently, motorists will go out of their way to avoid heavy vehicles such as tractor trailers even if it means joining a queue of two to three cars. All vehicles, when given the opportunity, spring for a buffer from queued lanes. Cash customers are perhaps more aware of the speed differential and add space between their vehicles and their ETC payment counterparts.

Using the feedback from the static evaluation, six other lane configurations were simulated using the December 2012 volume and O-D data. Scenario 3 with grouped payment lanes from the static evaluation provided the best overall performance with less than 1% difference from the baseline case. However, the currently configured plaza with exterior cash lanes and central E-ZPass lanes was verified by the simulation model to provide the highest plaza throughput.

The model represents driver confusion well, often times a driver will advance to a toll booth, unbeknownst that their payment method requires them to wait in the queue they just bypassed. In several simulation runs, decision guidance allocated vehicles properly in a manner that would most likely represent field traffic demand. From both observations of simulation and field video, weaving degraded overall plaza performance.

The VISSIM model developed in the process of this research could be a useful tool for toll authorizes and transportation agencies in the design or retrofit of toll facilities. The model could be improved for wider applicability in the analysis of different demands, origin-destination distributions, and other toll plazas to test their operational performance. The benefit to this continued research is the importance of toll plaza efficiency and realizing the best use of existing infrastructure.

References
New England Section of the Institute of Transportation Engineers

**Vermont State Chapter**

President: Jennifer Conley, P.E., PTOE

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President: Michael Morehouse, P.E.

Report Submitted by: Craig D. Yannes, P.E., PTOE

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This event was sponsored by NuCor Steel, Tighe & Bond, Fuss & O’Neill and VN Engineers, Inc. A total of 48 golfers grouped into 12 teams participated in the event which was played in a scramble format over 18 holes.

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Continued from Page 15

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