2013

Operational and Safety-based Analyses of Varied Toll Lane Configurations

Ian A. Mckinnon
University of Massachusetts Amherst, ianamckinnon@gmail.com

OPERATIONAL AND SAFETY-BASED ANALYSES OF VARIED TOLL LANE CONFIGURATIONS

A Thesis Presented

by

IAN A. MCKINNON

Submitted to the Graduate School of the

University of Massachusetts Amherst in partial fulfillment

of the requirements for the degree of

MASTERS OF SCIENCE IN CIVIL ENGINEERING

May 2013

Department of Civil and Environmental Engineering

Transportation Engineering

OPERATIONAL AND SAFETY-BASED ANALYSES OF VARIED TOLL LANE CONFIGURATIONS

A Thesis Presented

by

IAN A. MCKINNON

Approved as to style and content by:

____

Michael A. Knodler Jr., Chair

____

John Collura, Member

____

Eleni Christofa, Member

____

Richard N. Palmer, Department Head
Department of Civil and Environmental Engineering

DEDICATION

This thesis is dedicated to my parents, Andrew Ian and Helen Qualey McKinnon for their unending love and support throughout my life. It is through their persistence and value of education that afforded me the determination to seek this degree, and continue the pursuit of knowledge.

ACKNOWLEDGMENTS

I extend my sincere gratitude to my advisor Dr. Michael A. Knodler Jr. for his guidance and encouragement throughout this research. I thank him for him sharing his passion for transportation and the many ways he prepared me for the professional world. I would also like to thank my committee members Dr. John Collura and Dr. Eleni Cristofa for their esteemed feedback and confidence in my work.

Special thanks to my fellow Traffic Safety graduate students, Cole Fitzpatrick and Keith Wenners. The three of us were nearly inseparable for two years through which we learned much from one another and relished in laughter for which I will never forget.

Additionally, I'd like to thank the following people for their contributions to this research work: Jennifer Kennedy, Robin Reissman, Jeffrey Young, Andrew Paul, and Bill Moosey.

ABSTRACT

OPERATIONAL AND SAFETY-BASED ANALYSES OF VARIED TOLL LANE CONFIGURATIONS

MAY 2013

IAN A. MCKINNON,

B.S.C.E., UNIVERSITY OF MAINE

M.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Dr. Michael A. Knodler Jr.

Toll plaza operation is a critical component of roadway operations throughout the United States, as tolls provide both revenue for expansion and opportunity for demand management. Originally cash or physical currency based, tolling has morphed to meet the twentieth century demand in terms of throughput and efficiency in the form of electronic toll collection. Electronic tolling has introduced a new form of driver decision making at toll plazas due to the additional payment choice. Despite the user convenience these facilities provide to consumers, this form of collection has not come without safety and operational concerns. Confusion at the toll plaza, unsafe merging maneuvers, and the unexpected behavior has actually increased certain crash patterns at toll plazas in some electronic tolling facilities. Building upon existing research, further work was completed to quantify the related impacts of electronic toll collection on traffic operations through a microsimulation model, and static evaluation study.

While in Massachusetts overall toll plaza crashes are a minimal portion of 200,000 crashes each year in the Commonwealth at less than 0.1 percent of all crashes some toll plazas have higher crash rates than the state wide urban interstate average.

Interchange 14 in Weston, Massachusetts had the highest crash rate among state toll plazas. Rear-end and same direction sideswipe collisions accounted for the highest crash numbers between the years 2010 and 2012.

Microsimulation of various lane configurations derived from static evaluation feedback on driver decision making created six alternate configurations. Current plaza configuration was verified by the validated VISSIM microsimulation model to be the highest performing in terms of efficiency. A lane configuration with grouped payment lanes provided the best overall performance for alternatives with less than 1 percent difference from the current West Springfield interchange configuration.

Static evaluation and microsimulation results pointed to increased efficiency and safety benefits with combination lanes. Additionally, drivers tended to avoid following heavy vehicles through plaza lanes. Motorists were willing to make up to 3 lane changes to avoid queues and may avoid combination lanes as an electronic toll customer if they anticipate a greater delay than an adjacent dedicated electronic lane.

Recommendations for future research include: 1) further microsimulation modeling to examine traffic flow and safety impacts at toll plazas under varying traffic conditions and demand with open road tolling lanes strategies; and 2) developing enhancements to VISSIM to address parameter limitations associated with discrete choice modeling at toll plazas.

TABLE OF CONTENTS

LIST OF TABLES

TABLE Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Tolling has long been utilized to pay for roadways both public and private. The modern interstate system in the United States was conceptualized in the 1940's but was not prioritized as a major commercial conveyorbelt until the Eisenhower administration. Since then the national interstate highway system has provided access for moving products, services and people to the far corners of the nation. In recent years, with concerns of congestion and pollution, tolling has found another use as a way to balance roadway systems and deter users from congested urban centers.

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. According to 2007 statistics from the Federal Highway Administration (FHWA), state and, tolling agencies generated $9 billion in toll revenues per year (1). What was originally cash or physical currency based tolling, has morphed to meet the twentieth century demand needs while occupying the same similar physical footprint. Efforts to maximize vehicle throughput and reduce delay has lead 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. Additional research is needed in the domain of the safety and operationas of ETC equipped toll plazas.

1.1 General Toll Plaza Operation and Configuration

By means of an introduction to the topic being proposed within this thesis, it is important to first have a basic understanding of general toll plaza operation and configuration. The general operation and configuration of a toll plaza is based upon basic elements that may differ across various plazas, including the following:

- Plaza type;
- Lane types;
- Electronic tolling technology hardware; and,
- Electronic tolling technology software.

1.1.1 Plaza Types

Since the 1960's a barrier toll plazas have made up the majority of interchange installations. As shown in Figure 1, these plazas are typically located on the freeway itself and require a fare in order to proceed on the highway. These tolls are typically flat fee (by vehicle/axle type) to continue on to the next segment of the highway. Some barrier toll systems allow free movement between some exits. In some cases unrestricted access is implemented for intercity facilities where real estate is limited. Toll plazas are often located at the boundaries of urban areas and charge to enter the city from rural and suburban areas. The other type of toll facility, known as a ramp plaza, requires a toll to enter and exit. These tolls are most frequently distance based tolls, meaning the motorists receive a ticket upon entering and pay a toll upon exiting that is related to the distance traveled (2).

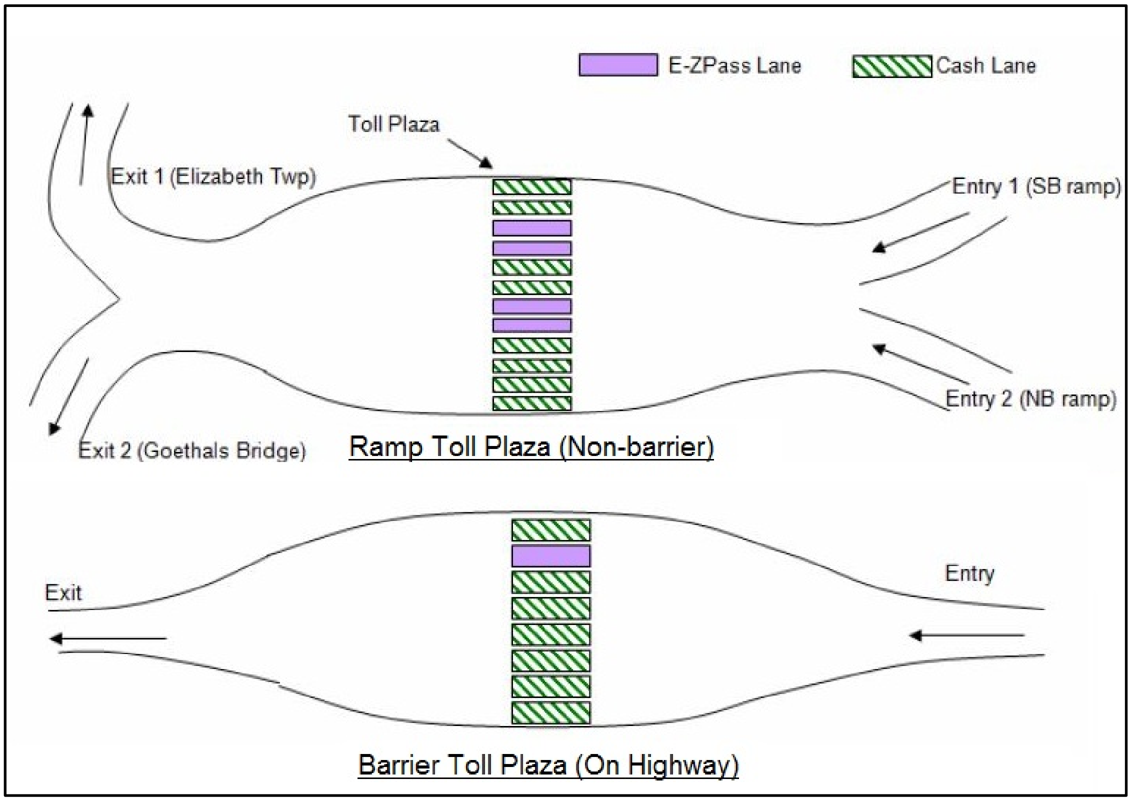


Figure 1: Toll plaza types (3).

1.1.2 Lane Types

There are five general types of toll plaza lanes in use today within the United States. The most basic lane type is the traditional cash lane where a toll attendant collects a fare physically in the form of currency. This method, while still used today, is a costly and time consuming form of fare collection. In hopes of automating the collection process, automatic coin counting machines were developed to reduce personnel costs and increase throughput. The next advancement in toll collection came in the form of electronic toll collection with transponders. ETC tolling was originally referred to as automatic vehicle identification (AVI) because transponders have unique serial numbers that link to a patron's pre-paid account (4). The vast majority of ETC lanes are exclusive, meaning only transponder subscribers are allowed to utilize those lanes. A hybrid of

ETC and cash lanes are referred to as combination or mixed use. These manned booths help reduce complications such as the serious hazard of a motorist backing up during arrival at the collection station in the wrong lane. The final category of electronic collection lanes are termed express because they require minimal to no deceleration allowing fare transactions at high speeds. Express lanes are loosely defined as a segregated expressway for electronic toll users. Known more commonly as open road tolling, express lanes are the most transparent form of tolling as they do not require motorists to exit the highway or reduce speed. Often plazas with express lanes will also have dedicated lanes in the plaza for motorists who miss these separate lanes (2). Electronic tolling lanes have substantial fare processing capacity over manual lanes as seen in Table 1. Electronic lanes only accept payments from ETC equipped vehicles and fine violators through a process of photographing license plates.

Table 1: Plaza Lane Types (5)

	Operational Toll Attributes		
Tolling Lane Types	Collection Method	Average Lane Speed (miles per hour)	Throughput (vehicles per hour)
Cash	Manual Attendant	Stop	300
Automatic	Manual Machine	Stop	500-600
Combination	Manual & Electronic	7	700
Dedicated	Electronic	15	1200-1500
Express	Electronic	55	1800-2200

1.1.3 Electronic Tolling Technology

Electronic tolling utilizes several robust hardware and software systems to enable accurate and reliable toll transactions. Utilizing wireline and wireless communications transactions originate at the toll booth and transmit information to a toll authority’s clearinghouse and eventually the customer’s financial institution.

1.1.3.1 Hardware

Electronic Tolling systems use a series of interconnected wireless and wireline communication devices to facilitate automatic vehicle identification (AVI). Transponders or tags are Radio-Frequency Identification (RFID) units that serve as the basis for modern electronic tolling. These devices communicate using Dedicated Short Range Communication (DSRC) to the toll reader system which registers identification and completes toll transactions.

1.1.3.1.1 Antennas

Emitters or antennas are the medium through which DSRC functions and exchanges identification from the passing vehicle to the stationary toll system. Antennas are connected to a lane controller to prevent transaction duplication. Additionally, the lane controller coordinates operations with the axle counter and vehicle enforcement system. Computer servers located on site function as a database and processing unit that connects and records transactions with the turnpike authority and financial institutions. Due to this important role, multiple redundancies are typically employed in nearly every function, (fiber optics, transmitters, and power supplies) at the local and regional level.

1.1.3.1.2 Transponders

Transponders operate on the 915 MHz radio frequency with an operating range of 32.5 feet. Transponders communicate with antennas using DSRC in a cycle of exchanging ID information and confirmation that lasts sixteen milliseconds. The device attempts to "handshake" ten times before the device is ignored.

1.1.3.1.3 Axle Counters

Axle counters are electronic circuits shaped in a loop located under the roadway used in violation enforcement and vehicle classification. The counter detects number of axles which is used to adjust vehicle classification and fares accordingly. In its violation enforcement role, the loop triggers cameras used to capture license plate photos used to process transponder misreads or violators.

1.1.3.1.4 Vehicle Enforcement System

Cameras take still photographs from the front and rear of each vehicle upon loop trigger. The redundancy of photographs prevents non-paying vehicles with only one license plate or those tailgating to escape through the lane unaccounted. The system takes pictures and reads RFIDs simultaneously regardless of traffic density, and speed. In mixed-mode or exclusive ramp lane setups, one antenna is used per lane. In express or open road tolling (ORT) lanes, multiple antennas will be mounted to capture shoulder and mid lane transactions. In open road tolling, antenna systems are more sophisticated to detect cars that may pass under in multiple lanes (6).

1.1.3.2 Software & Violator Services

Violator enforcement uses an image processing technology known as optical character recognition. The system converts license plate photographs to a text string and compares this registration number to the Registry of Motor Vehicle (RMV) database. Success of the enforcement system relies on license plate standardization and cooperation from RMV/DMVs nationwide (7). License plates must use similar font type, size, background contrast and reflectivity. Specially designed software automates this tedious process that must keep up with a log of thousands of potential violations every day.

Current systems can accurately identify over 98 percent of license plates without the need of human review.

According to a 2009 Massachusetts Department of Transportation (MassDOT) report, FastLane, the name of Massachusetts E-ZPass compatible ETC system penetration has reached 75 percent around the Boston metropolitan area (8). A high usage rate suggests toll lane configurations should be analyzed for optimal efficiency and safety. The number of patrons using electronic tolling could prompt a change in the number of E-ZPass lanes to provide convenience and access to the large portion of commuters. This large segment of users has spurred an investigation into its role in toll lane selection.

1.2 Problem Statement

The emergence of ETC has resulted in an array of challenges at toll plazas in the United States. The introduction of electronic toll collection has become increasingly widespread at tolling facilities throughout the United States as a result of documented benefits associated with its implementation. Toll operators laud ETC's efficiency, accuracy and cost effectiveness, while consumers enjoy the convenience and ease of use (9). Investments in ETC often have short return on investment periods due to their low cost per transaction and high levels of lane throughput. The advent of ETC lanes prompted agencies to slowly migrate more lanes over to this technology. Despite the user convenience, these facilities have introduced some additional challenges. Confusion at the toll plaza, difficult merging scenarios, and the unexpected behavior has actually increased certain crash patterns at toll plazas (4). The toll plaza environment is often blanketed with dozens of signs, fast lane changing, and toll plaza employees, among other environmental inputs that force the driver into increased cognitive workload.

Mixed use lanes, express lanes, and dedicated lanes vary from tolling agency to tolling agency with no standardization as to which lanes allow certain types of traffic (2). Toll plazas are often situated at the junction point of major arterials and highways where accidents and queues pose major safety and congestion concerns. Despite this challenge, research quantifying the various aspects of toll plaza operations and safety has been somewhat limited in scope. The history of ETC implementation occurred on a trial and error basis by tolling agencies, and while "lessons learned" have been shared, standardization remains deficient. More specifically, there is a need to expand upon existing research to further quantify the related impacts associated with toll plaza configurations. There is a need for research that explains how the use of different lane configurations, number of lanes, and placement of lanes affects both safety and operations in or around toll plazas. The research documented herein was developed to identify a methodology for identifying the root cause of safety issues at toll plazas by evaluating field work data coupled with elements of driver decision making processes from laboratory experiments. Furthermore, the research attempted to model driver behavior at toll plazas and to investigate the operational aspects through field observation.

1.3 Scope

Although there are many aspects of toll plaza operation that require additional research, the scope of the research effort was to examine configurations and driver behavior at current Massachusetts toll facilities. Specifically, the West Springfield plaza, which is exit 4 of the Massachusetts Turnpike and presented in Figure 2, developed special interest due to its unique configuration of combination, manual cash and dedicated E-ZPass lanes. The plaza had a crash rate of 0.71, above the average for urban interstates in the year 2010. Approaching the plaza from the south are the off ramps from I-90 westbound and I-90 eastbound. Existing to the north of the interchange, are connections to Route 5 and I-91. The interchange has short merging zones of approximately 200 feet on either side of the plaza booths. Exit 4 served as a basis for a number of additional plaza cases that were used to understand lane decision behavior and overall toll plaza operations.

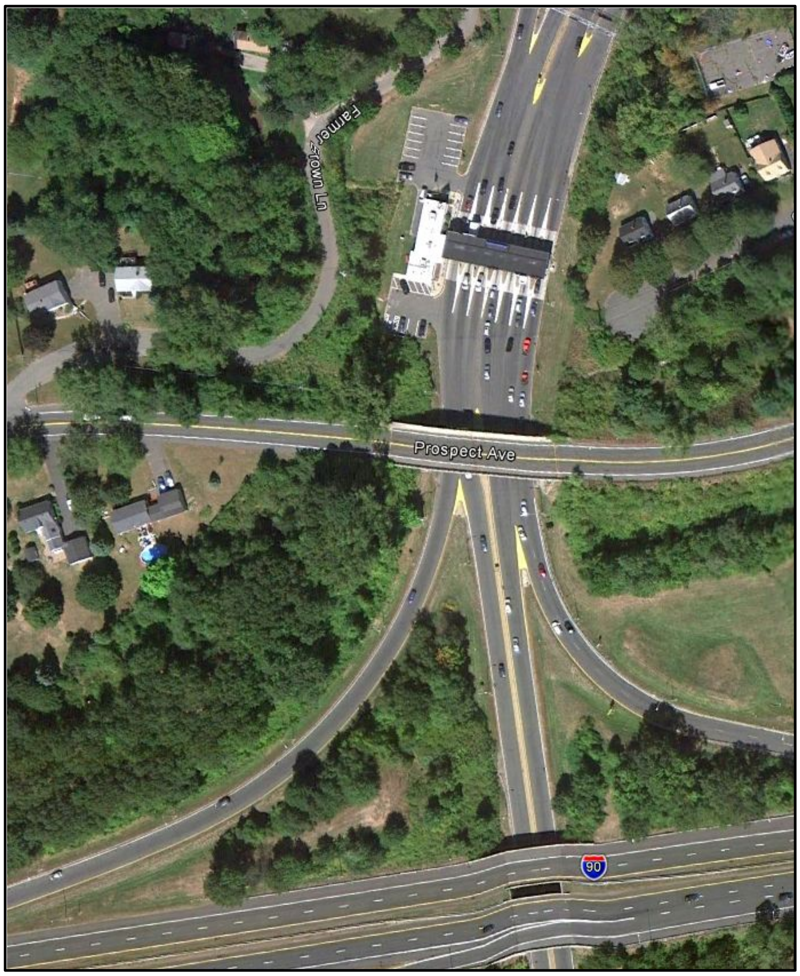


Figure 2: West Springfield Massachusetts Turnpike Exit 4

CHAPTER 2

BACKGROUND

The toll plaza environment is in many regards one of more complex and demanding places to drive in terms of safety and motorist involvement. Vehicles approach at high speeds and decelerate at various speeds while merging and scanning for signage and toll lanes. In order to understand the intricacies of toll plaza operations, a review of current and past literature was compiled. Studies highlight driver decision making, signage, lighting give light to the vast amounts of sensory information and methods of payment. Simulation efforts with ETC equipped toll environments have revealed the theoretical performance and introduced behavior models to hopes to replicate and predict real world events. The following background is by no means an all-encompassing review electronic tolling safety and simulation but should provide a backdrop for the research proposed herein.

2.1 Toll Plaza Safety Research

The field of toll plaza safety in regard to electronic tolling is relatively undeveloped. Several federal documents detail current engineering procedures, but much research is needed to explore geometries, lane layout and the role ETC has on safety and operations (9). There have been studies applauding the safety benefits of retrofitting toll plazas to main-line quasi-open road tolling express lanes. By definition open road tolling is exclusively electronic payments with no plazas. One study encountered a 49 percent crash reduction in segregated express lanes after competition (10). However the same study found an increase in crashes after dedicated ETC lanes located in plaza were implemented. Using an average injury crash cost of $50,512 and property damage cost of

$300, project evaluation criteria and monetary safety savings were calculated. Express lane implementation saved $107,000, roughly two accidents avoided across six converted in plazas in a one year period.

Contrastingly, a 2007 report of the New York State Thruway Authority crash records showed an increase in ETC related crashes as ETC penetration increased from 1992 to 1998 (11). Crashes on an Orlando Florida expressway doubled after installing dedicated ETC lanes. The crash rates involving dedicated ETC lanes and/or ETC vehicles rose from 3.375 crashes per month to 7.5 crashes per month. At the same toll facility, rear-end crashes increased as a result of a adding a dedicated ETC lane. Not even a year later a second adjacent ETC lane was installed, and again rear-end crash frequency increased. Speed was the leading cause of conflict and the culprit in raised accident rates. Prior to toll plaza renovations speed variance was low, but after construction velocities noticeably escalated (4). These results provide strong support to the idea that decision making spurred by ETC lanes may spark conflicts at toll plazas that are leading to additional accidents.

A study conducted at a busy Hong Kong tunnel plaza investigated the benefits of an improved signage scheme. A before and after study revealed average travel time decreased for ETC users by 18 percent and increased by 30 percent for cash customers. Reflective lane markings and improved gantry signs led diminished average lane-changing rate by 23 percent. Further discoveries showed a 40 percent reduction in conflicts as a result of improved lane searching (12).

Simulation and modeling has been a popular area of research that seeks to understand driver decision making and verify their assumptions through field studies.

Microsimulations developed of the San Francisco Bay Bridge suggested a large need for congestion treatment. Nearly all studies have evaluated approaching zone conflicts, but could diverging zone crashes be the result of deficient toll operations. A simulation was built based on a metered toll plaza design to alleviate the post plaza merging zone. The policy eliminates one of the trapezoidal regions of merging, allowing free flow speed to resume directly after the toll plaza. Compared to the control case, the simulation resulted in a drop of average vehicle delay of 96 seconds per vehicle per kilometer. While not entirely transferrable to real world implementation because of a flaw in this particular microsimulation which causes the assignment of traffic to the shortest plaza queues, the results are noteworthy to safety as it removes one zone of merging (13).

Another model, TPSIM, built by Correa et al. (2004) was able to reproduce typical toll plaza operations with lane decision based on queue length (14). This stochastic model was created to simulate the Holland East Plaza seen in Figure 3.

The deterministic toll plaza software SHAKER created by Florida Department of Transportation outputed most efficient plaza configurations by assigning approaching traffic to shortest queue lanes (15). TOLLSIM toll plaza model, developed by Wilbur Smith, now CDM Smith, estimates traffic characteristics such as delay and queues at a plaza (14).

Few studies have developed toll plaza microsimulations with widely available traffic simulation programs (AIMSUN, VISSIM, Paramics, CORSIM). The model produced by Mudigonda et al. (2008) revolves around maximizing user utility based on three parameters for ramp plazas was programmed into an API by Nezamuddin (16). The model validated mainline plazas on Orlando Orange County Expressway Authority

(OOCEA) toll facilities. The study found success in modeling field observations with correlating lane assignments on the order of 0.98 (3).

Fuller et al. worked with CORSIM developers to add a toll plaza module to CORSIM version 6.3 (17). CORSIM models in the past had used Stop and Yield Signs to emulate cash and manual payemnts. Previous attempts at modeling were deterministic and used shortrest queue for lane determination.

VISSIM toll plaza simulation was configured using OOCEA mainline plazas with substantial success (18). Russo (2008) created a deterministic model that used stop signs as cash lanes and reduced speed zones for dedicated ETC lanes.

A laboratory driving simulator study in Illinois compared seven experimental open road tolling signs. The simulation collected driver reaction and comprehension time for a series of proposed signs. Participants were assigned a role as a cash or ETC customer and drove through a toll gantry with the freedom to change lanes without repercussions. Conflicting results did not clearly pinpoint an optimal sign layout but eliminated options for the subsequent field study. The driving simulator proved to be a cost effective method of trial and error (19).

The majority of the remaining research and best design techniques have been at the federal toll agency level. These reports incorporate the lessons learned from the trials and tribulations of different toll systems and their treatment attempts. The FHWA has released two documents based on inputs from agencies around the US, in order to share and rank their strategies for mitigating certain areas of toll plaza safety risks (20). Another U.S. Department of Transportation document highlights toll plaza planning and design to incorporate safety considerations when including Electronic Tolling in new construction (2). The NHRCP Toll Plaza Design guide highlights a need to investigate ETC lane control in order to reduce motorist risk and improve operations at dedicated and mixed use (9).

2.1.1 Driver Decision Making

The design of toll plazas plays a significant role on driver's decision making while advancing in these highway environments. As drivers approach toll facilities, they naturally search for the optimal lane choice, which can result in slower traffic flow and inter-vehicle involvement. Rational drivers, those with average skill and self-interested driving behavior, arrive at a merging zone with the assumption that all lanes have equal merging performance. During off-peak periods, drivers can make their lane decisions farther upstream and move sooner as there are minimal queues. During peak hours, queues develop with very different lengths, leading to frequent jockeying for shorter queues near the tollbooths, with greatly increased risks for accidents (20). Queuing, paired with distracted lane searching drivers, may result in increased rear-end collisions. The most common crash types at toll plazas are classified as 40 percent rear-end collisions, followed by 25 percent sideswipe, and 22 percent fixed object (4). These accidents are the expected consequence of frequent lane changes and deceleration as motorists pick a toll lane. Sideswipe collisions occur most often in the left and center lanes, closest to the centerline, and can be accredited to merging maneuvers (21). Toll lane selection is summarized by the process of users searching for empty lanes, shortest queue lengths and their desired payment lane type (11). This process is exacerbated by the brief period of time allotted for drivers to settle on and enter a plaza booth. The underlying safety issue regarding driver decision making is based upon the high risk of lane merging during toll plaza ingress and egress.

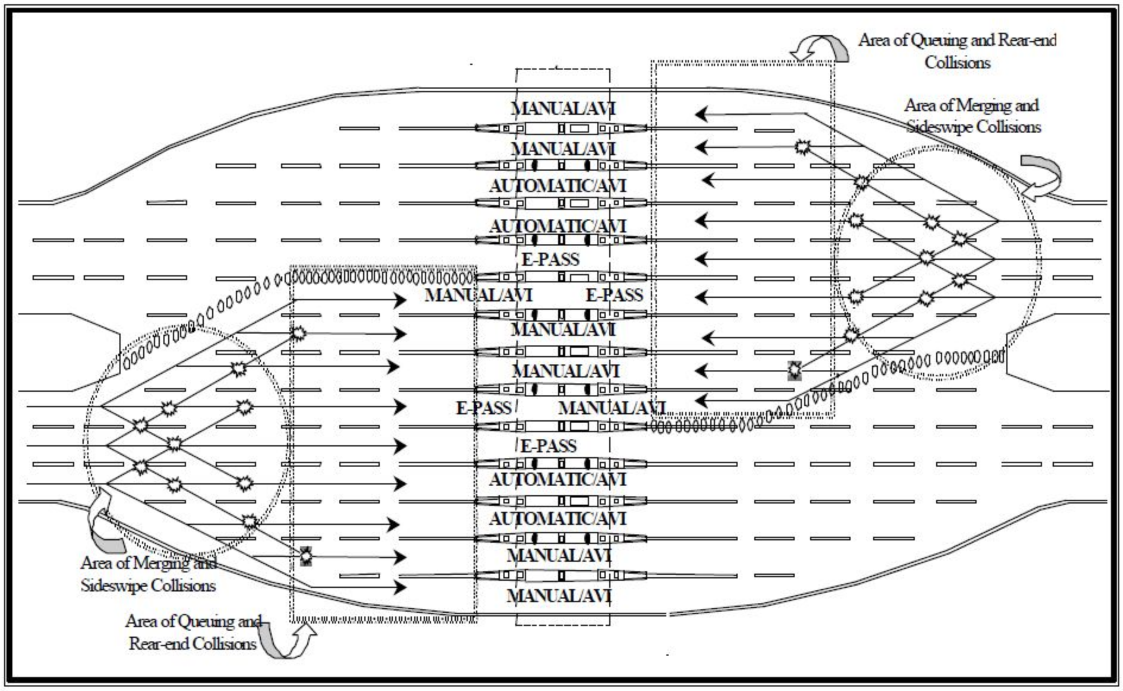


Figure 3: East Holland plaza configuration and conflict areas (14).

Crashes may involve not only vehicles but property and pedestrians as well. ETC lanes are responsible for more crashes involving infrastructure damage to plazas and barriers than cash lanes. Most pedestrian accidents may be attributed to ETC lanes, in particular combination lanes that allow cash and electronic tolling methods where toll-workers are present. Sources of these collision varieties are believed to be excessive vehicle speeds (11). Widening of ETC lanes may reduce potential property damaging collisions (4).

2.1.1.1 Driver Confusion

Toll plazas are naturally complicated environments to drive in. Unfamiliarity with signs, moving and lane-changing vehicles, and varying lane configurations produce a stressful and tiring driving experience. This issue is only intensified when users cannot expect to find any of these factors standardized between tolling agencies, toll plazas, or time of day. This wide array of visual inputs often times may simply be overloading the individual sensory capacity, and leading to human error. This disorder often causes erratic movements that lead to conflicts and events. Conflicts occur when more than one vehicle wants to occupy the same space at the same time (22). If serious enough, these interactions may results in side-swiping and rear-end collisions with other cars, infrastructure or even toll-workers. The largest source of driver confusion cited by toll operators is the unacquaintedness of some drivers with dedicated ETC lanes. Drivers often get stuck in these lanes and attempt to backup, or even worse, exit their vehicles and attempt to pay manual toll booth attendees. These situations are of high concern as they may impact not only themselves but other drivers and may trigger a shockwave of potential conflicts. To combat confusion, toll operators attempt to explicitly state which lanes are ETC only well in advance of the plaza through signage. In cases where lanes are reversible or lane openings change, electronic message boards are utilized to provide current lane availability (20). Other agencies have found success in eliminating violation warning signs and replacing them with commands to stay in the vehicle.

2.1.1.2 Sensory Overload

The source of many driver confusion problems and the primary hindrance to driver decision making can be attributed to the bombardment of sensory information.

Drivers are forced to recognize, read, interpret and act upon the many messages and signals in their environment when driving. The Perception-Interpretation-Emotion-Volition (PIEV) time, is the period required for signal detection, processing and action (2). Signage drastically increases at tolling junctions and is often a source of excessive distraction when drivers should be spending mental resources monitoring the changing velocities of other vehicles and making toll lane choices. While intended to provide the motorist with information, signs can often strain driver attention. To reduce the chances of overload, state agencies have attempted to limit the number of signs, simplify them, and move signs to make their interpretation easier. The recent push by the Manual on Uniform Traffic Control Devices (MUTCD) is to utilize symbols and language understood by all. Standards have necessitated the removal of complicated language, electronic tolling brand names and advertisement (20).

Other sources of distraction that plague not only toll plazas but all places where driving occurs include cell phones, radios, maps, food and drink. Driver distractions when combined with the multitude of sensory inputs at tolling facilities have the severe tendency to result in accidents. If not preoccupied with these factors, ETC users who "wave" their transponders can equally be inattentive to traffic. Often, by choice or misunderstanding, drivers neglect to mount their ETC tag and attempt to hold them up or physically gesture with them (20).

2.1.2 Sensory Information on the Roadway

User generated distractions remain a serious concern for driver concentration, but information in the environment exacerbates the strain on a motorist's mental capacity. Roadway signage, lighting and pavement markings are all road features designed to facilitate safe and convenient driving. However, while intended to assist travelers, these roadway solutions may be too numerous and consequently have a degrading effect.

2.1.2.1 Signage

Road signs are an integral medium for conveying road information to all drivers. Advanced signage helps to minimize weaving and disruptive lane changes prior to plaza arrival (2). While many frequent route users may ignore signs on their routes, toll plaza signage varies with traffic conditions. Many tolling facilities alter lane use, or utilize reversible toll booths to mimic traffic demand associated with commuters and special events. The need for current information places increased necessity for accurate and well-designed signage. Toll plazas are confusing environments, especially for new or foreign drivers. Signaling upstream is crucial to relieving confusion and providing lane assignment information before arriving at a plaza. Agencies must balance the need for operational information and warnings with user overload to improve safety.

Recent trends have shown a decrease in toll plaza signage in hopes of reducing sensory clutter (2). The Port Authority of New York and New Jersey (PANYNJ) has implemented not only signs to direct ETC customers to the left but also messages to guide non-ETC customers to the right in hopes of preventing their erratic lane changing behavior (20).

The MUTCD has a plethora of recommended and required signage designed to improve toll operations. The color purple has been assigned to represent information related to ETC. Regulatory signs and those that indicate lane restrictions must be provided over the respective lane in the form of a gantry banner sign. ETC lane speed limit signs are required when dedicated lanes are contained in the same plaza as other payment lane types. Toll rate signs must be placed upstream of the plaza but following the initial plaza warning sign. Simplification of sign terminology is a growing strategy to build user familiarity. Signs indicating cash lanes may only use the terms “FULL SERVICE”, “CASH”, “CHANGE”, or “RECEIPTS”. Signs for automatic lanes use the message “EXACT CHANGE”. Advance conventional plazas must utilize at least one sign warning an upcoming facility. An important tactic for combating late merging is relating lane assignments effectively. Lane positions must be relayed at least a ½ mile in advance and use the terms “LEFT LANE(S)”, “CENTER LANE(S)” and “RIGHT LANE(S)”.

Toll plaza canopy signs must be attached above each toll booth entrance to show acceptable payment types and applicable restrictions. Dedicated ETC lanes must also have a set of flashing beacons at the bottom of the each lane sign. ETC program contact telephone and web address information signage is prohibited on highways (23). Overhead circular lane signals indicate lane closures. Red signal heads or an X is universal for a closed lane and green or an arrow down indicates an open lane. On ETC lanes a feedback indicator sign, known as a patrol toll display, reveals account status or transaction success (9). Feedback signs serve as a form of natural metering as patrons innately wait momentarily to verify their transactions.

Types of Toll Plaza Signage

- Lane designation
- Speed Limit
- Stop signs
- Toll Rate

- Pay Toll/Take Ticket Warning Sign (May contain mileage info)
- Pay Toll Plaque (above/below guide signs)
- Last Exit before Toll Warning Plaque
- Route Signs
- Non-toll to Toll highway Auxiliary Signs
- Toll Plaza guide signs
- Toll Plaza Canopy Signs

2.1.2.2 Lighting

Safety concerns are intensified at night and lighting is integral for providing motorists the contrast they need to detect sensory information. Luminance, like the merging zone, transitions the motorist for the conditions at the toll booth. Lighting should be placed to avoid sign glare and emulate equal levels of light in the plaza itself. Standard pole height of 30-50 feet tall should allow for a minimum 20 foot-candles (light intensity equal to one lumen per square foot) around toll lanes (9).

2.1.2.3 Pavement Markings

Toll operators utilize several traffic control devices to augment and shift travel lanes into the merging zone and to direct vehicles into lines sooner. Lane lines designate booth entrances and help arrange queues accordingly. Logos and painted text often compliment roadway signage in designating lane collection method. Another form of booth designation, known as gore or bullnose stripping, precedes lane lines as a painted extension of the toll island. A third form of pavement marking, known as transverse markings facilitates speed control as vehicles approach the payment junction (9). Pavement markings while effective as signage are unfortunately subject to wear, and blockage by snow, ice and queuing vehicles (2). These treatments are only one aspect to the overall toll plaza design.

2.1.3 Modeling Driver Behavior

Modeling driver decision making at toll plazas have evolved over the years from queuing models to full scale microsimulation models. Simulations can provide an in-depth look into how traffic operations may perform in a real environment within accurate geometries and adjacent network traffic. The difficulty of modeling is perfecting the very erratic nature of human decision making at the toll plaza. Several studies have found some success in attempting to understand how humans make these difficult questions in a time-dependent, stressful environment.

2.1.3.1 Barrier Plaza Simulations

Cash lanes that overspill merging zones may block ETC lanes and reduce all forms of tolling according to a simulation by Astarita et al. (2001). In this simulation two parameters were used to model driver decision making, queue length and number of cars in the current lane. This model was the first to introduce driver aggression and accounted for how close to the toll station a motorist was willing to make a lane changing maneuver. One omission to the model is the lack of adjacent vehicle interaction (24).

2.1.3.2 Non-barrier Plaza Simulations

A model built by Mudigonda was an extension of the work completed by Astarita et al. (2001) on discrete choice models based on utility maximization (3). Mudigonda made some additional assumptions in his model of ramp plazas. He assumed drivers would opt for lanes closest to their origination lane and that naturally drivers tend to avoid unnecessary weaving movements. Conversely if drivers are aware of exit ramp directions, they may weigh lane choice off exit or desired downstream lane as well. Three factors were considered in the model were travel time, path length, and queue length; a decision criterion estimated from motorist experience and perception (3). Another advantage built into the New Jersey Turnpike Plaza model Mudigonda devised is the influence of decision reconsideration. Drivers do not typically make one lane choice decision and commit to it through the entire approach period. He suggests that humans are constantly weighing queue length with the risk of weaving. This model attempts to highlight driver impatience by periodically performing a user maximization calculation based on whether or not they were in congestion or stuck in a queue. It is assumed that a driver does not notice or likely ignores other lanes until they notice delay themselves. If a nearby lane or grouping of equivalent payment type lanes had a 20 percent greater utility, then it made an attempt to merge.

Taking real-time decision making one step further, the model includes a rebalancing of decision parameter coefficients or weights to realize the compromises drivers make to escape delays. The model was used to predict a four hour lane volume probability distribution to compare to field data. The research showed surprisingly accurate lane decision predictions with correlations of non-barrier plazas at 0.976 and 0.898. A control group comparing a main-line plaza with only queue length decision criterion yielded a lower correlation of 0.623 suggesting his model does not transfer well to that type of plaza.

2.1.4 Toll Plaza Design

A 2006 appeal from the National Transportation Safety Board beckoned tolling agencies to retrofit and otherwise implement improvements to reduce the widespread risk of rear-end collisions (10). These junction points on the nation's interstate systems are high crash locations and necessitate a set of guidelines to fill the regulation void (25). Agencies have produced several guides in an attempt to streamline design, but the majority of lessons learned come from the tolling agencies themselves. The lack of standardization between tolling facilities prohibits travelers from building familiarity with the tolling experience.

Vehicle conflicts, such as those observed with a conflict and event study, can serve as a proxy to gauge toll plaza safety (22). Statistics can be used to verify if changes in a toll plaza retrofit have yielded substantial improvements. Menta hypothesized that at a toll plaza, as ETC penetration rose, safety risks would decrease or at least maintain prior levels. These proportion of ETC users were divided up by vehicle type; passenger cars, trucks and buses.

The PANYNJ uses a traffic model for toll plaza design. The model for tollbooths allocates the marginal vehicle to the lane with the absolute lowest queue regardless of lane movements required to reach that toll booth. In the case where queue lengths are equitable, the alogorithm routes vehicles to the right. The model is used to determine how many ETC lanes should be operated but fails to show where to locate these lanes effectively (22).

According to the NHRCP Toll Plaza Design guide, only 28 percent of tolling agencies have wide load lanes on the rightside of toll plazas (9). Lane alignment is only a flexible parameter if land usage is accomodating. Geometric limitations have a large impact on toll plaza placement. Toll plazas placed on trumpet-shaped exchanges converging to one egress tangent provide very short straight sections to position queue lanes and are therefore avoided. Plaza placement is also discouraged at the intersection of major highways due to high volume and speed. Plazas should also not be located within a mile of another interchange to adhere to approach and divergence length requirements (2). The number of plaza lanes is a function of geometric availability and traffic demand.

The Federal Highway Administration (FHWA) recommends using at least as many entering highway lanes for dedicated ETC service or the total throughput volume divided by 1500 (the hourly flow capacity in vehicles) (2). The results of converting lanes to dedicated ETC revealed that as ETC penetration increased, conflict potential subsequently fell and a "more organized" traffic flow or efficient stream of traffic developed.

2.1.4.1 Merging Zone

Design of the merging zone or area of influence in the travel lanes upstream and downstream of a toll plaza is essential for safe operations. These zones range in width and length, but maintain a trapezoidal shape to allow for cross traffic movement to efficiently process fare transactions at a variety of toll lane types. The following geometric constraints are general engineering practice as designated in national safety guidelines (26). Average taper rate is 10:1 for departure and 7.5:1 for arrival zones. Minimum deceleration zone length is 450 feet but is a function of number of toll stations and highway design speed. Minimum acceleration length is 730 feet for a design speed of 50 mph. This area should sufficiently hold six (6) tractor trailers in queue upstream of the junction (9). The queue area downstream of the plaza should be long enough to allow acceleration to highway speed before elimination of last additional merging lane. In situations where reversible lanes are not implemented, physical barriers are highly recommended for directional isolation (2). Merge areas could be optimized by lengthening these critical zones and gradually widening to full plaza width. One study suggested a series of stepped widenings that transitions travel lanes from three to six on the way to nine booths (4).

2.1.4.2 Reducing Conflict Potential

Beyond physical treatments, one organizational recommendation has surfaced to group lane types for conflict potential reduction. A study out of the University of Central Florida suggests positioning analogous lanes next to one another (4). The multitude of vehicle class types and lane class types introduces multiple forms of vehicle interaction. Recommendations from the FHWA proposes using only two types, thus eliminating one of the group options leading to faster decision making (2). Studies recommend segmenting lane types to reduce potential lane movements. It is believed that drivers, if given signage notice will move to these zones sooner and potentially reduce conflicts and crashes (27). One example where this may help is if a tractor trailer is only able to use lanes on the right due to height constraints but may be riding in the left lane on approach. In a dual transaction scheme the driver only can make a relative booth decision once and maneuver less, if at all, downstream. In another case, a passenger vehicle may be riding in the right and may need to find his way to the left hand dedicated ETC lane because he does not carry cash. In extreme ramp plaza cases where traffic consistently builds queues and merging conflicts are the choke point, an argument could made to switch lanes over to all mixed use to remove lane choice (2).

2.1.4.3 Merging Challenges

Traffic convergence is integral to the operation of toll facilities and processing fare collection. Occurring both before and after toll plazas, merging is one of the largest safety challenges for toll operators. The advent of electronic tolling has only increased this problem as the speed variance between vehicles leaving plazas has increased. Electronic payment users tend to exit at speeds in excess of 10 miles per hour and often as high as 35 miles per hour. Cash or manual payment patrons must accelerate from a stop to merge with faster moving ETC clientele. The difference in speed often creates weaving conflicts as motorists attempt to resume highway speeds (20). According to a study in 2007, driver indecision and the gap of different speeds are leading to higher crash severity (11). However, plazas have a built-in metering effect due to the nature and unpredictability of toll processing times by various payment types (2).

Merging itself is a function of the number of entering vehicles. As the number of advancing vehicles increases, merging traffic interactions also increase while critical capacity is approached. When flow exceeds capacity, serious conflicts occur, which trigger extreme deceleration and post plaza acceleration. If demands exceed capacity, overall system capacity drops between 5-20 percent may occur due to major merging conflicts (13). This degradation in operations may spawn further impacts to the variance in speed.

2.1.4.4 Speed Differentials

Another conflict mitigation tactic attempts to reduce speeding, a contributing factor to post plaza conflicts. Regulating speed is crucial to lane operation, but must be supported with proper enforcement, or compliance will be minimal. The PANYNJ is one of two agencies to implement automated speed enforcement at the plaza level. Speeds are recorded as they pass through the plaza junction and those found to be in violation of posted speed limits are billed by mail. Those who ignore state-issued invoices may have their E-ZPass tag suspended or revoked. This system works with the toll collection violation systems which photograph every license plate as it passes the tolling terminus. Many agencies use digital displays in toll booths to provide real-time speeds. At least one agency saw decreases in speeding by 70 percent after display implementation (20); others only saw minimal changes with this treatment and had concerns with sign overload. In the state of Florida, legislation has been passed to treat toll plaza zones similar to construction zones with doubled fines for speeding (20).

In addition to enforcement, physical treatments have been implemented around the United States to combat excessive and unsafe vehicles speeds in toll plazas. Many agencies installed gates to lanes primarily to fight revenue leakage, but found this equally beneficial in controlling vehicle velocity. While not commonly installed on ETC lanes, gates can be used for automatic forms of payment and lift systematically after payment processing. Gates are effective in reducing transitional speeds, but often are feasible if high throughput is required. Rumble strips or road grooves placed upstream are effective in alerting drivers to become aware of their speed and a red flag for the toll zone ahead. Similarly, transverse pavement markings trigger drivers to decelerate as they approach toll gantries. Transverse markings are spaced increasingly closer together, giving the illusion that the vehicle is passing over these points at an increasing rate, prompting a need to break and slow down even though they were not changing speed (20). A FHWA organized assessment of tolling authorities named at least one agency has found these additional pavement markings confusing for drivers and may distract motorists from the more crucial lane dividers (20). A well designed plaza should utilize roadway geometries to regulate motorist speed and provide an easy arrangement to navigate.

2.1.4.5 Safety Solutions

In order to ensure safe operations toll operators and highway departments have experimented and developed solutions to combat the risk associated with toll facilities. Operators gradually deployed electronic toll collection to meet the demand of and level of equipped customers. Placement of these lane types is a serious consideration when retrofitting existing manual collection facilities. Additionally, several physical treatments have proven helpful in protecting toll plaza resources, motorists and overall efficiency of the highway.

2.1.4.5.1 Lane Configurations

Planning lane configuration is essential to a safe and efficient tolling venue. The American Association of State Highway and Transportation Officials (AASHTO), MUTCD and state agency guidelines provide little direction on lane assignment and configuration (2). In the early engineering phases, importance must be placed on ETC penetration and traffic demand to determine lane assignments. ETC usage dictates the number of dedicated lanes and plaza size (24). Traffic demand has many important facets to consider when arranging lanes. The breakdown of vehicle type, estimated queue lengths, and trip purpose should all be evaluated for intended plaza performance (20).

The common logic of placing ETC lanes to the left is derived from the understanding that faster moving traffic seeks the left hand lanes. This commonality extends to the toll plaza as electronic tolling allows for faster fare processing time. However, this temperament may be contributing to higher rates of rear-end crashes when drivers are expecting less vehicles to enter these lanes (11). Locating ETC lanes all to one side may not be feasible if exit ramps exist just downstream of a plaza (20). Other organizations including New York and New Jersey have ETC lanes in the middle to provide equal service for ramp plazas that may have exits from two opposite directions (2). Other theories place highest demand lanes, typically ETC, in the center to mimic a bell curve of approaching vehicles that build in queue (2). Many state highway systems restrict tractor trailers to travel in the right lane(s). However, it has been commonplace to locate ETC lanes on the left, and serve as "thru lanes".

Right aligned ETC lanes have been experimented with to prevent dangerous merging movements that commercial vehicles may take to pay a fare. If a car driver moving parallel to a truck seeks to use ETC, its driver may have problems weaving over to use lanes only allocated to the left. For this reason many plaza operators have placed ETC lanes on the right to keep tractors from causing merge disruptions. Some toll agencies have opted to locate ETC lanes on both sides of a plaza to reduce abrupt weaving movements from one side to other. However, lanes on both sides may lead to driver confusion, and potentially could be blocked by queues of cash only lanes. These issues are part of the two-sided ETC lane debate because of the argument of increased or decreased weaving movements (20). Motorists may also avoid exterior cash or combination lanes if bordered by dedicated ETC lanes for fear of having to merge with higher speed vehicles upon plaza exit (3). Lane configuration may provide operators with improvements to toll operations; but it may not always be feasible to rearrange lanes.

2.1.4.5.2 Other Solutions

Toll agencies and researchers have proposed alternate non-physical or operational methods of improving safe merging and lane choice. The recurring theme of pushing driver decisions upstream before plaza taper points may be satisfied by other means. One way to reduce dangerous last-second maneuvers is to restrict these opportunities altogether by channelizing traffic. Ideally a physical barricade is the best option as it completely separates traffic between faster moving lanes and slower traffic. Nonetheless, this option, while widely used for express lanes, often proves to be costly to install and maintain.

Many agencies now utilize open channeling methods to separate vehicle payment type well in advance of toll gantries thereby limiting late merging. A more economical solution uses either portable or permanent delineators, which limit vehicles to their lanes and has great success in impeding unsafe movements (20). While not complete physical barriers, high-visibility flexible delineators, cones or flexible stanchions provide an effect similar to jersey concrete modular barriers. Another plaza safety device, known as an impact attenuator, is designed to absorb a crash of a four ton vehicle at 45 miles per hour. Typically placed on the upstream side of a plaza, these devices provide a safeguard for toll employees, infrastructure and drivers. Other safety features include pipe bollards, sand barrels and concrete ramparts that prevent damage (9). For optimal performance, agencies should implement this cure on both sides of the plaza to allow cash vehicles to match ETC traffic speed.

2.1.4.5.3 Open Road Tolling

Open road tolling is an ideal solution for improved plaza throughput and conflict diminution. While succesful in many instances, open road tolling is limited by situational constraints to benefit its users. Isolated or express ETC lanes with a median reduce the number of possible conflicts between vehicles. By separating traffic upstream, ETC customers merge on the freeway versus the trapezoidal merge area (5). A 2005 survey indicated that 91 percent of Toll agencies locate their express lanes to the left (2). Tradional toll plaza abolishment with true open road tolling would remove major deceleration/acceleration merging zones. Safety may be improved with the removal of these bottlenecks and is a key step to transitioning to all-electronic payment services (5). Tolling agencies are encourage the usage of electronic toll transponders as the preferred form of payment.

2.1.5 Summary

Motorists are constantly making comparisons and judgments based on sensory information to quickly and safely manuever toll plazas. Highly accepted by most, electronic toll collection among with other roadway technologies are a part of a trend that will inevitably prevail in highway transportation. The problem with achieving standardization is that ETC lanes were developed and pioneered on a trial basis by various toll agencies. A formal large scale trial and research before implementation did not take place, which has resulted in many unanswered questions regarding safety and operations. Driver education programs lack training regarding decision making at toll plaza approaches.

Research should be conducted to study how sensory information truly affects driver decision making. Efforts should be made to investigate how driver demographics influence lane choice and exactly what components of the driving environment travelers perceive and employ. Lane choice remains a driver decision, but with the current trends of assisted driving technologies, this may not always be the case. Perhaps within the forseeable future your vehicle may announce “Please use lane four for fastest service”, leaving a computer algorithm to resolve lane choice. Until such advances, toll plaza decision making in regard to electronic toll collection should be a prioritized field of study.

CHAPTER 3

METHODOLOGY

3.1 Research Objectives

To address the aforementioned problem statement and need for further research, a research methodology was constructed. The procedure included three objectives and respective tasks to accomplish the proposed objectives to answer the problem statement as shown in Figure 4.

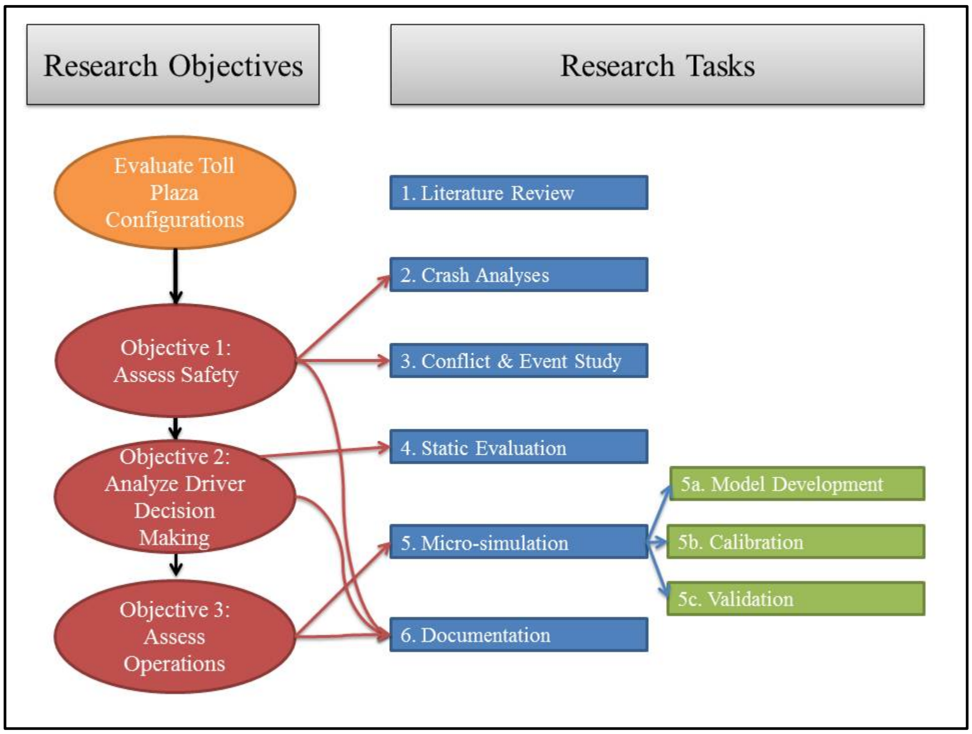


Figure 4: Research objectives and methodological task map

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 was to evaluate issues related to toll plaza configuration and driver decision making resulting from the introduction of ETC. This overall objective resulted in three specific research objective focusing on driver decision making analysis, operations and safety assessment. Under the safety objective, work focused initially on statewide crash analyses and progressed to a conflict & event study in the field. The driver decision making objective was addressed by analyzing driver behavior with a computer-based simulation model. To achieve the operations objective, a model was developed, tested and implemented to forecast toll plaza operations based on lane configuration. The research objectives are discussed further below.

3.1.1 Objective #1: Assess Safety

To assess safety the research included an analysis of crashes at toll plazas followed by a conflict and event study. An initial crash analysis was completed to identify key toll plazas of high potential crash risk. Crashes were spatially analyzed using geographical tagging at the police collection level. The intent of the crash analysis was to identify the nature of the relationship between collision trends, toll configurations and the extent to which driver attention is diverted. A conflict and event study was supplemented by video footage taken from Exit 4 of the Massachusetts Turnpike system.

3.1.2 Objective #2: Analyze Driver Decision Making

The driver decision making objective strived 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. Specifically, this study sought to identify how confusion spawned by the multitude of sensory information impacts driver decisions such as those made when approaching toll interchanges. The role of electronic toll 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. Drivers may be exasperating their mental and sensory potential in search for the lane opportunities in turn leading to a high rate of rear-end crashes due to a loss in forward attention. Analysis from these studies aimed to discern consistent patterns of how drivers analyze, and act upon information on the approach to a toll plaza.

3.1.3 Objective #3: Assess Operations

The intent of the operations-based research objective was to model driver behavior at toll plazas with multiple forms of payments forcing decision making. Many traffic software platforms are available for microsimulation including Paramics, CORSIM, AIMSUN, VISSIM and Synchro. The stochastic software microsimulation package VISSIM by PTV America, Inc., was selected for its depth of configuration and dynamic traffic assignment features. Video footage from toll plazas supplied the model with substantive parameter values. The model was then tested and verified against the same plaza with a varied configuration in an effort to accurately simulate activity at these high conflict areas. Investigations may determine whether plazas are operating as expected or if certain configurations are inducing conflicts and events jeopardizing operability. The traffic operations associated with toll plazas could subsequently be used to inspect the impacts of varied lane configuration performance.

3.2 Research Tasks

The aforementioned objectives were completed by the following research tasks detailed below. The following subsection provides instruction into the scientific and analytical process used to complete the research contained within this thesis. The methods for researching the nature of safety and operations at toll plaza were tailored to the availability of both data and physical environmental resources. The research commenced with a background of current related research and completed safety assessment, driver decision making and operational analysis.

3.2.1 Task 1: Literature Review

The initial research task, which was introduced at the onset of the research development, was a thorough review of the literature related to this topic. The systematic review of pertinent background research articles began with journal and database keyword searches. More specifically, studies on lane configuration, simulation and driver decision making were the focus of the literature review. Several databases were examined based on relevance to human factors and transportation peer-reviewed journal research. The National Transportation Library, a branch of the Research and Innovative Technology Administration (RITA) and Transportation Research International Documentation, and Transportation Research Board's database were selected as primary search engines. Other journal catalogs used were Engineering Village, Web of Knowledge, LexisNexis Academic, SciVerse, and Ebscohost.

Search keyword logic was developed after subsequent search engine explorations. Toll plaza safety, electronic toll collection, plaza configuration and sideswipe crashes were the initial search terms. This rationality provided an exorbitant amount of resources. Search terms were refined and tweaked to minimize the wealth of articles into a useful collection. Keywords were found to be too broad, and were replaced with specific terms. Using electronic tolling system names (e.g. E-ZPass, SunPass) served as an excellent filter. Changing the logic from the “OR” operator to the “AND” operator and separating the differentiating keywords provided much needed discriminating power. The key filter terms after trial and error included safety, crash, merge, sideswipe and queue. The final search revision used the following logic where articles must return one term from each column.

$$\begin{bmatrix} electronic\ toll \\ open\ road\ tolling \\ etc \\ AVI \\ ITS \\ toll\ plaza \\ e-zpass \\ e-z\ pass \\ sunpass \\ txtag \\ tolltag \\ pikepass \\ mnpass \\ fastrak \\ k-tag \end{bmatrix} + \begin{bmatrix} safety \\ crash \\ merge \\ sideswipe \\ queue \end{bmatrix}$$

Background literature was updated as new information became available during the course of this work. The literature review served as the background information for the research.

3.2.2 Task 2: Crash Data Analysis

Task 2 was designed to address research objective 1 as described above. The data used for crash analysis was derived from the UMassSafe Traffic Safety Data Warehouse. The warehouse utilizes several datasets linked together to create a robust collection of information. Datasets are united through several linkages including matching material from medical, citation and motor vehicle data sets. The research task began with an SQL query was performed on the database to extract data from 2010 through 2012. These years were the three most recent years of data available to the data warehouse. However, it should be noted data from 2012 has not been officially closed by MassDOT so the data herein is not complete and some reporting agencies may still have not submitted all reports.

Datasets provided by the SQL query include crash level and driver level attributes. Crash level details include items on the Commonwealth of Massachusetts Motor Vehicle Crash Report form. These items include an identifying crash number, date, time, city, road surface, weather, traffic control, light conditions, injury status, manner of collision, harmful events, XY coordinates and narratives. The driver level details include age, sex, driver contributor code and vehicle type. These attributes were used in data analysis to identify trends.

3.2.2.1 Data Preparation

The data was primed for trend analysis first by geographically identifying toll related crashes. This analysis only includes crashes geolocated to an XY coordinate on a latitude-longitudinal plane. The remainder of crashes without XY coordinates were removed from consideration. It should be noted that the geolocation information varies from police agency to police agency. It was recognized that some agencies have accurate in-vehicle capabilities in crash location identification, while others must manually pinpoint and generate XY coordinates. The research herein is limited by agency accuracy and may not be complete or may contain erroneous crashes.

In 2010, 196,410 of 212,285 or 92.5 percent of crashes were geolocated leaving 15,875 of those crashes with unknown locations. In 2011, 200,477 of 211,915 or 94.6 percent of crashes were geolocated leaving 11,438 with unknown locations. In 2012, 153,031 of 172,025 or 88.9 percent of crashes were geolocated leaving 18,994 incidents at unknown locations.

Data analysis began with mapping of all 2010, 2011 and 2012 crashes using ESRI's geospatial mapping software ArcMap ©. Using buffer and intersect tools, crashes that were appropriate and close to toll plaza were isolated for further analysis. A 1000 foot radius was used as the threshold range of crashes. Crashes from both the upstream and downstream sides of each plaza were added to the toll plaza crash dataset. Graphical verification was used to isolate and remove crashes on overpasses, or adjacent roads that fell within 1,000 feet buffer. While more accidents may fall out of the 1,000 foot range, queue lengths could not be verified to provide an accurate cut off point. One thousand feet was deemed the extent of the scope of the project as the intentions of this analysis was to get a picture of the safety issue at toll plazas and the trends that jeopardize it and not identify every single vehicle collision.

3.2.2.2 Crash Trends

After extraction of toll plaza-related crashes, single and double variable analysis was conducted. Results can be found in section 4.2. Statistical analysis was limited due to small yearly sample sizes. Double variable relational statistic were not possible for combinations where sample sizes were (N=10) or smaller.

3.2.3 Task 3: Conflict and Event Study

Task 3 was a follow up to task 2 and aimed to further address objective 1. A conflict and event study serves as a surrogate measure of safety to identify potential safety concerns associated with the operational aspects of selected toll plazas. Queuing conditions and traffic turbulence were observed and used to prepare the computer based static evaluations. Traffic conflicts are defined as an incident with two or more vehicles attempting to occupy the same physical space where one driver has to make an evasive maneuver to avoid collision. When a driver is not forced to make drastic movements, a traffic event occurs. Traffic events are unusual, dangerous or illegal operations such as backing up, hesitation or otherwise impeding the flow of traffic (28). These roadway incidents and actual collisions are recorded and collected in a traffic conflict and event study. These studies are often accepted as a supplement to crash data for estimating crash potential.

A study by Glauz et al. (1985) suggested the relationship between conflict studies and crash rates may sufficiently serve as a surrogate measure of safety (29). Using a conflict and event study, engineers can observe and record events that may not have otherwise been made aware of. Toll plazas are one such location where crash analysis indicate low crashes on average in terms of total miles travelled. This research used field video data to explore other events in the toll plaza environment that may be jeopardizing motorists. A conflict and event study was conducted at toll facilities West Springfield Exit 4 in Massachusetts to evaluate the risk for crashes. Field observations were based on Federal Highway Administration’s Traffic Conflict Techniques for Safety and Operations Observers Manual (30). Among the manual’s 14 conflict scenarios, slow-vehicle, same-direction conflict and lane-change conflict and secondary conflicts were anticipated to be the highest occurring. Conflict and event data was generated from aggregated data sheets from field examinations.

3.2.4 Task 4: Computer Based Static Evaluation

Task 4 was created to tackle objective 2 as described above. 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 static evaluation gave participants a series of toll plaza scenarios and asked them to make a lane decision based upon personal judgment of conditions. General participant demographics were also collected to determine the facets that connect driver decision making attributes at toll plazas. A model of results was formulated to allow to with a specified degree of certainty, the probability a driver will choose a lane to pass through the toll plaza scenario. Figure 6:

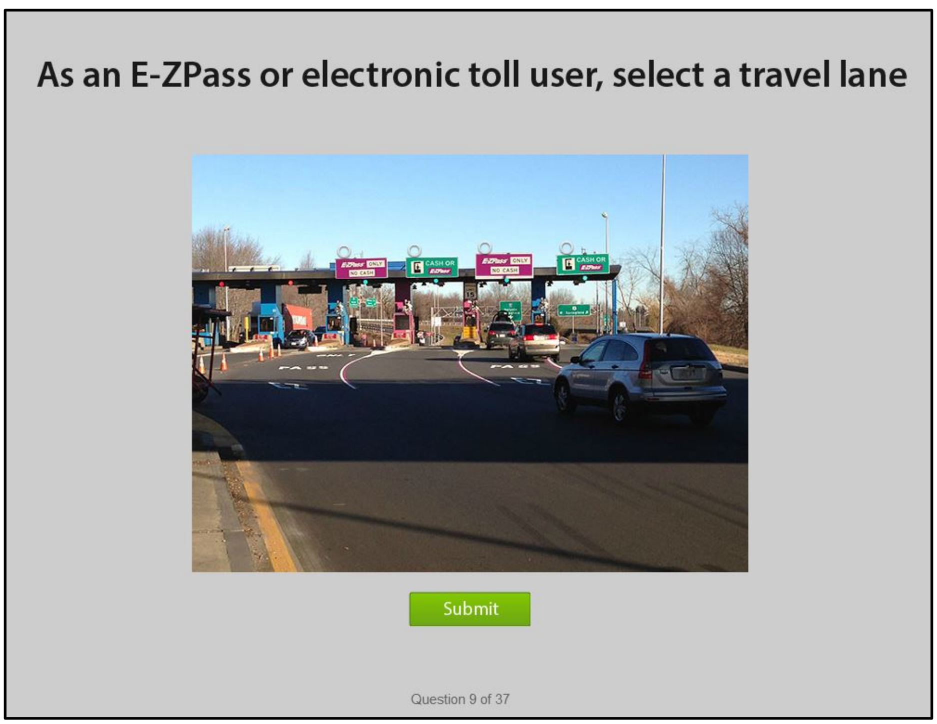


Figure 5: Sample static evaluation screenshot.

3.2.4.1 Design of Evaluation

The computer evaluation attempted to mimic the decision process that drivers face on toll plaza approaches. The evaluation provided participants with a photo from the driving perspective shown in and asked them to select one lane to use based on the information they could deduce from the one frame. A static evaluation was created using Adobe Captivate, a learning management software (LMS) with built-in quiz and multimedia capabilities. A within subject design assigned participants as either a cash or ETC customer as they approach an interchange and then reversed the role. The evaluation began with instructions as seen in Figure 6 and then randomly sent the subject one of two branches of the evaluation.

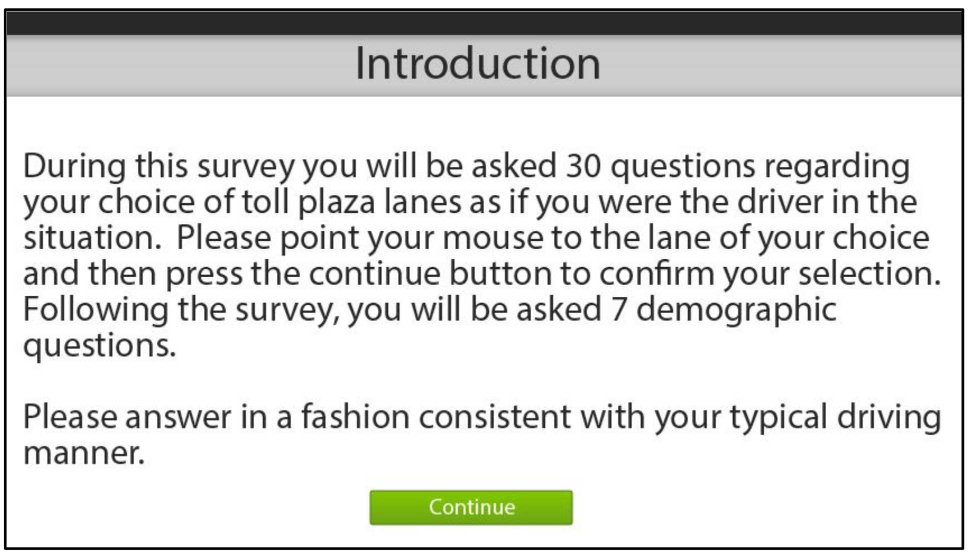


Figure 7: Static evaluation instructions.

Each branch had the user emulate a different payment method as seen below in Figure 7 and answer a series of lane choice questions based on static photographs from toll plaza scenarios.

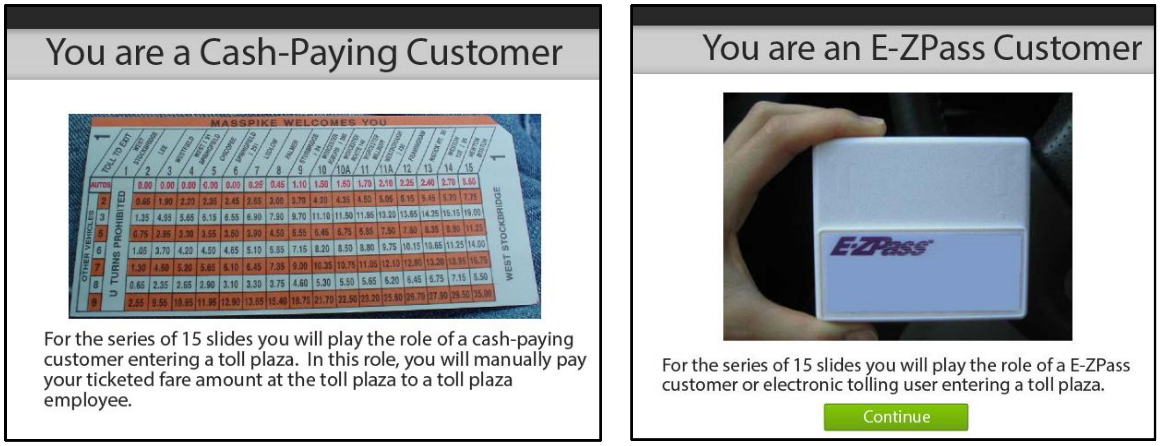


Figure 8: Payment method instructions.

Fifteen scenarios were presented with varied queue lengths (number of vehicles), number of lanes, ETC placement (left, right, center, both left and right), and lane type (Manual, Automatic, ETC, Mixed). A table of scenarios found in Table 2 framed the scenarios of interest to study driver behavior as a cash and electronic toll customer. A total of 30 unique scenarios (2 of each 15 scenarios) were incorporated into the static evaluation. Each scenario was created by manipulating photos taken from Exit 4 off Interstate 90 in West Springfield, Massachusetts on December 20, 2012. All photos used in static evaluation scenarios are included within Appendix A.

The lane selection process used radio buttons to limit lane selection to one per toll plaza scenario. 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.

3.2.4.2 Administration of Evaluation

The evaluation was shared with colleagues 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. Captivate recorded user results to an XML file to a local server.

3.2.4.3 Analysis of Evaluation

Evaluation responses were compiled and results were aggregated through extraction of each individual XML file. Data was sorted by scenario number and demographic responses. Resulting figures representing driver's lane selections were generated and can be found in section 4.3. Results provided feedback and configurations to pilot in the microsimulation model development in task 5.

Table 2: Static Evaluation Scenarios

	Lane Types[a] Left			Right		
Scenario	**Lane 4**	**Lane 3**	**Lane 2**	**Lane 1**	**Variable**	**Queue Scenario**
1	D	M	M	M	Left ETC	Short Queues
2	D	M	M	M	Added Queue on Dedicated ETC	10 Car Queue on Dedicated Lane
3	M	M	M	D	ETC on both sides	10 Car Queue on Left Dedicated Lane
4	D	M	M	D	ETC on left	Short Queues
5	D	C	C	C	Combination Lanes	10 Car Queue on Dedicated Lane
6	D	C	C	D	ETC on both sides	Short Queues
7	D	C	C	D	ETC on both sides	10 Car Queue on Left Dedicated Lane
8	D	D	M	M	Two ETC Lanes on Right	Short Queues
9	D	D	M	M	Two ETC Lanes on Right	10 Car Queue on Left Dedicated Lane
10	D	M	C	M	Center Combination Lanes	10 Car Queue on Left Dedicated Lane
11	C	M	D	C	West Springfield Scenario	Short Queues
12	C	C	D	C	All Combination Lanes	10 Car Queue on Dedicated Lane
13	D	C	D	C	Ideal Scenario	10 Car Queue on Left Dedicated Lane
14	C	D	D	C	Center Dedicated Lanes	10 Car Queue on Left Dedicated Lane
15	D	C	D	C	Variation of W Springfield Scenario	10 Car Queue on Right Dedicated Lane

[a]: M-Manual (Cash Lanes), D-Dedicated ETC (E-ZPass/FastLane), C-Combination (Accepts Cash or FastLane/E-ZPass)

3.2.5 Task 5: Microsimulation with VISSIM

Task 5 was conceived to address research objective 3 as mentioned previously. Based upon the safety and driver decision making analysis resulting from tasks 2-4, an attempt was made to improve the operation modeling of toll plazas as a function of lane configuration. A microsimulation VISSIM model was developed to evaluate the operational aspects of toll plazas. 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 and control traffic as if a toll plaza were present. The West Springfield toll plaza was built in the microsimulation package. Video data was collected and analyzed for toll plaza safety and performance. This data was used as an input for a VISSIM model of a sample toll plaza.

After development, parameters were calibrated to mimic observed behavior. The first round of calibration involved visually inspecting the model for normal traffic operations. Weaving, queuing, and minor amounts of unpredictable maneuvers are expected at a toll plaza and were monitored. The visual inspection observed for gridlock or other anomalies in the model.

Following calibration, another toll plaza configuration representing the configuration in January 2012 was built into VISSIM using the calibrated model to compare to actual performance. The validation model's measure of effectiveness was to be within ten percent of total throughput of the observed field volumes. The end product was capable of predicting traffic operability based of configuration and an origin destination study. A critical benefit of this model may be the ability to aid toll plazas managers in optimizing lane configuration.

3.2.5.1 Model Development & Base Data

In an effort to build a robust microsimulation model, good field data must provide the framework to erect a reasonable representation of realistic activity. Field data was collected during the year 2012. The available datasets are summarized in Table 3 below. Unfortunately both data sets were not recorded at the exact time of day, but were both recorded mid-week, off peak hours. Location of this particular toll plaza is not susceptible to large swings in destinations due to commuting.

Table 3: Field Collection Datasets

Date	Time	Hours Collected	Location	Cameras	Toll Plaza Lane Configuration	Weather
19-Dec-12	12PM	1.25	West Springfield - Exit 4	2	Cash-EZPass-EZPass-Cash	33 degrees, overcast
13-Jan-12	11AM	1	West Springfield - Exit 4	1	Combination-Cash-EZPass-Combination	34 degrees, overcast

3.2.5.1.1 Data Reduction and Preparation

In order to prepare the data to serve as model inputs, our video data was reduced to usable inputs. Raw volumes and traffic class information were collected using a JAMAR Technologies count board with 15 minute increments as archived in Table 4. Car and heavy vehicle (single units, buses, tractor trailers) volumes were separated for vehicle classification.

Table 4: Calibration Volumes

	2013 Calibration Volumes in Vehicles Per Hour					
	Vehicle Type	**Lane 4** Cash	**Lane 3** E-ZPass	**Lane 2** E-ZPass	**Lane 1** Cash	Total
00:00-00:15	Cars	62	96	120	64	342
	Heavy Vehicles	3	19	18	2	42
	Total	65	115	138	66	384
00:15-00:30	Cars	62	84	113	72	331
	Heavy Vehicles	3	17	18	1	39
	Total	65	101	131	73	370
00:30-00:45	Cars	75	66	102	76	319
	Heavy Vehicles	5	20	10	5	40
	Total	80	86	112	81	359
00:45-01:00	Cars	60	75	110	54	299
	Heavy Vehicles	5	13	12	3	33
	Total	65	88	122	57	332
01:00-01:15	Cars	79	86	94	62	321
	Heavy Vehicles	3	13	18	2	36
	Total	82	99	112	64	357
	Hourly Flow (VPH)	275	390	503	277	1445
	Heavy Vehicle %	6%	18%	12%	4%	11%
	Peak 15 Minutes	82	115	138	81	416
	Peak Hour (VPH)	328	460	552	324	1664

Origin and destination figures were required for dynamic assignment. Exit 4 on the Massachusetts turnpike has two entrances and two exits. Exits included one from the westbound direction and one from the eastbound direction on the turnpike. Destinations were the interchange with I-91 north and southbound and Route 5. The origin destination information was collected with a two camera setup as shown in Figure 8 Camera setup schematic. Camera one was angled towards the toll plaza on the overpass of Prospect

Avenue. The second camera faced the merging zone and entrances from I-90 eastbound and I-90 westbound.

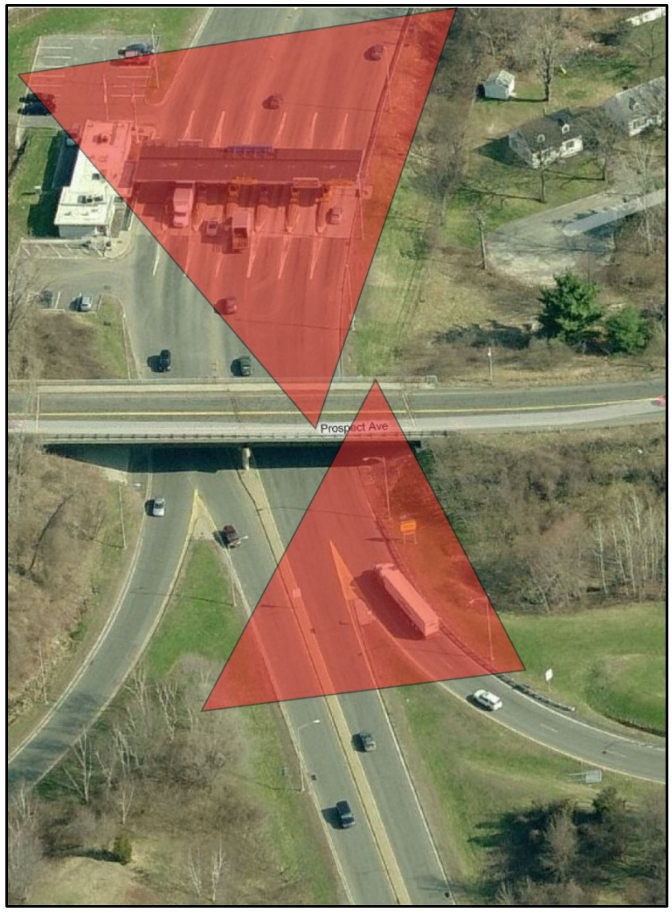


Figure 9: Camera setup schematic.

Each vehicle was tracked from their entrance lane, through the toll plaza to their final destination from camera 1 to camera 2 as seen in Figure 9 Field data video screenshot. Payment method, lane choice, and number of lane maneuvers were noted in addition to origination and destination. This process indicated how many customers of each toll payment method were originating eastbound, westbound and their decision at the toll plaza to travel on to I-91 or Route 5.

Figure 10: Field data video screenshot.

The second calibration input 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 passes the physical toll booth (commencement time) to the time when the rear bumper passes the end of the toll booth and passes the traffic signal displaying a green ball (completion time). Commencement time was standardized for cash and ETC customers by using a consistent physical benchmark. 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 $1/29^{th}$ of a second. One hundred transaction times were randomly sampled from each lane from calibration videos, and were recorded with transaction type and vehicle class.

Distributions and statistics were generated using the statistical software Minitab. Cumulative distribution figures were developed from raw data to serve as input for plaza dwell time. Figure 10 below reveals the transaction time distributions, mean and standard deviation for cash transactions for both passenger vehicles and heavy vehicles. Figure 11 provides the same distributions and statistics for the ETC payment method.

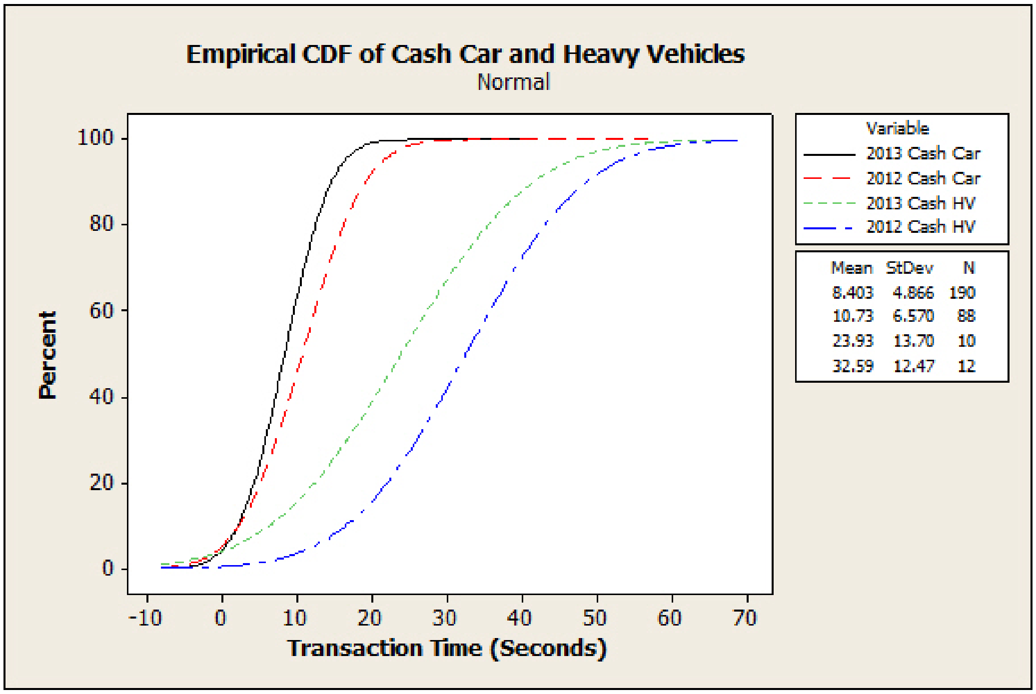


Figure 11: Cumulative Distribution Function for cash vehicle transaction times.

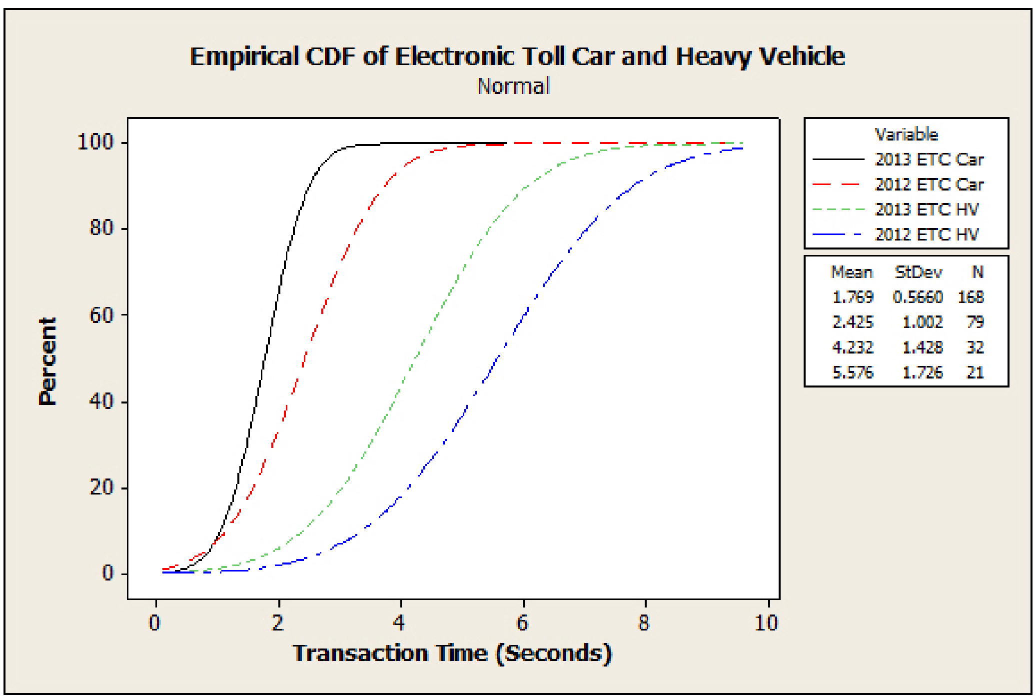


Figure 12: Cumulative Distribution Function for ETC vehicle transaction times.

3.2.5.1.2 Vehicle Classifications & Traffic composition

In order to differentiate different behaviors in VISSIM, four vehicle “classes” were formed. Classes allow the microsimulation programmer to specify certain behaviors, rights and restrictions to a group of vehicles. Classes can involve multiple vehicle types or just a single type. Four classes were established: cash cars, E-ZPass cars, cash heavy vehicles and E-ZPass heavy vehicles. Car classes had one vehicle type, cars, with default characteristics of width, length, acceleration. Heavy vehicles had a mixture of single unit, bus and tractor trailer units with default characteristics. The quantity and distribution levels of these classes are assigned in the traffic/vehicle composition menu and were determined by field data. The vehicle compositions and desired speeds are demonstrated in the screenshot in Figure 12 below.

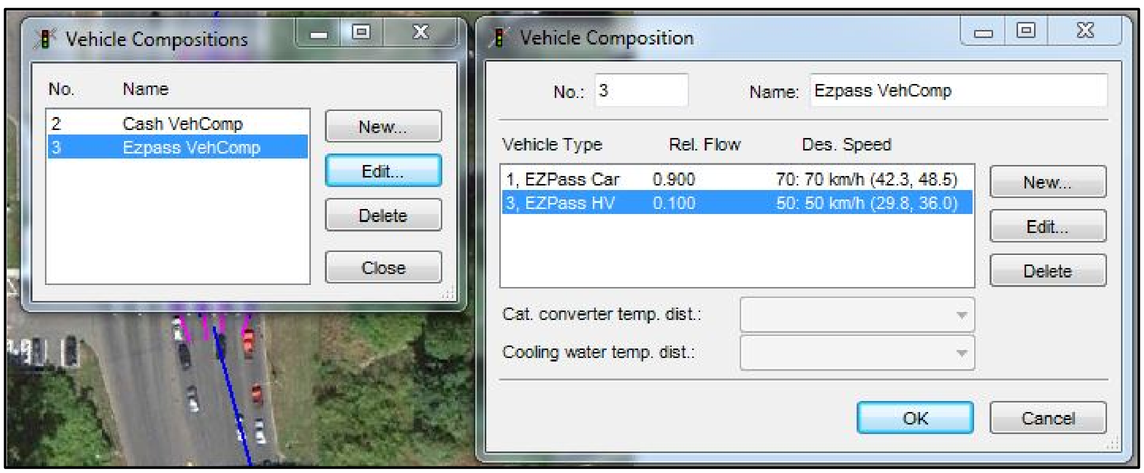


Figure 13: VISSIM vehicle composition.

3.2.5.1.3 Vehicle Inputs

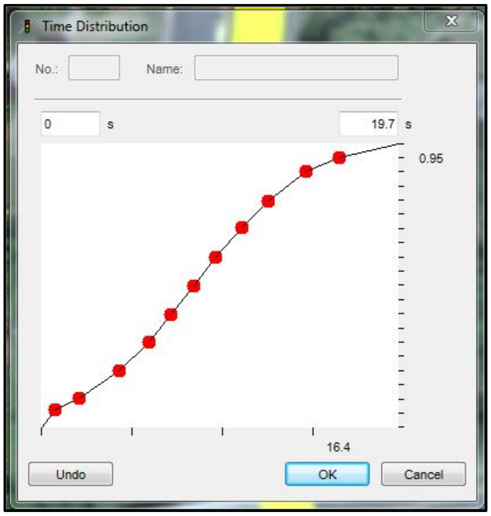
Hourly volume data was collected from December 2012 video data and processed into 15 minute intervals. These hourly volumes, seen in Figure 15 were raw volumes from each hour of respective video. Volumes were assigned to each group of traffic composition, cash vehicles and E-ZPass vehicles. These volumes were added to the O-D matrix for zone-based dynamic assignment.

3.2.5.1.4 Reduced Speed Limit Zones

Reduced speed limit zones allowed the model to emulate electronic toll collection 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. These distributions were assigned by vehicle class a 90 foot long reduced speed zones for each lane accepting an ETC payment. In the case of a combination lane, the reduced speed zones would only apply to E-ZPass vehicle classes and cash customers would be unaffected by the zone. Cash vehicles decelerated on arrival to virtual stop signs that provided a means to emulate manual transactions.

3.2.5.1.5 Stop Signs and Dwell Distributions

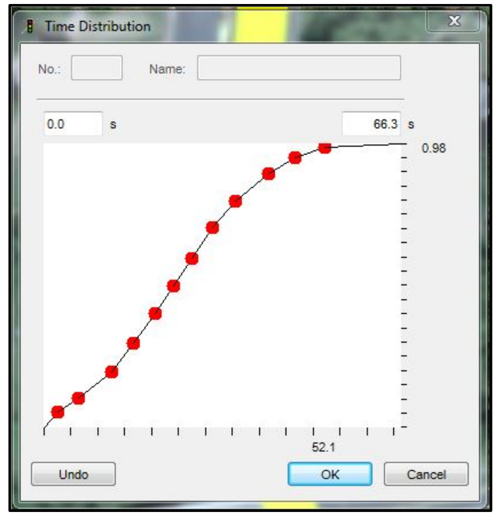
Stop signs were used as a means to emulate cash toll transactions. This function of VISSIM was deemed suitable due to the majority of vehicles coming to a complete stop during a manual cash toll transaction. Field data generated empirical dwell distributions were designated by vehicle class to assign varying stop or transaction times randomly on plaza arrival. Car and heavy vehicle dwell distributions programmed for this model are shown below in Figure 13.



Frequency

Seconds

Passenger Vehicle Dwell Distribution



Frequency

Seconds

Heavy Vehicle Dwell Distribution

Figure 14: Vehicle dwell distributions.

3.2.5.1.6 Dynamic Assignment & Discrete Choice Modeling

VISSIM's dynamic assignment feature was employed to capture driver decision making based on traffic conditions. Using zones of origination and destination called "parking lots"; a discrete choice model can be made to evaluate in real time the shortest paths (31). VISSIM solves a modified version of the shortest path algorithm and distributes traffic demand with the logit model. The key to route choice analysis is allowing the shortest path algorithm to evaluate path cost. The best route contains the series of edges that combined have the lowest path cost. Cost is a weighted sum of the travel times, distance and link financial cost. The travel time is an average of travel times from the beginning to the end of particular route in the simulation. After each vehicle exits the network, its route and travel time is recorded for analysis in the next time interval. The Equation 1 below illustrates the weighted formula. Coefficients alpha, beta and gamma can be modified but were left to their default values.

$$(1) \quad Cost = \propto * Travel\, Time + \beta * Link\, Distance + \gamma * Link\, Cost$$

The cost formula is used in a utility function that evaluates the value of a particular path in the discrete choice model. In turn, the utility function is used in the logit model to calculate the probability that a certain path *j* is selected. The logit function utilized by VISSIM incorporates a coefficient that allows the user to select the sensitivity of small deviations in travel time. The route choice probability model as seen below in Equation 2 uses the Kirchhoff distribution formula, which is analogous to the famous Kirchhoff's current law where road links traffic inbound is equal to outbound at any given node. The model assigns "resistance" values to links based on demand much like an electrical circuit with resistors. The sensitivity value, *k*, was left at the default value of 2.50 for this simulation model.

$$(2) \quad p(R_j) = \frac{U_j^k}{\sum_i U_i^k} = \frac{e^{k*\log U_j}}{\sum_i e^{k*\log U_j}} = \frac{e^{-k*\log C_j}}{\sum_i e^{-k*\log C_j}},$$

$$where\ U_j = \ utility\ of\ route\ j, C_j = cost\ of\ route\ j\ , k = sensitivty\ factor$$

Prior to route choice analysis, edges in the network were established. VISSIM utilizes nodes to recognize decision points. At these nodes VISSIM searches for edges or road segments leading from node to node. Each possible combination of edges creates an array of paths within the network. A node was added at each merge, diverge, entrance and exiting point. Nodes allow VISSIM edge selection to find paths from origin and destination zones established in the O-D configuration file matrix. A schematic of possible trip routes is visualized in Figure 14 below.

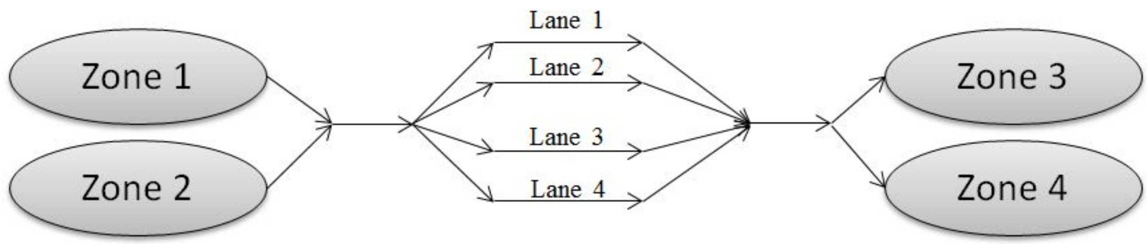
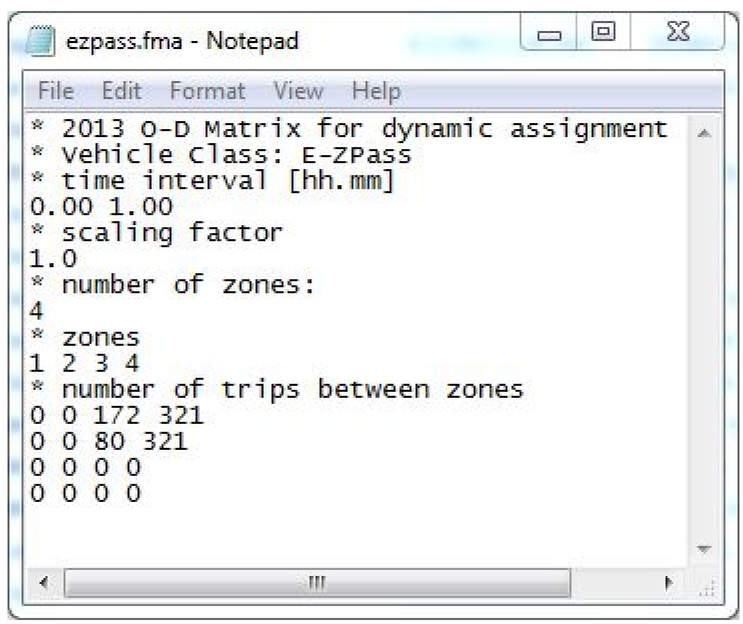


Figure 15: Origin and destination zones.

Trips are derived from a text file containing an O-D matrix as one of its parameters. The ".FMA" input file in Figure 15 allows for any number of zones and different matrices and assigns traffic demand to each defined simulation time period by vehicle class.


ezpass.fma - Notepad

File Edit Format View Help

```
* 2013 O-D Matrix for dynamic assignment
* Vehicle Class: E-ZPass
* time interval [hh.mm]
0.00 1.00
* scaling factor
1.0
* number of zones:
4
* zones
1 2 3 4
* number of trips between zones
0 0 172 321
0 0 80 321
0 0 0 0
0 0 0 0
```

Figure 16: Sample O-D file matrix input file.

To prepare a network for dynamic assignment, parking lots must be added to the network as "zone connectors". Figure 16 specifies 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 connectors 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 or physical spaces.

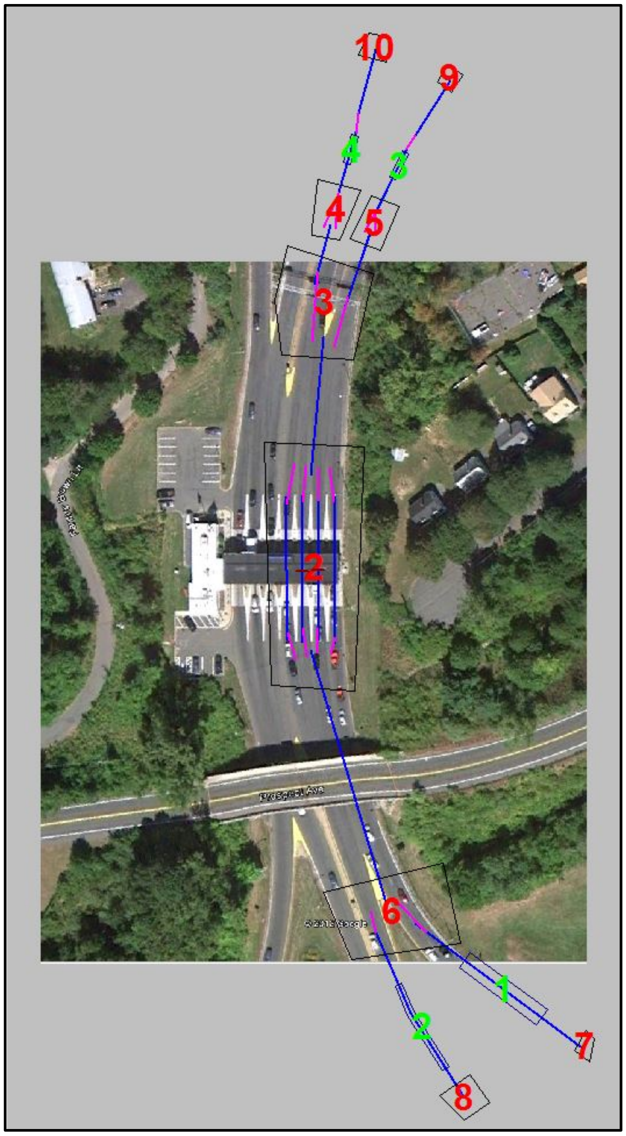


Figure 17: VISSIM Node and parking lot schematic.

The shortest path algorithm is refreshed on a user selected simulation evaluation interval. In most applications a 5-10 minute recalculation interval would be appropriate for path travel times. However, in an attempt to highlight driver decision making on toll plaza approaches where lane choice reevaluation occurs frequently, a lower value was selected. Ten seconds was the minimum allowable value in VISSIM; it was selected as the reevaluation interval. At the end of each dynamic assignment iteration, all travel times of vehicles that exited within the previous simulation interval were successively averaged by path. The simulation model did not use route tolls or link costs and other parameters of the utility function were not assessed.

3.2.5.2 Model Calibration

The FHWA's Guidelines for Applying Traffic Microsimulation Modeling Software as seen in Figure 17, was referenced for guidance in model calibration (32). Steps 1-4 of the guide had been completed up until this point of the model development process. Calibration, or step 5 of the project, involved a series of visual and quantitative testing the model for validity. The model used 2012 data for volumes, O-D assignment and dwell times. The following sections review calibration methods, driver and environmental settings used to tweak the base case model.

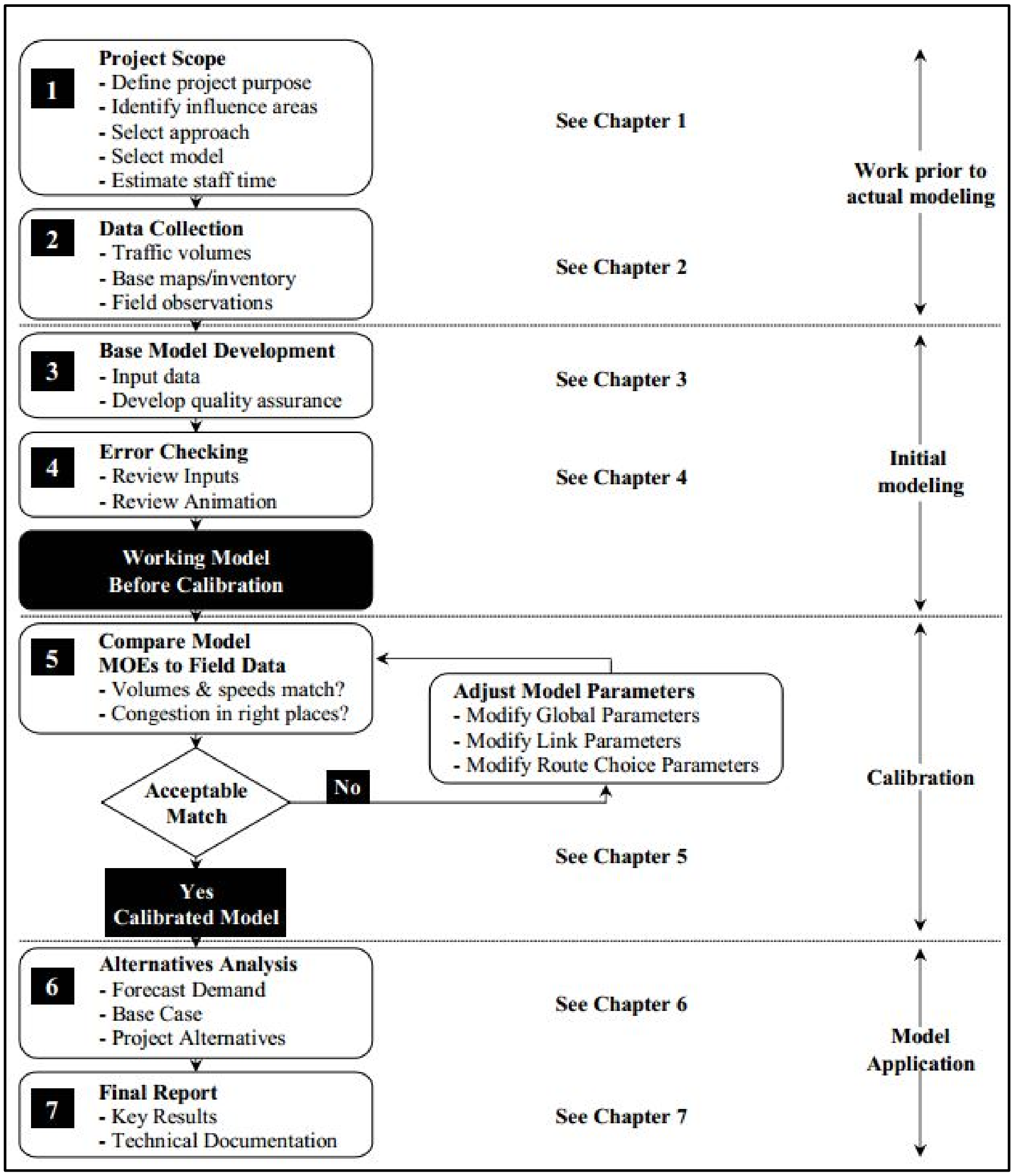


Figure 18: FHWA Microsimulation model calibration procedure.

3.2.5.2.1 Driver Behavior

The simulation software uses Wiedemann's car following logic to calculate and continuously update car position, speed, acceleration based on the position of a forward positioned car. VISSIM allows access to the 1974 and 1999 versions of Wiedemann's car following model to utilize driver vehicle car unit behavior. Based upon previous research, the 1999 version was selected (18). Each of these entities has several configurable parameters.

<u>Driver Based</u>

- Headway, look ahead/back distance, attention

<u>Vehicle Based</u>

- Acceleration/deceleration, safety factors
- Vehicle weight, power, acceleration
- Length, occupancy, width

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. 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 naturalize 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 sitting waiting for gap to change lanes to stay on its route before it removed from the network. This parameter helped remove gridlock situations troubling the microsimulation.

3.2.5.3 VISSIM Output

VISSIM has many output evaluations ranging from delay, to travel time, lane changes and queue length. For the process of validating a toll plaza model, video data throughput or volumes per lane were used to compare. Individual sensors were placed on toll lanes 1-4 and configured to collect this data. Ten simulation runs were averaged together to create a scenario throughput for each lane of the toll plaza. The averaged results can be found in section 4.4.

3.2.6 Task 6: Documentation of Findings

The findings of this research resulting from the crash analyses, static evaluation results assessment and microsimulation model, as well as any conclusions related to toll plaza simulation and lane configuration are documented in the form of this Master's Thesis for submission to the Graduate School of the University of Massachusetts Amherst.

CHAPTER 4

RESULTS

This chapter presents the major results of each task of Chapter 3.

4.1 Conflict and Event Study Notes (Task 3)

The conflict and event study supplemented the field data collection the microsimulation model development. Utilizing practices from FHWA's observers guide to Traffic Conflict techniques, a review of safety and operations was conducted at the West Springfield I-90 toll plaza (30).

Conflicts vary depending on origination of vehicles competing for the same roadway space. For the purpose of this research, same direction conflicts were nearly exclusively studied. While opposing conflicts may occur, their risk at exit and entrance plazas in Massachusetts is mitigated by stanchions, cones, low speeds and center lane closures. Pedestrian conflicts from toll plaza employees do occur from time to time but authorities limit exposure to this risk through training.

Same direction conflicts in toll plazas are primarily related to lane-changing events. In these instances, the overtaken vehicle is in danger of rear ending or sideswiping the provoking vehicle. The result of conflict may lead to a secondary conflict where a following or nearby vehicle may have to decelerate, maneuver unevenly to avoid a collision. Secondary conflicts commonly appear as a more relaxed deceleration. While a secondary conflict may seem to trigger a tertiary conflict, no such term exists.

Honking was a common occurrence as summarized in Table 5, in the limited video data collection periods, two vehicles backed up out of a lane to proceed to an adjacent lane, neglecting to observe current traffic conditions.

Table 5: Conflict and Event Results

Conflict and Event Register	
Abrupt stop	1 per hour
Evasive maneuver	4 per hour
Car honking	9 per hour
Swerving	1 per hour
Secondary braking	7 per hour

4.2 Crash Analyses (Task 2)

Crash analyses were performed on crashes occurring in the Commonwealth of Massachusetts from January 2010 through December 2012. All crash figures were linked geographically to toll plazas on the basis of proximity and contributing role in the collision. All toll plazas, mainline and entrance and exiting were considered for inclusion regardless of whether there was a transaction or just a "ticket" or digital "ticket" issued for interstate entrance. Traffic count data from MassDOT contained transactional toll records of exiting vehicles; therefore crash rates were based on the dataset of crashes exclusive of entering vehicles. All other plazas including mainline plazas, tunnels, and bridge facilities contained all toll crashes.

Table 6: 2010-2012 Toll Crashes

Interchange	2010	2011	2012	Average Crashes per year
Interchange No. 1 - West Stockbridge	2	8	4	5
Interchange No. 2 - Lee	0	0	0	0
Interchange No. 3 - Westfield	1	4	1	2
Interchange No. 4 - West Springfield	3	5	16	8
Interchange No. 5 - Chicopee	2	1	3	2
Interchange No. 6 - Springfield	6	3	8	6
Interchange No. 7 - Ludlow	0	0	1	1
Interchange No. 8 - Palmer	0	0	2	1
Interchange No. 9 - Sturbridge	3	7	4	5
Interchange No. 10 - Auburn	6	7	10	8
Interchange No. 10A - Millbury	2	2	4	3
Interchange No. 11 - Millbury	0	0	1	1
Interchange No. 11A - Hopkinton	7	7	6	7
Interchange No. 12 - Framingham	2	1	1	2
Interchange No. 13 - Natick	6	2	0	3
Interchange No. 14 - Weston	18	20	22	20
Interchange No. 15 - Weston	20	28	22	24
Interchange No. 16 - Boston Extension	9	11	11	11
Interchange No. 18 - Entrance to WB Turnpike	0	1	0	1
Interchange No. 18 - Exit from EB Turnpike	16	22	14	18
Sumner Tunnel Toll Plaza	1	3	5	3
Ted Williams Tunnel (WB Only)	3	0	0	1
Tobin Bridge (SB only)	6	0	1	3
TOTAL CRASHES	113	132	136	135

4.2.1 Crash Level Trends

The preliminary round of trend analysis looked at several isolated crash attributes. In order to identify complex multi-attribute relationships, single variables were first considered to explain the nature of crashes at toll plazas.

4.2.1.1 Crash Rate per Plaza

Crash rates were normalized and based upon a million entering vehicles. Annual average daily traffic (AADT) information needed for these calculations was derived from

2012 MassDOT plaza transaction records. The highest crash rate plaza for the three year analysis period was interchange 14 at the intersection of I-95 at 1.98 crashes per million entering vehicles. Additionally, interchange 18 in Allston had the second highest rate with 1.62 crashes per million entering vehicles. These rates are well above the statewide rates of 0.55 for urban interstates (33). The remainder of interchange crash rates are listed in TABLE 7 and represented graphically on the map in Figure 18.

Table 7: Crash Rates by Plaza

Interchange	Crash Year			Avg	Exiting AADT[a]	Crash[b] Rate
	2010	2011	2012			
Interchange No. 1 - West Stockbridge	2	4	4	3.3	11100	0.82
Interchange No. 2 - Lee	0	0	0	0.0	5910	0.00
Interchange No. 3 - Westfield	1	3	1	1.7	11225	0.41
Interchange No. 4 - West Springfield (I-91)	3	2	10	5.0	19244	0.71
Interchange No. 5 - Chicopee	0	0	0	0.0	9536	0.00
Interchange No. 6 - Springfield	5	2	7	4.7	14411	0.89
Interchange No. 7 - Ludlow	0	0	1	0.3	7495	0.12
Interchange No. 8 - Palmer	0	0	1	0.3	9028	0.10
Interchange No. 9 - Sturbridge (I-84)	2	4	3	3.0	28728	0.29
Interchange No. 10 - Auburn (I-290)	5	4	7	5.3	21923	0.67
Interchange No. 10A - Millbury (Rt 146)	1	1	4	2.0	10965	0.50
Interchange No. 11 - Millbury	0	0	1	0.3	6999	0.13
Interchange No. 11A - Hopkinton (I-495)	2	4	4	3.3	31364	0.29
Interchange No. 12 - Framingham	2	0	1	1.0	15244	0.18
Interchange No. 13 - Natick	5	0	0	1.7	24119	0.19
Interchange No. 14 - Weston (I-95)	18	20	22	20.0	27692	1.98
Interchange No. 15 – Weston[c] (Mainline)	20	28	22	23.3	70350	0.91
Interchange No. 16 - Boston Ext (Mainline)	9	11	11	10.3	94849	0.30
Interchange No. 18 - Allston/Brighton	16	22	13	17.0	28714	1.62
Interchange No. 20 - Brighton/Cambridge	0	0	0	0.0	27025	0.00
Sumner Tunnel Toll Plaza (SB Only)	1	3	5	3.0	24685	0.33
Ted Williams Tunnel (WB Only)	3	0	0	1.0	21267	0.13
Tobin Bridge (SB only)	6	0	1	2.3	32500	0.20
[a]Note AADT Data from 2012 Massachusetts Turnpike Authority Traffic Report, data is for exit tolls only						
[b]Crash Rate Per Million Entering vehicles (crashes do not include vehicles entering toll facility)						
[c]Weston Exit 15 includes Exits 55 EB & WB						

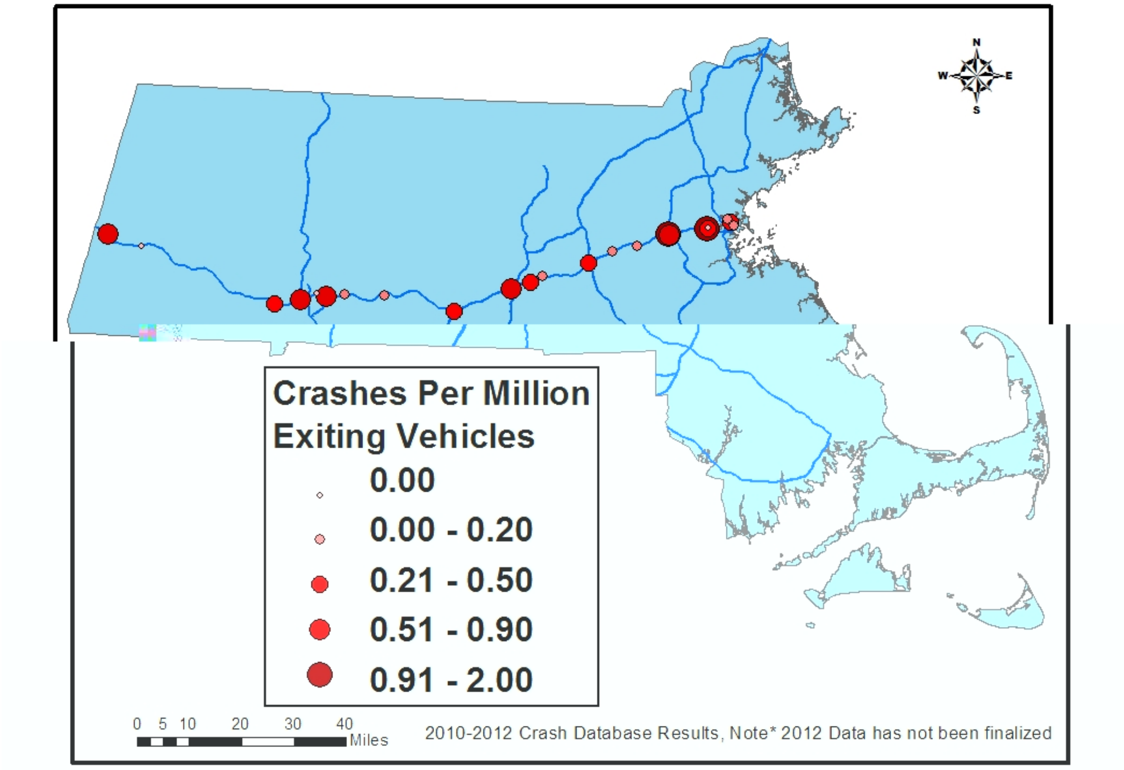


Figure 19: Toll plaza crash rate map.

4.2.1.2 Time of Day

Table 8: Time of Day Crash Results

Time	2010	2011	2012	Total
6AM-10AM	37	34	43	114
10AM-2PM	13	26	23	62
2PM-6PM	35	33	33	101
6PM-10PM	19	19	29	67
10PM-2AM	6	13	5	24
2AM-6AM	3	7	3	13

Time of collision was another factor investigated to improve understanding into crash causation. Crashes were categorized into time period buckets for analysis. Most toll plaza collisions occurred during normal commuting hours. TABLE 8 above reveals the 6AM to 10AM time period was the most active with 114 crashes over three years.

During the afternoon commuting period, 2PM – 6PM, there were 101 crashes at toll plazas.

4.2.1.3 Injury Status

Table 9: Injury Status Crash Results

Injury Status	2010	2011	2012	Total
No injury	96	105	101	302
Non-fatal injury	13	21	17	51
Non-fatal injury - Incapacitating	1	1	1	3
Non-fatal injury - Non-incapacitating	5	6	10	21
Non-fatal injury - Possible	7	14	6	27
Unknown	4	6	18	28

The majority of crashes at toll plazas have a non-injury outcome. No fatal crashes were reported during the analysis period from 2010-2012; however they have occurred in recent years. Very few crashes result in serious injury as indicated by the incapacitation level found in TABLE 9. The unknown crash category included injury statuses labeled "not reported" and "unavailable" information.

4.2.1.4 Age

Raw results are presented strictly by quantity per age group in Figure 19 and then again in the form of normalized rates from licensed records. Massachusetts driving population records from 2008 were used to normalize crash rates based on number of licensed drivers in each age range in Figure 20 below.

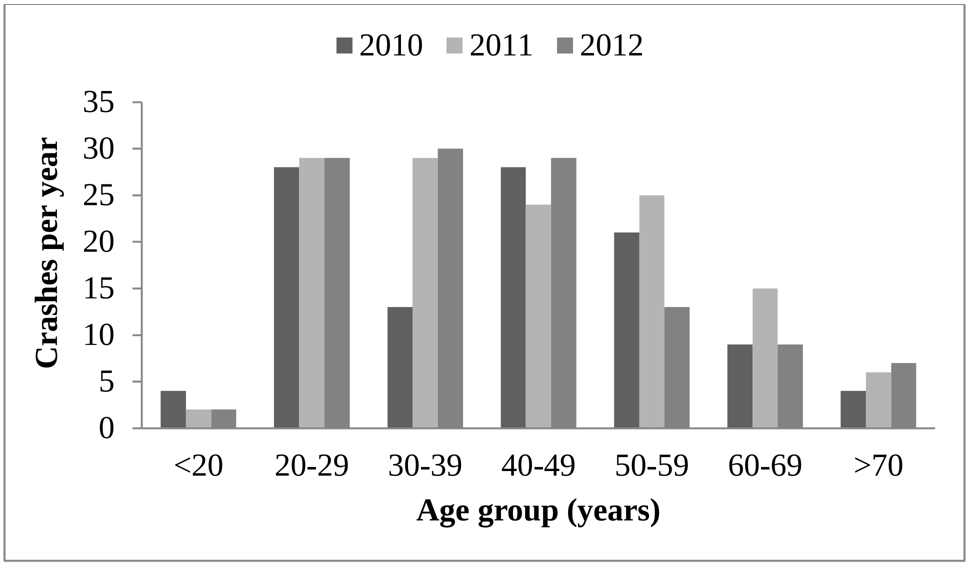


Figure 20: Crashes by age group.

Quantity based age groups failed to shed light on groups at risk properly. The normalized data below shows representative crash rates per 100,000 licensed drivers in the Commonwealth of Massachusetts.

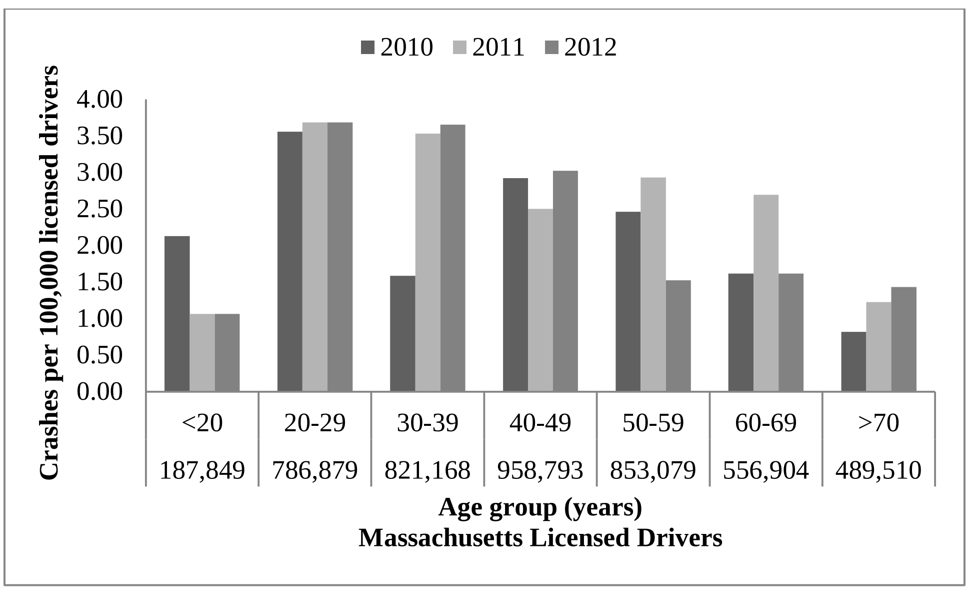


Figure 21: Normalized crash rates by age group.

The age range 20-39 years held the highest rates and subsequently was analyzed further in Figure 21 to identify any particular age or time period in a young drivers' life that may particularly be of risk.

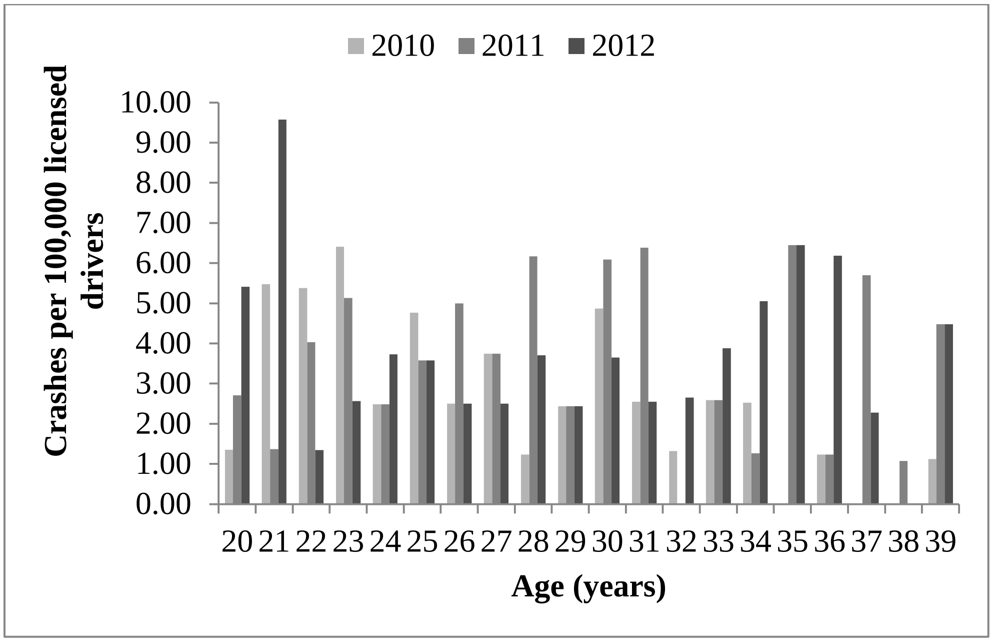


Figure 22: Normalized crash rates ages 20-39.

Ages 21 and 30 had on average the highest crash occurrences during the three year analysis period.

4.2.1.5 Manner of Collision

Manner of collision explains how vehicles in motion involved in a crash initially come into contact. Manner of collision signify injury seriousness or lead to potential contributing factors to the series of events that led to a crash.

Table 10: Manner of Collision Crash Results

Manner of Collision	2010	2011	2012	Total
Single Vehicle Crash	12 (11%)	19 (15%)	25 (19%)	56
Rear-end	57 (50%)	59 (46%)	49 (36%)	165
Angle	15 (13%)	20 (16%)	25 (19%)	60
Sideswipe, same direction	28 (25%)	30 (23%)	36 (27%)	94
Head on	1 (1%)	0 (0%)	0 (0%)	1

Table 10 and Figure 22 expose the majority of the crash types at toll plazas were rear-end with a quarter of crashes a result of a sideswipe action. Head on and opposite direction sideswipe collisions were nearly non-existent due to the divided nature of highway infrastructure.

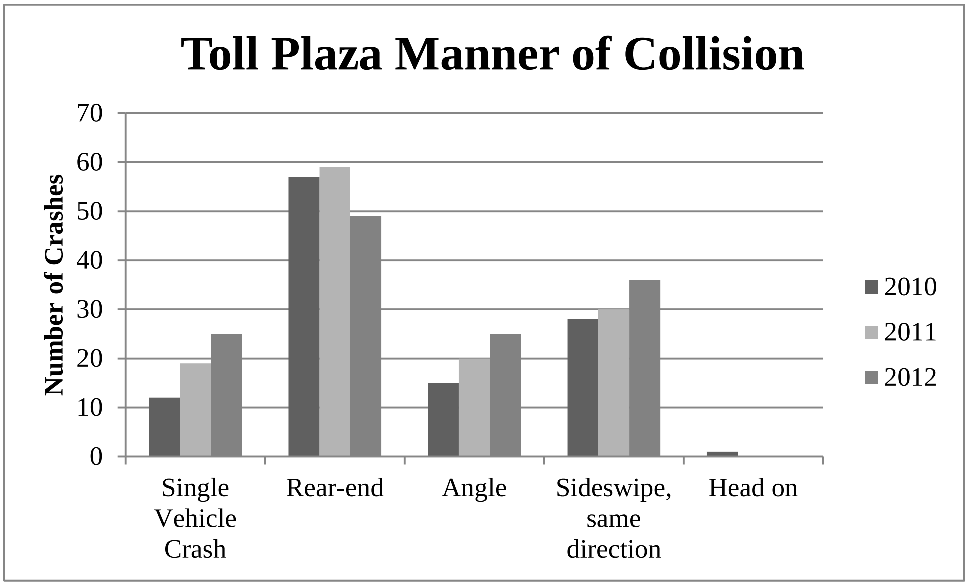


Figure 23 Manner of collision crash results.

4.2.1.6 Vehicle Type

Vehicle Type analysis may provide more than just the relative size of a vehicle and its associated drivetrain, it could point to vehicle trip purpose among other things.

Table 11 Vehicle Body Type Crash Results

Vehicle Body Type	2010	2011	2012
Passenger Car	94 (87%)	108 (82%)	114 (86%)
Single Unit	1 (1%)	5 (4%)	4 (3%)
Tractor Trailer	13 (12%)	19 (14%)	15 (11%)

Passenger vehicles comprise the majority of vehicles in toll plaza crashes, with a consistent 80 percent or more for each analysis year. The heavy vehicle percentage in TABLE 11 confirms the role of this interchange as a commercial truck route.

4.2.1.7 Driver Contributing Code

The driver contributing code indicates what action by each driver of each vehicle in a crash that may have caused the incident. For the purpose of this analysis each crash was assigned one contributing code based off the "at fault" driver in each case. Drivers coded 97, 98, 99 indicating unknown, not reported or other actions respectively, were deemed not at fault. TABLE 12 displays the leading driver contributing codes from 2010-2012.

Table 12 Driver Contributing Action Code Results

Driver Contributing Action Code	2010	2011	2012	Total
No Improper Driving	17	13	12	42
Exceeded speed limit	3	5	2	10
Disregarded traffic signs, signals, road markings	3	1	2	6
Failed to Yield Right of Way	6	11	9	26
Followed Too Closely	14	15	22	51
Made an improper turn	6	6	6	18
Driving too fast for conditions	6	7	5	18
Failure to keep in proper lane	3	8	5	16
Operating vehicle in erratic, reckless, aggressive	4	3	15	22
Over-correcting	2	0	0	2
Glare	0	1	0	1
Emotional	0	0	1	1
Visibility Obstructed	0	1	0	1
Inattention	15	16	10	41
Distracted	1	1	2	4
Fatigued	0	2	2	4
Operating defective equipment	0	1	0	1
Cellular Telephone	0	1	0	1
Unknown	33	40	43	116

Following too closely and driver inattention were the leading actions in toll plaza crashes. Driving technique errors comprised the majority of crash causes. These errors include speeding, failing to stay in lane, and failing to yield the right of way.

4.2.1.8 Injury Status vs. Plaza

Table 13 provided a double variable analysis, divulging which plaza was most harmful.

Table 13 Injury Status Versus Plaza Crash Results

Plaza	Non-Injury	Injury	Unknown	Total
Interchange No. 1 - West Stockbridge	11	3	0	14
Interchange No. 2 - Lee	0	0	0	0
Interchange No. 3 - Westfield	5	1	0	6
Interchange No. 4 - West Springfield	19	2	3	24
Interchange No. 5 - Chicopee	6	0	0	6
Interchange No. 6 - Springfield	16	0	1	17
Interchange No. 7 - Ludlow	1	0	0	1
Interchange No. 8 - Palmer	2	0	0	2
Interchange No. 9 - Sturbridge	11	1	2	14
Interchange No. 10 - Auburn	21	2	0	23
Interchange No. 10A - Millbury	5	2	1	8
Interchange No. 11 - Millbury	1	0	0	1
Interchange No. 11A - Hopkinton	17	2	1	20
Interchange No. 12 - Framingham	4	0	0	4
Interchange No. 13 - Natick	7	1	0	8
Interchange No. 14 - Weston	46	9	5	60
Interchange No. 15 - Weston	54	9	7	70
Interchange No. 16 - Boston Extension	21	5	5	31
Interchange No. 18 - Entrance to WB Turnpike	1	0	0	1
Interchange No. 18 - Exit from EB Turnpike	40	9	3	52
Sumner Tunnel Toll Plaza	5	4	0	9
Ted Williams Tunnel (WB Only)	3	0	0	3
Tobin Bridge (SB only)	6	1	0	7

Interchanges at Weston and Boston Extension had the highest number of injury crashes. The western turnpike exits 1 through 8 had very few serious injury crashes.

4.2.1.9 Manner of Collision vs. Plaza

Manner of collision was paired with individual toll facilities in the comparison summarized in Table 14. This relationship identified which plazas had trends of single vehicle crashes, rear-end, angle, sideswipe (same direction crashes) and head on collisions.

Table 14 Manner of Collision Versus Plaza Crash Results

Plaza	Single Vehicle Crash	Rear-end	Angle	Sideswipe, same direction	Head on	Total
Interchange No. 1 - West Stockbridge	3	4	4	3	0	14
Interchange No. 10 - Auburn	4	7	4	7	0	22
Interchange No. 10A - Millbury	4	2	2	0	0	8
Interchange No. 11A - Hopkinton	2	3	5	5	0	15
Interchange No. 12 - Framingham	1	1	4	2	0	8
Interchange No. 13 - Natick	2	4	1	1	1	9
Interchange No. 14 - Weston	3	45	1	11	0	60
Interchange No. 15 - Weston	9	31	10	20	0	70
Interchange No. 16 - Boston Extension	5	14	6	6	0	31
Interchange No. 18 - Exit from EB Turnpike	5	28	3	14	0	50
Interchange No. 3 - Westfield	1	2	2	0	0	5
Interchange No. 4 - West Springfield	4	6	3	11	0	24
Interchange No. 5 - Chicopee	3	5	5	10	0	23
Interchange No. 6 - Springfield	3	2	2	3	0	10
Interchange No. 7 - Ludlow	1	0	0	0	0	1
Interchange No. 8 - Palmer	1	1	0	0	0	2
Interchange No. 9 - Sturbridge	2	4	4	4	0	14
Sumner Tunnel Toll Plaza	2	2	2	3	0	9
Ted Williams Tunnel (WB Only)	0	2	0	1	0	3
Tobin Bridge (SB only)	2	3	1	1	0	7

Weston and Boston Extension area toll plazas posted highest in rear-end, angle and sideswipe collisions. Interchange 15 had the most single vehicle and angle crashes. Interchange 14 had the highest number of rear-end collisions. Figure 23 below shows a weak correlation (R^2=0.36) between the total number of lanes at a toll plaza and sideswipe collisions.

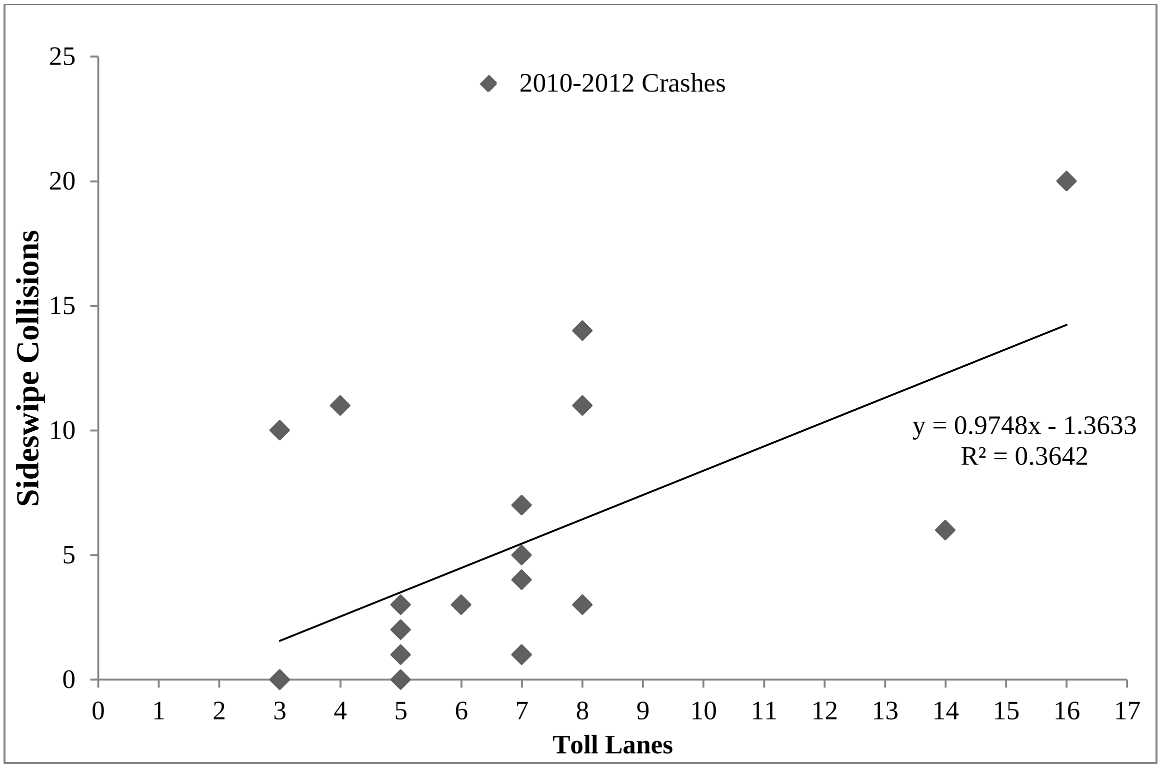


Figure 24 Sideswipe crash potential versus plaza size (number of toll lanes).

4.2.1.10 Time of Day vs. Injury Status

Time of day relationship was subjected to another step of analysis by pairing it with injury status in Figure 24. Injury severity was not significantly higher during off peak hours or peak hours. The afternoon and evening hours of 2PM to 10PM had the highest injury numbers.

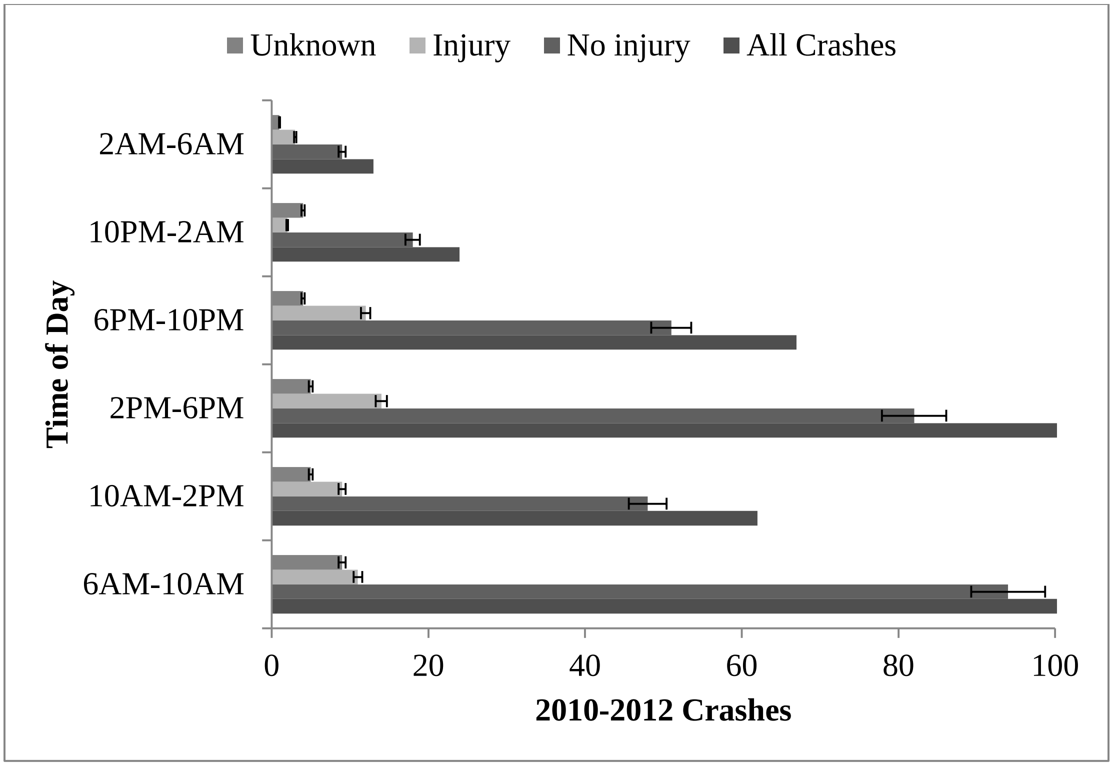


Figure 25 Time of day versus injury status.

4.3 Static Evaluation (Task 4)

The static evaluation was administered over the course of 5 weeks in spring 2013. One hundred evaluation responses were collected and tabulated. The field 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 and equal 50 percent split of male and female respondents. Educational background of the evaluation pool was 74 percent college educated, 16 percent some college, 8 percent high school degree and 2 percent no degree. Fifteen percent of evaluation results indicated over 10,000 miles of driving per year, 45 percent selected 1 to 10,000 miles per year and forty percent did not drive at all. Fifty seven percent of participants indicated they are typically ETC users, 33 percent were cash users and 10 percent used a mix of both. Eleven percent of participants were daily toll users, 12 percent were weekly users, 44 percent were monthly users and 33 percent used toll lanes less than 10 times per year.

Chi-square independence of variable statistic was completed on each group of lane choices based on their payment type. The following results for each scenario are summarized below.

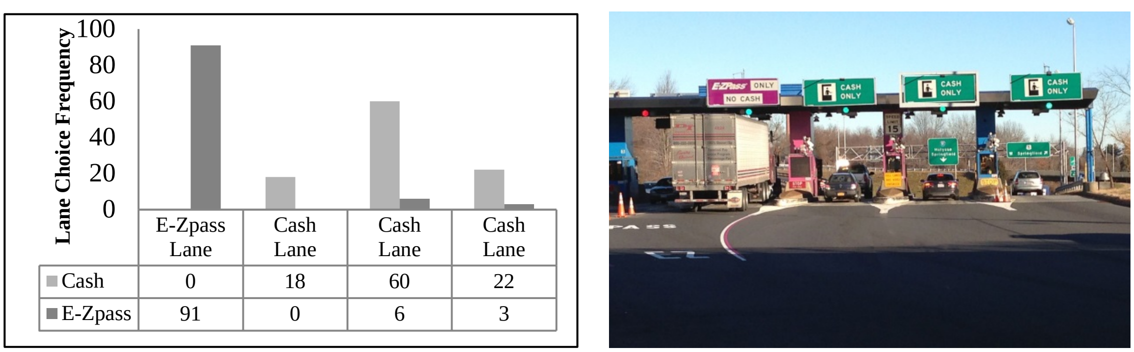
4.3.1.1 Lane Choice Results

The following figures uncover decision making distributions from each of the 15 scenarios. It should be noted that scenario photos were cropped for the results section and are for reference only. Selected scenarios had significant trends by demographic group; an absence of additional trend information meant no differences were found in that scenario's results. For full detailed photographs of scenarios and traffic conditions, please refer to Appendix A.

4.3.1.1.1 Scenario 1

Scenario 1 introduced a queue on the only ETC lane as shown in Figure 25.

Scenario 1 – Left Side E-ZPass Lane



P-Value: 0.00

Figure 26 Scenario 1 static evaluation results.

As expected, the majority of E-ZPass customers selected lane 4, the left most lane and only ETC capable lane. The majority of cash customers split their selections among the three cash only lanes, with the highest proportion selecting the center right lane (lane 2). The chi-square p-value independence test suggests unbiased selections.

4.3.1.1.2 Scenario 2

Scenario 2 in Figure 26 had short queues on 2 of 3 cash lanes and maintained the queued ETC lane on the left.

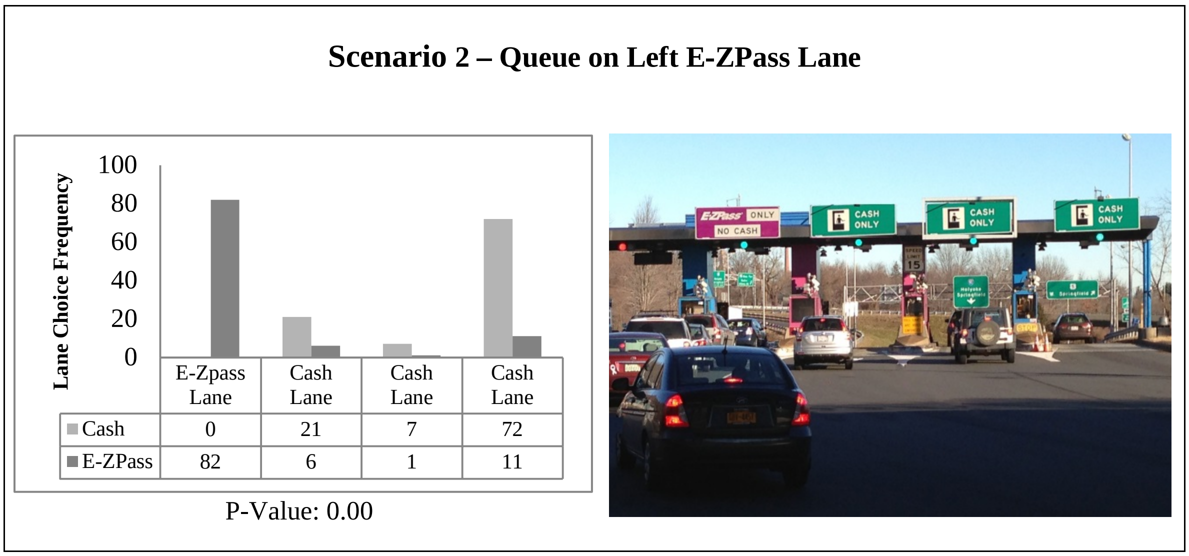


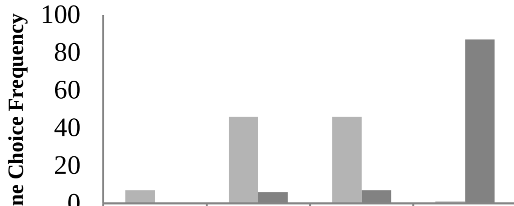
Figure 27 Scenario 2 static evaluation results.

The dedicated E-ZPass lane on the left (lane 4) was selected most often; however 18 percent of participants selected a cash lane. Nearly three quarters of cash users selected the far right lane as their desired lane.

4.3.1.1.3 Scenario 3

Scenario 3 swapped the placement of the TC lane to the right as shown in Figure 27.

Scenario 3 – Right Side E-ZPass Lane with Queue



	Cash Lane	Cash Lane	Cash Lane	E-Zpass Lane
Cash	7	46	46	1
E-ZPass	0	6	7	87

P-Value: 0.00

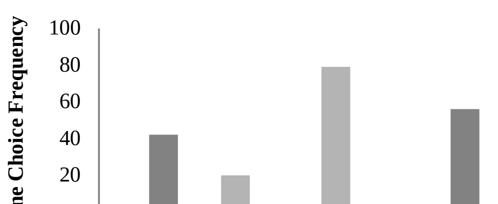
Figure 28 Scenario 3 static evaluation results.

The only dedicated E-ZPass lane on the right was selected most frequently, but ETC payment users still selected Cash only lanes. Open center cash lanes were selected equally, with the far left lane receiving very few selections.

4.3.1.1.4 Scenario 4

Scenario 4 added a second ETC lane on either side of the toll plaza as exposed in Figure 28.

Scenario 4 – Short Queues on E-ZPass Lanes



	E-ZPass Lane	Cash Lane	Cash Lane	E-ZPass Lane
Cash	0	20	79	1
E-ZPass	42	0	2	56

P-Value: 0.00

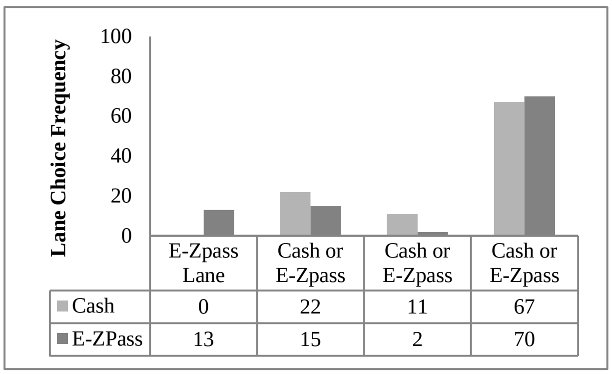
Figure 29 Scenario 4 static evaluation results.

E-ZPass customer decisions were fairly equalized in both lane opportunities in this scenario. Cash customers on the other hand heavily favored the center right lane at 79 percent.

4.3.1.1.5 Scenario 5

Scenario 5 in Figure 29 introduced combination lanes capable of accepting cash and ETC transactions.

Scenario 5 – Queue on Left E-ZPass Lane



P-Value: 0.00

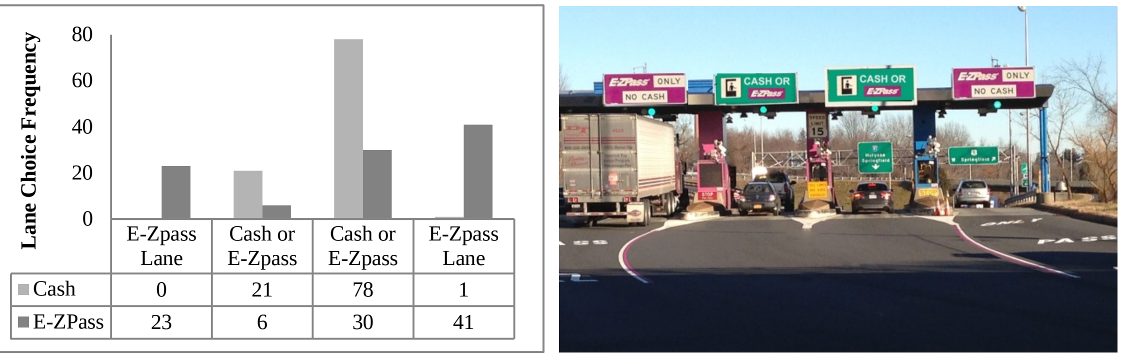
Figure 30 Scenario 5 static evaluation results.

Seventy percent of E-ZPass customers defected from the dedicated ETC lane to take a combination lane with no queue. Cash customers elected the right lane as preferential in this scenario.

4.3.1.1.6 Scenario 6

Scenario 6 in Figure 30 replaced the left plaza aligned queue with a heavy vehicle.

Scenario 6 – Small Queue on E-ZPass Lanes



	E-Zpass Lane	Cash or E-Zpass	Cash or E-Zpass	E-Zpass Lane
Cash	0	21	78	1
E-ZPass	23	6	30	41

P-Value: 0.00

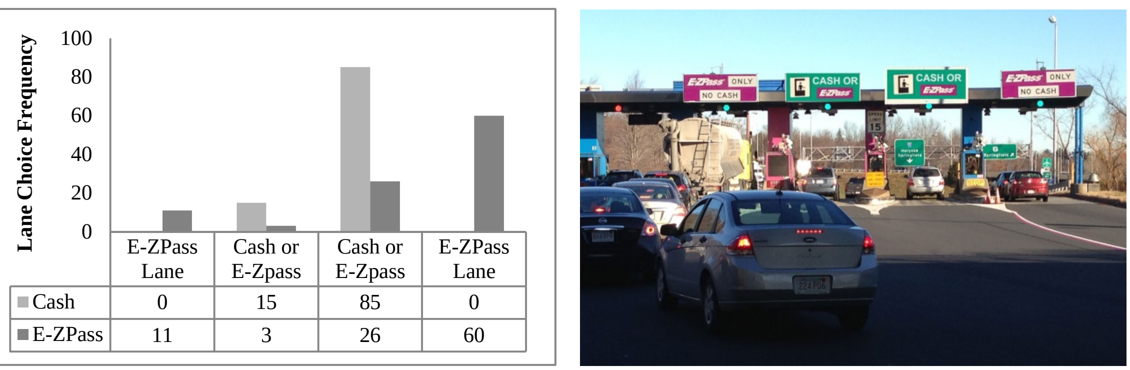
Figure 31 Scenario 6 static evaluation results.

No E-ZPass lane has a majority of lane decisions, while cash users selected the center right lane as their preference. Demographic data reveals female ETC users (N=15) were nearly twice as likely to pick the left dedicated E-ZPass lane than men (N=8)

4.3.1.1.7 Scenario 7

Scenario 7 in Figure 31 invoked a queue on the left ETC lane.

Scenario 7 – Queue on Left E-ZPass Lane



	E-ZPass Lane	Cash or E-Zpass	Cash or E-Zpass	E-ZPass Lane
Cash	0	15	85	0
E-ZPass	11	3	26	60

P-Value: 0.00

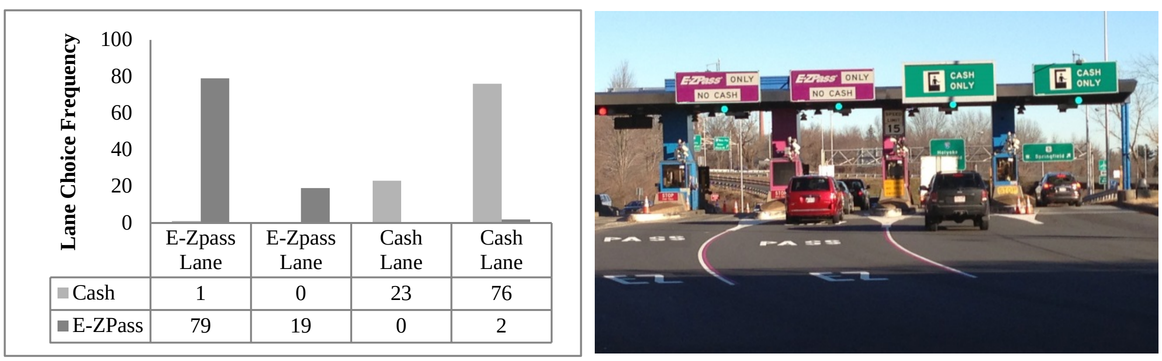
Figure 32 Scenario 7 static evaluation results.

Scenario 7 had distributed lane choices for ETC customers with the far right lane reeling in the majority. The center right combination lane was selected overwhelmingly 85 percent of the time for this scenario.

4.3.1.1.8 Scenario 8

Scenario 8 moved ETC lanes to the left, placing them adjacent to one another. The other two lanes were reverted to cash lanes as shown in Figure 32.

Scenario 8 – Double inside E-ZPass Lanes



P-Value: 0.00

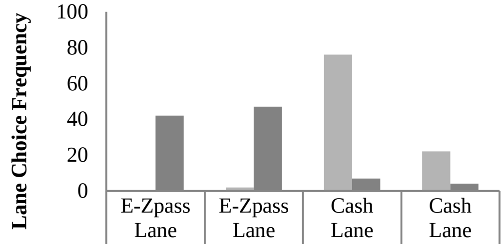
Figure 33 Scenario 8 static evaluation results.

The majority (79 percent) of E-ZPass customers elected far left lane 4. Cash customers opted for right lane for toll plaza navigation. Lane choice percentages are nearly mirrored about the center of the plaza.

4.3.1.1.9 Scenario 9

Scenario 9 in Figure 33 added a car and a heavy vehicle queue to ETC lanes on the left. Lane 3 has 3 cars while lane 4 has one heavy vehicle.

Scenario 9 – Double Left E-ZPass Lanes with Queues



	E-Zpass Lane	E-Zpass Lane	Cash Lane	Cash Lane
Cash	0	2	76	22
E-ZPass	42	47	7	4

P-Value: 0.00

Figure 34 Scenario 9 static evaluation results.

E-ZPass lane selection was divided approximately equal between both left plaza aligned lanes. Cash users opted for the center right lane 76 percent of the time. Demographic data reveals (34 of 57) typical or frequent E-ZPass users selected E-ZPass lane 3 while (21 of 33) frequent cash users elect the left most lane 4. Demographic groups containing (41 of 51) users of the 20-30 year old age group and (46 of 57) from the frequent E-ZPass customer group preferred the center right lane when evaluated as a cash user.

4.3.1.1.10 Scenario 10

Scenario 10 introduced a mixture of all three booth types as demonstrated in Figure 34.

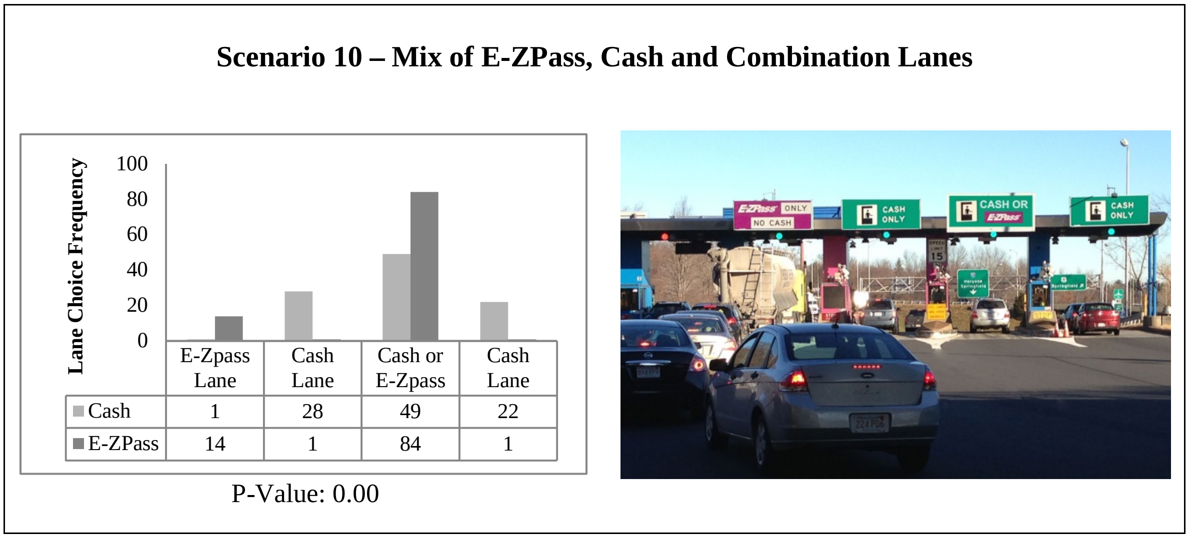


Figure 35 Scenario 10 static evaluation results.

Combination lane 2 drew the highest preference for both payment classes. Cash customers had a distributed level of lane tendency for all available cash-accepting lanes.

4.3.1.1.11 Scenario 11

Scenario 11 in Figure 35 moved the dedicated ETC lane to center left and maintained a mix booth type.

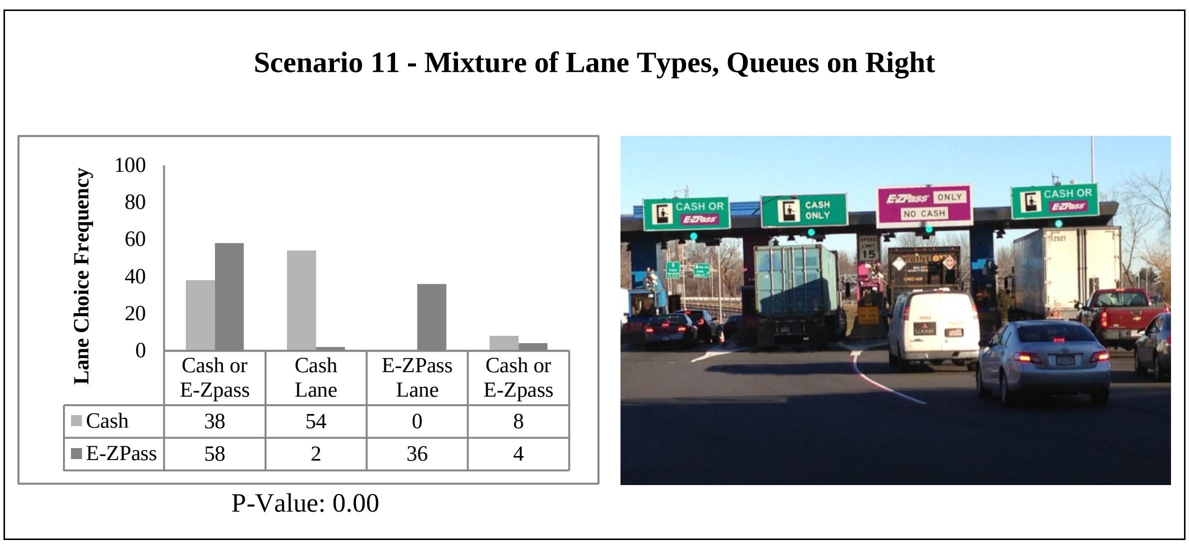


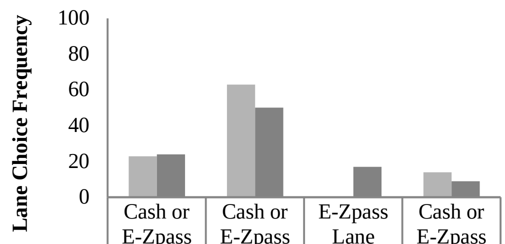
Figure 36 Scenario 11 static evaluation results.

A majority of E-ZPass users elected the left combination lane with the shorter queue. The preference among the cash class of customers was lane 3, the dedicated cash lane.

4.3.1.1.12 Scenario 12

Scenario 12 opened up the plaza from all but one queue on the dedicated ETC lane. Figure 36 reveals that all lanes accept E-ZPass.

Scenario 12 – Combination Lanes, Queue on Dedicated E-ZPass Lane



	Cash or E-Zpass	Cash or E-Zpass	E-Zpass Lane	Cash or E-Zpass
Cash	23	63	0	14
E-ZPass	24	50	17	9

P-Value: 0.00

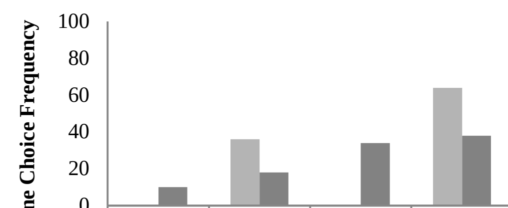
Figure 37 Scenario 12 static evaluation results.

Driver lane choice for scenario 12 was distributed for all available lanes for each class of customer. Cash customers preferred combination lane 3 63 percent of the time and this exactly half of all responses.

4.3.1.1.13 Scenario 13

Figure 37 contains scenario 13 which alternated ETC and combination lanes. This configuration provides a balanced opportunity for vehicles to select a lane regardless of how they approach the plaza

Scenario 13 – E-ZPass and Combination Lanes, Left lane Queue



	E-Zpass Lane	Cash or E-Zpass	E-Zpass Lane	Cash or E-Zpass
Cash	0	36	0	64
E-ZPass	10	18	34	38

P-Value: 0.00

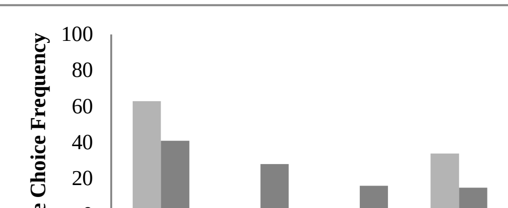
Figure 38 Scenario 13 static evaluation results.

E-ZPass users had nearly equal lane preference on lanes 1 and 2. Cash customers had indicated lane 1 as their choice 64 percent of the time. E-ZPass lane selection has increasing preference to right-sided lanes in this scenario.

4.3.1.1.14 Scenario 14

Scenario 14 in Figure 38 shifted ETC lanes to the center. This is a modified version of present day Exit 4's configuration.

Scenario 14 – Center E-ZPass Lanes with Short Queues



	Cash or E-Zpass	E-ZPass Lane	E-ZPass Lane	Cash or E-Zpass
Cash	63	3	0	34
E-ZPass	41	28	16	15

P-Value: 0.00

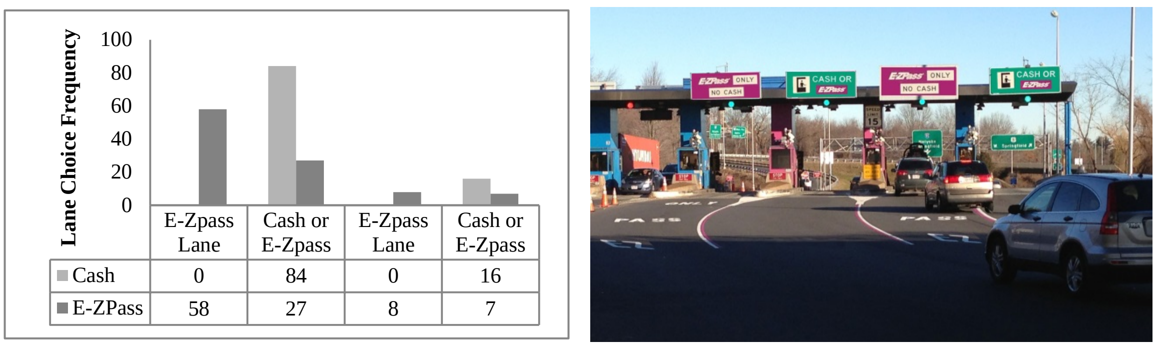
Figure 39 Scenario 14 static evaluation results.

E-ZPass lane selection was distributed and not heavily concentrated on any particular lane. Cash users preferred the left most lane at 63 percent.

4.3.1.1.15 Scenario 15

Scenario 15 in Figure 39 is a revision of scenario 13 with a queue on the right dedicated ETC lane.

Scenario 15 –E-ZPass, Combination Lanes, Queue on Center Right



	E-Zpass Lane	Cash or E-Zpass	E-Zpass Lane	Cash or E-Zpass
Cash	0	84	0	16
E-ZPass	58	27	8	7

P-Value: 0.00

Figure 40 Scenario 15 static evaluation results.

A high majority of cash customers elected open lane 3, while E-ZPass preference favored the open dedicated lane in position 4 to the left of the combination lane 3.

4.4 Microsimulation Results (Task 5)

The methods of evaluating the microsimulation results or measures of effectiveness (MOEs) can be categorized in two forms, observational and quantitative. Observational results encompassed a real time review of the simulation visually. In this process, simulations were reviewed to compare to field videos. While exact duplication was not expected, similar traffic operations were anticipated. Quantitative results contained a comparison between observed and simulated throughput results. Volumes were examined individually by lane and by total throughput.

4.4.1 West Springfield Present Day Plaza Calibration

West Springfield exit 4 of the Massachusetts Turnpike provided the base case for microsimulation model development and testing. This scenario used December 2012 volumes, O-D data and current lane configuration of the plaza. Lane layout offered two cash manual 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 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 15. The microsimulation model resulted in a similar distribution of lane choices. Parameter tweaking, resulted in a throughput of 8 percent lower than observed.

Table 15 Model Calibration Volumes

		Volume (Vehicles per hour)					
Case	Lane Configuration	Lane 4	Lane 3	Lane 2	Lane 1	Total	% Change
2013 Observed Data	Cash-E-ZPass-E-ZPass-Cash	270	390	503	277	1440	
2013 Configuration	Cash-EZPass-EZPass-Cash	220	368	496	240	1324	-8%

4.4.2 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 MassDOT 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 from this configuration to the base case served as an evaluation of the model's effectiveness. The validation was successful in terms of total throughput volumes with only a 3 percent difference in volumes as seen in Table 16 below.

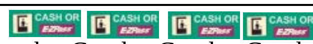
Table 16 Model Validation Volumes

		Volume (Vehicles per hour)					
Case	**Lane Configuration**	**Lane 4**	**Lane 3**	**Lane 2**	**Lane 1**	**Total**	**% Change**
2012 Observed Data	Combo-Cash-EZPass-Combo	149	189	455	340	1133	
2012 Configuration	Combo-Cash-EZPass-Combo	400	84	212	476	1172	3%

4.4.3 New Configurations

The research goals outlined the practicality of this research as a tool for toll plaza operation 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 are summarized in Table 17 below.

Table 17 Microsimulation Alternate Configuration Results

Case	Lane Configuration	Volume (Vehicles per hour) Lane 4	Lane 3	Lane 2	Lane 1	Total	% Change
2013 Observed Configuration	 Cash-EZPass-EZPass-Cash	270	390	503	277	1440	
Case 4	 EZPass-Cash-Cash-EZPass	284	148	240	388	1060	-20%
Case 6	 EZPass-Combo-Combo-EZPass	156	220	324	240	940	-29%
Case 8	 EZPass-EZPass-Cash-Cash	576	304	200	232	1312	-1%
Case 13	 EZPass-Combo-EZPass-Combo	188	228	160	368	944	-29%
Case 14/15	 Combo-EZPass-EZPass-Combo	368	108	164	408	1048	-21%
Combination lanes	 Combo-Combo-Combo-Combo	364	208	336	484	1392	5%

Case 6 configuration provided the lowest plaza throughput as a whole, while the all combination lane configuration provided the highest throughput of all cases. The current configuration remained the highest throughput result for all configurations tested.

CHAPTER 5

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Conflict and Event Study

Crash histories provide engineers with trends in moderate to severe safety concerns in the form of collision reports. Other incidents may be occurring that due not lead to a crash but nonetheless may be jeopardizing the safe and efficient passage of vehicles through a toll plaza. The conflict and event study results addressed the objectives outlined in section 3.1.1.

Honking and secondary braking were the most prevalent events triggered by other vehicles in the toll plaza environment. Lane changes and last second maneuvers may be the result of the late epiphany by drivers that they may be sitting in an inappropriate toll lane. Alternatively, these events may be the consequence of an aggressive driver in the pursuit of shedding 20 seconds off their commute to work.

Configurations that minimize lane changes were considered in the static evaluation and microsimulation tasks based upon this feedback.

5.2 Crash Analyses

Aforementioned in Chapter 4 results, crash analyses were completed by single and double variables in an attempt to gain insight into toll plaza safety. Crash history analysis fulfilled objective 1 outline in Chapter 3. Reviewing toll plaza statistics led to the following considerations. The Weston exit 15 boundary plazas had the highest number of plaza crashes. While overall toll plaza crashes are a minimal portion of 200,000 crashes each year in the Commonwealth at less than 0.1 percent of all crashes some toll plazas have higher crash rates than the state wide urban interstate average. Nonetheless, investigation into the origin of these highway mishaps may prevent future injury and improve overall highway safety at these frequented highway junctures.

5.2.1 Crash Rate per Plaza

The Weston and Allston/Brighton plazas have crash rates 3 times higher than statewide averages. Furthermore, a total of seven plazas have higher crash rates than statewide crash averages for interstates. Concerning as these rates may seem, multi-variable trends may provide insight to what may be leading to these safety issues. Certainly, high travelled roads introduce higher probabilities of vehicle to vehicle interactions. Congestion on the other hand may have a secondary and unintentional safety benefit that lowers average speeds around plazas and ultimately decreases the severity and perhaps collision frequency.

5.2.2 Time of Day

Time of day analysis indicated a higher amount of crashes during the busiest times of the day. Results were not normalized for hourly traffic volume variations due to a lack of data availability for all plazas. The records do not suggest a higher number of crashes during late night due to free flow conditions and a driver's ability to travel at higher speeds as previously predicted.

5.2.3 Injury Status

One sixth of all crashes resulted in an injury. Remaining crashes were deemed non-injury which could be attributed to the low speeds at toll plazas. Twenty collisions a year were more serious and inflicted bodily harm. Low incapacitation numbers provide relief that collisions are relatively minor.

5.2.4 Age

Driver's age often surfaces when discussing human error in at fault crashes. Surprisingly, young and old drivers, the two categories of drivers typically most at risk, had the lowest crash occurrences. Highest rates came from the 20-40 year old range, with a significant decline in middle aged drivers. Further detailed age analysis of this age group yielded no significant trends but higher rates from young twenty year olds.

5.2.5 Manner of Collision

Crash type analysis returned high rear-end crash numbers as expected at toll plazas where queuing is common. Sideswipe incidents are also understandable due to merging zones prior to and following the toll booths. A high number of single vehicle crashes seems to signify collision with either infrastructure or other form of the driving environment. Rear-end collisions at toll plazas are typically the result of driver inattention, following too closely or exceeding reasonable speeds.

5.2.6 Vehicle Type

Vehicle type could signify to toll plaza safety issues if a particular vehicle body type was over represented in crash analysis. In this circumstance, passenger cars including light duty pickups were the common vehicle in collisions. Tractor trailers account for 1 in 8 crashes but are not necessarily more or less at fault. It would be reasonable to assume commercial drivers, having more experience driving through toll environments would learn the safest and most efficient paths of least resistance or lane changes. Vehicle type data by itself does not provide any grave insight into crash trends.

5.2.7 Driver Contributing Code

Stemming from manner of collision results, rear-end results and sideswiping collisions are the product of following too closely and failing to yield or straying out of a lane. Interestingly enough, distraction and inattention are highly at fault as well with almost 40 percent of contributing actions. Distracted driving is a problem on every form of roadway but highly important at toll plaza junctions due to the rapid decision making required at these facilities. Signage, lane assignments and other vehicles all compete for drivers focus and mental resources. Inattention may be mislabeled as distraction or vice versa in some instances. However, unnecessary fault may be placed upon drivers if when operating under control and as expected the environment introduces confusion and risk. Excessive or inopportunely placed signage may be consuming more resources than necessary for the benefit of the end users information on lane and payment type. Many states have adopted the policy of accepting any form of payment at every lane to avoid confusion and panic by drivers.

In field observations, drivers infrequently come to complete stops in dedicated ETC lanes. In some rare incidents they will backup and traverse to cash or manual lanes to complete their payment. This poses a risk to that vehicle and every other vehicle approaching the plaza. Other drivers may not understand the intentions of a misguided vehicle and cause a chain of unpredictable and dangerous maneuvers to adjacent or following cars. A solution for this problem may be to employ a policy accepting all payment forms.

5.2.8 Injury Status vs. Plaza

Interchanges at Weston (I-95) and Boston Extension (Newton) had the highest number of injury related crashes. These three collocated plazas were also the highest crash rate plazas in the state as well, which provides little credible evidence of out of the ordinary operations. Further exploration into manner of collision and contributing actions by the "at fault" driver may shed light into environmental influences at these busy plazas. Interchanges 14, 15, 16 are all large in size with seven or more lanes to choose from one approach. Current lane assignments have distributed ETC lanes on boundary lanes and manual lanes in the center. However, none of these plazas employ multiple payment methods.

5.2.9 Manner of Collision vs. Plaza

Rear-end crashes are most common at high demand plazas. Generally, the number of lanes a plaza has, directly correlates to a higher rate of angle and sideswipe collision potential. Larger plazas have a tendency to have more sideswiping collisions, but with such a small sample size of crashes, this relationship cannot be officially verified with any significance.

5.2.10 Time vs. Injury Status

Commuting hours proved to be most harmful with over 25 injury related crashes between the AM and PM peak travel hours during the analysis period. The overnight hours were low in crashes and few in injuries. While speeds may decrease due to congestion on highways, injuries remain an issue during most daylight hours.

5.3 Static Evaluation

The static evaluation identified driver decision making trends based upon a snapshot view of varied lane configurations. The order of scenarios as delineated in section 3.2.4, task 4 dictated the research strategies exercised to understand driver decision making. The following discussion of scenarios reviews underlying decision criteria and answer the objectives sought after under objective 2 in section 3.1.2.

5.3.1 Scenario 1

Scenario 1 static evaluation results provided some initial feedback to lane choice decision making. E-ZPass customer responses were anticipated; users rightfully picked the only dedicated lane. However, (N=9) E-ZPass customers chose cash only manual lanes, which may suggest a bit of driver confusion. Combination payment lanes may help in similar instances. In the educated and 20-30 year old driver groups, users overwhelmingly picked the center right cash lane. Additionally, albeit a small demographic (N=4), elder drivers which are those in excess of 70 years, maintained a safe buffer by selecting the right lane every time. Eighty two percent of all users selected a non-adjacent lane, suggesting a preference in buffer lanes.

5.3.2 Scenario 2

Scenario 2 results reconfirmed the findings from scenario 1 with regards to the ETC usage. However, interestingly enough, a one car queue in scenario 2 was enough to motivate the masses to move their selection one lane to the right. This shift creates an even larger buffer against queued ETC customers. There is reason to believe that drivers are seeking to minimize their travel time through toll plaza maneuvers even with a short queue.

5.3.3 Scenario 3

Results from this scenario lend to estimation that drivers tend to steer towards center lanes when an ETC lane prevents them from occupying the right most lanes. Thirteen users selected cash lanes when acting as an ETC customer, propagating the confusion notion though proposed in earlier scenarios.

5.3.4 Scenario 4

Lane choice behavior for ETC customers was typical in this scenario. Short queues on lanes 2, 3, 4 do not seem to play a role. Cash decision making is weighted heavier on the center right lane. Perhaps cash customers tend to stay to the right on approach of a toll plaza. Demographic data points suggest significant relationships to account for this behavior.

5.3.5 Scenario 5

Cash and ETC users prefer to be impacted by a one car queue and consequently selecting the open lane for their path in scenario 5. Interestingly, both cash and E-ZPass customers preferred the center lane as their second highest choice despite proximity to a queue and leaving no lane as a buffer.

5.3.6 Scenario 6

In scenario 6 dedicated lanes were preferred as ETC lanes when combination lane queues are short. Drivers may be considering the relative transaction time of one E-ZPass customer versus one cash customer. On approach, 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. This scenario also demonstrated a trend of cash users preferring right lanes over left with 78 percent selecting lane 2.

5.3.7 Scenario 7

Cash customers in this Scenario appeared to be deterred from selecting the center left lane by the apparent blockage from the car queued in lane 4. Sixty percent of ETC customers elected to stay in a dedicated lane to the far right, requiring more than likely up to 3 lane changes if arriving on the left. For the same queue length, ETC users prefer dedicated lanes over shared payment method lanes.

5.3.8 Scenario 8

In scenario 8, both user groups elected to take the most open lane per their payment method. While these outside lanes habitually surface as the tendency for each respective payment class, this Scenario provides no further evidence proving that relationship.

5.3.9 Scenario 9

Scenario 9 uncovers evidence to suggest drivers profile the vehicle type of queued automobiles. In lane 4 a heavy vehicle and tractor trailer, presumably a slower moving vehicle through a toll lane, was avoided by almost half of participants despite the longer queue existing on the other lane of choice for ETC users. Demographic data of typical toll plaza payment method verifies this notion. Sixty percent of typical E-ZPass payment users elected lane 3 over 4 despite the longer queue. Surprisingly, 76 percent of users preferred lane 2 or the center right cash lane which contradicts the trend of other scenarios that show a right side inclination for cash users. Despite a queue and lack of buffer lane in the adjacent lane 3, users opted for lane 2 to avoid one vehicle exiting lane 1 in our snapshot.

5.3.10 Scenario 10

Lane selection in Scenario 10 revealed a high majority of E-ZPass customers deferred to the empty combination lane 2. However, despite large queues of 5 or more vehicles, 14 percent of participants elected to stay in the dedicated E-ZPass lane to the left. This scenario differs in lane 2 from Scenario 2 which unexpectedly drew a high preference from both user groups. High lane 2 selections from E-ZPass customers is expected due to the queues on lane 4, however cash users seem to prefer this lane despite two other adjacent equally short queue cash only lanes. This behavior could be explained by a preference of a center right lane which would better position a driver for downstream maneuvers if applicable.

5.3.11 Scenario 11

Scenario 11 introduces a multi-level decision making process for both user classes. For cash customers, a heavy vehicle sits in the lowest queued cash lane available but manages to acquire 54 percent of users' selections despite the lane of only cars to the left. E-ZPass customers are drawn to the shorter queue of lane 4; however 36 percent may deem this decision a risk. The risk could have evolved from waiting out the remainder of the ETC vehicles queues on the right or the potential cash user sitting in lane 4. 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 of 20-60 seconds on the far most left lane. This weighing of travel time benefit to cost is a cyclical evaluation that drivers at facilities that offer combination lanes must make on toll plaza approaches.

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.

As discussed in Section 4.2.1.7, driver inattention is the second leading crash contributing factor at toll plazas in Massachusetts. As drivers approach a plaza they evaluate lanes based on several key factors with the goal of minimizing travel time. If at some point conditions change and the benefit of time saved outweighs maneuvering risks, a driver will likely change lanes. Additional stimuli may not necessarily be the intent of a combination lane, but additional lanes to monitor may add to the mental workload of drivers. While most drivers are highly risk adverse, those aggressive drivers seem to be in the most danger for making an error.

5.3.12 Scenario 12

In scenario 12 both lanes 3 and 4 were identical lane types and free of queues. From this information, the majority of drivers picked the center left lane in both payment classes. This behavior has also been elicited in Scenarios 7, 9 and 10. It may suggest drivers know that a merge point exists after the plaza and have positioned themselves to make a safer maneuver. However, 17 percent of ETC users were undeterred and persistent on using a queued dedicated E-ZPass lane.

5.3.13 Scenario 13

Surprisingly, 44 percent of E-ZPass users selected dedicated lanes despite the lower queued combination lanes afforded in this scenario. E-ZPass selection preference increased from left to right, which can most aptly be explained by the inverse of queue lengths on these lanes. Interestingly enough, ETC choices picked a dedicated lane with queues over an empty adjacent combination lane.

5.3.14 Scenario 14

A centralized set of ETC lanes invokes a distribution of lane choice in this scenario. Despite a queue of one vehicle, drivers deviate from their paths to a boundary toll lane. These decisions may be explained by the queues themselves or familiarity with the plaza in question. This Scenario would mimic the layout of Exit 4 of the Mass Turnpike if present day cash lanes were converted to combination lanes. However, payment transaction history at the plaza would seem to discourage these percentages of lane choice. Table 18 reveals the comparison of lane selection distributions between the static evaluation and actual transaction data.

Table 18 Static Evaluation Versus Transactional Distributions

	Percentage of Users Selecting Lane			
	Lane 4	Lane 3	Lane 2	Lane 1
Cash Evaluation	63	3	0	34
E-ZPass Evaluation	41	28	16	15
2012 Transactions	22	20	37	21

5.3.15 Scenario 15

This scenario reinforced the likelihood that ETC users prefer dedicated lanes despite an open combination lane in a closer path to them. Sixteen cash users were willing to risk merging across a dedicated E-ZPass lane.

5.3.16 Discussion on Driver Lane Choice

Scenarios were designed with certain theories in mind in order to frame and test them as discussed in section 4.4.3. The static evaluation provided some insight into alternate configurations; others not and even revealed other driver decision making that may be in effect at toll plazas. Throughout the scenarios, drivers are taking 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.

Some participants may have been familiar with this plaza and taken that into consideration when selecting a lane. While others may not know the decision point downstream, they rely on the metering effect of the toll plaza. This metering effect is best served when vehicles of different exiting velocities are located adjacent to one another. Lanes of similar exiting trajectories may channel or block drivers into making decisions downstream of the plaza. Experienced drivers may use prior knowledge to position themselves for easier merging movements.

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 transactions. However, added ETC vehicles to lanes that serve cash customers degrade the level of service and increase both customer type delays. 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 stack of cars in an ETC lane.

Vehicles ahead in queue seemed to play a role in 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 small 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 counterparts.

5.3.17 Unanswered topics

The static evaluation provided an initial glance into lane selection decision making. Further research may answer the lingering questions of how much risk drivers wager in lane changing. The evaluation only contained 4 lanes to minimize scenario permutations. Future work may be interested in mega plazas of 7 or more lanes as their operations would certainly vary with traffic demand.

5.4 Microsimulation Model

Traffic at toll plazas exhibit stochastic behavior by nature, the model developed within the scope of this research aimed to best represent realistic operations. The model developed may help engineers and toll operators alike predict the impact of constructing specific configurations, closing lanes and how to arrange lanes to maximize safety throughput and minimize driver confusion. Through the previous two tasks we have analyzed the past safety record at toll plaza infrastructure and quantified the users' understanding of lane types and configuration. This model realizes the goals as proposed in objective 3 of section 3.1.3.

5.4.1 Base Model

The development of the initial model proved to be an arduous task. Decisions were made to adjust parameters to align with available field data. Assumptions were grounded on driver decision making configurations commonly accepted in practice, and some default built-in values that VISSIM provided.

5.4.2 Baseline Configuration and Calibration

The initial model used O-D zonal trips from December 2012 field data. Route choice analysis conducted using VISSIM's dynamic assignment permitted vehicles to reevaluate route choice at the toll plaza approach. The model was calibrated to best represent observed lane throughputs for the baseline case configuration. Believed to be stimulated by unfamiliarity and unpredictable behavior, the stochastic nature of toll interchanges often disrupts traffic flow. The closest representation of simulation throughput only reached 92 percent of observed throughput, but allowed calibration to proceed and select the configuration from earlier in 2012 as its validation period.

5.4.3 Baseline Validation

Validation was successful and provided some feedback regarding the dynamic assignment model. Overall throughput volumes were used as the benchmark for validation. However, lane volumes did not accurately mimic observed traffic counts from January 2012. Most notably different in volume was the interior combination lane in position 4. Observed data has 149 vehicles per hour while the model outputted almost three times that number with 400 vehicles. Additionally, the cash only lane 3's throughput was underestimated by the model by nearly 100 vehicles in the simulated hour. Discrete choice modeling may be to blame for this shift in volume. The cash lane path on lane 3 would have certainly had a higher overall travel time on average than combination lane 4. As a result trip assignment would allocate vehicles take the lower travel cost route more often. This happens because the higher volume of ETC vehicles on lane 4 and the other combination lane (lane 1) produce a lower average travel time when combined with cash vehicles. Using varying alpha coefficients would help the model's performance in properly shifting vehicles to dedicated ETC lanes.

5.4.4 Other Configuration Performance

Using the feedback from the static evaluation, six other configurations with the December 2012 volume and O-D data were simulated. Scenario 8 with grouped payment lanes from the static evaluation provided the best overall performance with less than 1 percent 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 most efficient 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 video and field video, weaving degraded overall plaza performance.

This model has its limitations with dynamic assignment. The iterative process interval of 10 seconds was a seemingly long period of time between reevaluations as compared to other toll plaza models suggested in the past (3). This model ignored link costs which could be implemented to emulate toll violators. This model removed lanes from dynamic assignment that were not a part of their applicable payment options and prevented violations all together. In real world operations, while violators are few, they do occur and would certainly affect plaza operations.

5.5 Research Contributions and Recommendations

Toll plazas, while designed to be an undemanding and forthright revenue generator, are often times vastly unpredictable and make driver behavior difficult to understand. A significant benefit of this continued research in this area will be improved configurations and design recommendations for toll plaza operators and managers. The lack of investigation in the area has inspired studies to understand in a controlled environment, exactly what parameters motorists use when they approach a toll plaza and select a lane. The research indicated drivers are willing to engage in up to 3 lane changes to minimize their travel time and pass quickly through a toll plaza. Drivers tend to avoid following heavy vehicles and avoid combination lanes if they anticipate a greater delay than an adjacent ETC lane. Combination lanes improved traffic operations and minimized driver confusion at the toll plaza. The model developed in the process of this research could be a useful tool for toll authorities and Departments of Transportation in the design or retrofit of existing toll facilities. Two inputs are required for the toll model, volumes by payment type and an O-D matrix if the plaza has multiple entrance and exit points.

5.6 Further Research

Although the completed research provided significant insight on varied toll plaza operation and safety, additional research questions remain. Completion of thesis tasks resulted in several recommendations on where to expand research of these highway environments.

Integration of a driving simulator would be a logical next step to evaluate driver decision making for several reasons. Eye trackers are one feature of most modern driving simulators, which provide visual insight into driving behavior. While drivers approach plazas they tend to scan for signage, other vehicles on their route to an optimal lane by weighing lane changes to queues and payment methods. By gauging human factor trends and time spent on these tasks, engineers could better design toll facilities.

The VISSIM model developed as part of this thesis effort utilizes many aspects of the microsimulation software, but could be improved for wider applicability. The addition of varying traffic conditions and demand, and open road tolling lanes would allow this model to simulate most toll plazas in existence today.

The microsimulation model had parameter limitations of the discrete choice model. Future research would involve programming an application programming interface (API) into VISSIM with a discrete choice model such as one proposed by Mudigonda (3). A programmed driver decision model could be easily modified to add driver parameters as research in the toll environment expanded.

APPENDIX

STATIC EVALUATION SCENARIO PHOTOS

Scenario 1

Scenario 2

Scenario 3

Scenario 4

Scenario 5

Scenario 6

Scenario 7

Scenario 8

Scenario 9

Scenario 10

Scenario 11

Scenario 12

Scenario 13

Scenario 14

Scenario 15

REFERENCES

1. Highway Statistics 2007. *Federal Highway Administration.* [Online] February 2009. http://www.fhwa.dot.gov/policyinformation/statistics/2007/hf10.cfm.

2. **Smith, Richard F; Wilbur Smith Associates; et al.** *State of the Practice and Traffic Control Strategies at Toll Plazas: Best Practices.* Washington, D.C. : Federal Highway Administration, 2005.

3. *Microscopic Modeling of Lane Selection and Lane Changing at Toll Plazas.* **Mudigonda, Sandeep, Bartin, Bekir and Ozbay, Kaan.** 2008, Transportation Research Board, pp. 1-18.

4. *Safety Considerations in Designing Electronic Toll Plazas: Case Study.* **Mohamed, A A, Aty, M A and Klodzinski, J G.** 2000, ITE Journal.

5. *Evaluation of Open Road Tolling and Express Lanes on Toll Road Facilities.* **Klodzinski, Jack, Al-Deek, Haitham M and Gordin, Eric.** Riyadh : s.n., 2007. Gulf Roads Conference. pp. 1-19.

6. **Gallagher, Timothy O and Worrall, Harold W.** *The Path to Open Road Tolling.* Oviedo, FL : Transportation Innovations, Inc., 2005.

7. *The End of the Toolbooth?* **Suarez, Evelio and Hoeflich, Kevin.** s.l. : Federal Highway, 2005, Public Roads, pp. 64-70.

8. **Cambridge Systematics, Inc. and Vanasse Hangen Brustlin Inc.** *Massachusetts Turnpike: Metropolitan Highway System Traffic and Revenue Study Final Report.* Boston : Massachusetts Department of Transportation, 2010.

9. **Schaufler, Albert E; National Cooperative Highway Research Program.** *Toll Plaza Design.* Washington, D.C. : Transportation Research Board, 1997.

10. *Safety Benefits from Deployment of Open Road Tolling for Main-Line Toll Plazas in Florida.* **Gordin, Eric, Klodzinski, Jack and Dos Santos, Cristina.** 2011, Transportation Research Record, pp. 85-92.

11. *Impact of ETC on Traffic Safety at Toll Plaza.* **Ding, Jiping, Ye, Fan and Lu, Jian.** Shanghai : International Conference of Chinese Transportation Professionals, 2007. Plan, Build, And Manage Transportation In China. pp. 695-701.

12. *The effects of a traffic guidance scheme for auto-toll lanes on traffic safety at toll plazas.* **Wong, S C, et al., et al.** 2006, Safety Science, pp. 753-770.

13. *Toll Plaza Merging Traffic Control for Throughput Maximization.* **Spiliopoulou, Anastasia D, Papamichail, Ioannis and Papageorgiou, Markos.** 2010, Journal of Transportation Engineering, pp. 67-76.

14. *TollSim: Simulation and Evaluation of Toll Stations.* **Correa, E, Metzner, C and Nino, N.** 2, s.l. : International Transactions in Operational Research, 2004, Vol. 11.

15. **Radwan, Essam and Zarillo, Marguerite.** *Calibration and Validation of SHAKER and TNCC for Deployment on Florida's Turnpike.* Tallahassee : Florida Department of Transportation, 2009.

16. *Developing Microscopic Toll Plaza Model Using Paramics.* **Nezamuddin, N.** Orlando : University of Central Florida, 2006.

17. *Integration of Toll Plaza Modeling Into CORSIM.* **Fuller, Brett Allen.** Gainesville : University of Florida, 2011.

18. *The Calibration and Verification of Simulation Models for Toll Plazas.* **Russo, Christopher S.** Orlando : University of Central Florida, 2008.

19. *Open Road Tolling Signing Studies.* **Benda, John, et al., et al.** Indianapolis : Transportation Research Board, 2011. 3rd International Conference on Road Safety and Simulation. pp. 1-24.

20. **Rephlo, Jennifer, et al., et al.** *Strategies for Improving Safety at Toll Collection Facilities.* Washington, D.C. : Federal Highway Administration, 2010.

21. *Assessment of freeway traffic parameters leading to lane-change related collisions.* **Pande, Anurag and Abdel-Aty, Mohamed.** 2006, Transportation Research Record, pp. 936-948.

22. *Safety evaluation of electronic toll collection lanes at the Holland Tunnel.* **Menta, Vijay K, Saracena, A J and Strate, H E.** 1997, Transportation Research Board, pp. 1-11.

23. **Federal Highway Administration.** *Manual on Uniform Traffic Control Devices.* Washington, D.C. : US Department of Transportation, 2009.

24. *A microscopic traffic simulation model for the evaluation of toll station systems.* **Astarita, Vittorio, Florian, Michael and Musolino, Giuseppe.** Oakland : Institute of Electrical and Electronic Engineers, 2001. IEEE Intelligent Transportation Systems Conference. pp. 692-697.

25. **Rosenker, Mark V; National Transportation Safety Board.** *Hampshire, Illinois, Highway Accident Report Safety Recommendation.* Washington, D.C. : National Transportation Safety Board, 2006.

26. *A Policy on Geometric Design of Highways and Streets.* Washington D.C. : American Association of State Highway and Transportation Officials, 2004.

27. **Chao, Xiuli.** *Design and Evaluation of Toll Plaza Systems.* Newark : Department of Industrial and Manufacturing Engineering, New Jersey Institute of Technology, 2000.

28. *Traffic Conflicts Associated with Protected/Permitted Left-Turn Signal Displays.* **Noyce, David A., Fambro, Daniel B and Kacir, Kent C.** 2000, Transportation Research Board.

29. *Expected Traffic Conflict Rates and Their Use in Predicting Accidents.* **Glauz, W. D., Bauer, K. M. and Migletz, D. J.** 1985, Transportation Research Record 1026, pp. 1-12.

30. **Parker, M R and Zegeer, C V.** *Traffic Conflict Techniques for Safety and Operations: Observers Manual.* Washington D.C. : Federal Highway Administration, 1989.

31. **Planung Transport Verkehr AG.** *VISSIM 5.10 User Manual.* Karlsruhe, Germany : s.n., 2008.

32. **Downling, Richard, Skabardonis, Alexander and Alexiadis, Vassili.** *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Software.* Washington, D.C. : Federal Highway Administration, 2004. FHWA-HRT-04-040.

33. Average Crash Rates. *MassDOT Highway Divison.* [Online] MassDOT, January 23, 2013. [Cited: February 8, 2013.] http://www.mhd.state.ma.us/default.asp?pgid=content/traffic/crashrate&sid=about.