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Traffic Safety Assessment of Different Toll Collection Systems on Expressways Using Multiple Analytical Techniques

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TRAFFIC SAFETY ASSESSMENT OF DIFFERENT TOLL COLLECTION SYSTEMS ON EXPRESSWAYS USING MULTIPLE ANALYTICAL TECHNIQUES

by

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ABSTRACT

Traffic safety has been considered one of the most important issues in the transportation field. Crashes have caused extensive human and economic losses. With the objective of reducing crash occurrence and alleviating crash injury severity, major efforts have been dedicated to reveal the hazardous factors that affect crash occurrence. With these consistent efforts, both fatalities and fatality rates from road traffic crashes in many countries have been steadily declining over the last ten years. Nevertheless, according to the World Health Organization, the world still lost 1.24 million lives from road traffic crashes in the year of 2013. And without action, traffic crashes on the roads network are predicted to result in deaths of around 1.9 million people, and up to 50 million more people suffer non-fatal injuries annually, with many incurring a disability as a result of their injury by the year 2020.

To meet the transportation needs, the use of expressways (toll roads) has risen dramatically in many countries in the past decade. In fact, freeways and expressways are considered an important part of any successful transportation system. These facilities carry the majority of daily trips on the transportation network. Although expressways offer high level of service, and are considered the safest among other types of roads, traditional toll collection systems may have both safety and operational challenges. The traditional toll plazas still experience many crashes, many of which are severe. Therefore, it becomes more important to evaluate the traffic safety impacts of using different tolling systems. The main focus of the research in this dissertation is to provide an up-to-date safety impact of using different toll collection systems, as well as providing safety guidelines for these facilities to promote safety and enhance mobility on expressways.

In this study, an extensive data collection was conducted that included one hundred mainline toll plazas located on approximately 750 miles of expressways in Florida. Multiple sources of data available online maintained by Florida Department of Transportation were utilized to identify traffic, geometric and geographic characteristics of the locations as well as investigating and determination of the most complete and accurate data. Different methods of observational before-after and Cross-Sectional techniques were used to evaluate the safety effectiveness of applying different treatments on expressways. The Before-After method includes Naïve Before-After, Before-After with Comparison Group, and Before-After with Empirical Bayesian.

A set of Safety Performance Functions (SPFs) which predict crash frequency as a function of explanatory variables were developed at the aggregate level using crash data and the corresponding exposure and risk factors. Results of the aggregate traffic safety analysis can be used to identify the hazardous locations (hot spots) such as traditional toll plazas, and also to predict crash frequency for untreated sites in the after period in the Before-After with EB method or derive Crash Modification Factors (CMF) for the treatment using the Cross-Sectional method. This type of analysis is usually used to improve geometric characteristics and mainly focus on discovering the risk factors that are related to the total crash frequency, specific crash type, and/or different crash severity levels. Both simple SPFs (with traffic volume only as an explanatory variable) and full SPFs (with traffic volume and additional explanatory variable(s)) were used to estimate the CMFs and only CMFs with lower standard error were recommended.

The results of this study proved that safety effectiveness was significantly improved across all locations that were upgraded from Traditional Mainline Toll Plazas (TMTP) to the Hybrid

Mainline Toll Plazas (HMTP) system. This treatment significantly reduced total, Fatal-and-Injury (F+I), and Rear-End crashes by 47, 46 and 65 percent, respectively. Moreover, this study examined the traffic safety impact of using different designs, and diverge-and-merge areas of the HMTP. This design combines either express Open Road Tolling (ORT) lanes on the mainline and separate traditional toll collection to the side (*design-1*), or traditional toll collection on the mainline and separate ORT lanes to the side (*design-2*). It was also proven that there is a significant difference between these designs, and there is an indication that *design-1* is safer and the majority of crashes occurred at diverge-and-merge areas before and after these facilities. However, *design-2* could be a good temporary design at locations that have low prepaid transponder (Electronic Toll Collection (ETC)) users. In other words, it is dependent upon the percentage of the ETC users. As this percentage increases, more traffic will need to diverge and merge; thus, this design becomes riskier.

In addition, the results indicated significant relationships between the crash frequency and toll plaza types, annual average daily traffic, and drivers' age. The analysis showed that the conversion from TMTP to the All-Electronic Toll Collection (AETC) system resulted in an average reduction of 77, 76, and 67 percent for total, F+I, and Property Damage Only (PDO) crashes, respectively; for rear end and Lane Change Related (LCR) crashes the average reductions were 81 and 75 percent, respectively. The conversion from HMTP to AETC system enhanced traffic safety by reducing crashes by an average of 23, 29 and 19 percent for total, F+I, and PDO crashes; also, for rear end and LCR crashes, the average reductions were 15 and 21 percent, respectively. Based on these results, the use of AETC system changed toll plazas from the highest risk sections on

Expressways to be similar to regular segments. Therefore, it can be concluded that the use of AETC system was proven to be an excellent solution to several traffic operations as well as environmental and economic problems. For those agencies that cannot adopt the HMTP and the AETC systems, improving traffic safety at traditional toll plazas should take a priority.

This study also evaluates the safety effectiveness of the implementation of High-Occupancy Toll lanes (HOT Lanes) as well as adding roadway lighting to expressways. The results showed that there were no significant impact of the implementation of HOT lanes on the roadway segment as a whole (HOT and Regular Lanes combined). But there was a significant difference between the regular lanes and the HOT lanes at the same roadway segment; the crash count increased at the regular lanes and decreased at the HOT lanes. It was found that the total and F+I crashes were reduced at the HOT lanes by an average of 25 and 45 percent, respectively. This may be attributable to the fact that the HOT lanes became a highway within a highway. Moreover adding roadway lighting has significantly improved traffic safety on the expressways by reducing the night crashes by approximately 35 percent.

Overall, the proposed analyses of the safety effectiveness of using different toll collection systems are useful in providing expressway authorities with detailed information on where countermeasures must be implemented. This study provided for the first time an up-to-date safety impact of using different toll collection systems, also developed safety guidelines for these systems which would be useful for practitioners and roadway users.

To Allah
And Then to Prophet Mohamed
And Then to Libya, My Mother and My Father's Soul

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This dissertation is dedicated to my beloved country Libya, to my father's soul, and to my beloved mother who taught me the value of education. I am deeply indebted to her for her untiring prayers and persistent faith in me.

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LIST OF ACRONYMS/ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AETC	All-Electronic Toll Collection
AMF	Accident Modification Factor
CAR	Crash Analysis Reporting
CG	Comparison Group
CMF	Crash Modification Factor
CMFunction	Crash Modification Function
EB	Empirical Bayes
F+I	Fatal and Injury
FB	Full Bayes
FDOT	Florida Department of Transportation
FM	Financial Management
GPL	General Purpose Lanes
HMTP	Hybrid Mainline Toll Plaza
HOT-Lanes	High-Occupancy Toll lanes
HOV	High-Occupancy Vehicle lanes
NB	Negative Binomial
PDO	Property Damage Only
RCI	Roadway Characteristics Inventory
SE	Standard Error

SLD	Straight Line Diagram
SPF	Safety Performance Function
TMTP	Traditional Mainline Toll Plaza
TRB	Transportation Research Board

CHAPTER 1: INTRODUCTION

1.1 Overview

Traffic safety is one of the most growing researched topics in transportation not only because of lives of people are priceless but also because of tremendous delays and loss in operation performance that these crashes can cause. Crashes have caused extensive human and economic losses. With the objective of reducing crash occurrence and alleviating crash injury severity, major efforts have been dedicated to reveal the hazardous factors that affect crash occurrence. With these consistent efforts, both fatalities and fatality rates from road traffic crashes in many countries have been steadily declining over the last ten years. Nevertheless, according to the World Health Organization, the world still lost 1.24 million lives from road traffic crashes in the year of 2013. And without action, traffic crashes on the roads network are predicted to result in deaths of around 1.9 million people, and up to 50 million more people suffer non-fatal injuries annually, with many incurring a disability as a result of their injury by the year 2020.

The use of toll roads has risen dramatically in many countries around the world, and in some countries, toll roads' miles have almost doubled in the past decade. For example, in the United States, there are currently many tolled road facilities; these facilities vary in type, size, ownership, and tolling systems deployed. Some of these facilities are private along with those owned and operated by various public agencies around the States. Even though toll roads offer high mobility benefits, traditional toll facilities may pose high traffic safety risk; past studies and the current data have indicated that certain locations at the Traditional Mainline Toll Plaza

(TMTP) and the Hybrid Mainline Toll Plaza (HMTP) are more likely to experience traffic crashes than the regular segments on the expressway (Yang et al., 2014) (Abuzwidah, 2011) (Brown et al., 2006).

In April 2006 in Washington, D.C., investigators for the U.S. National Traffic Safety Board (NTSB) revealed that the most dangerous locations on the highways are toll plazas. In the same year, the NTSB reported that 49 percent of all crashes on expressways in Illinois occurred at toll plazas, and three times as many people died in them as in crashes on the rest of the same roadways. Also, 30 percent of all crashes on the Pennsylvania Turnpike happened at toll plazas and 38 percent of all collisions on New Jersey toll highways were toll plaza incidents (NTSB, 2014). An older study (Mohamed et al., 2000) found that about 32 percent of the total crashes that occurred on the Central Florida expressways were located at the traditional mainline toll plazas.

In order to improve the traffic safety on these facilities, Intelligent Transportation Systems (ITS), including Electronic Toll Collection (ETC) technologies, are becoming widely used in the U.S. and Europe (Brimley et al, 2012). ETC is widely recognized as a successful ITS application with numerous benefits such as lower transaction time, improved throughput, and reduced air pollution and fuel consumption. However, ETC systems on traditional barrier toll plazas still require vehicles to slow down into channeled toll lanes, which itself requires vehicles to make complex lane-choice decisions at relatively high speeds. Therefore, safety concerns at barrier toll plazas still exist despite increased throughput.

Different toll collection systems have been adopted by different toll agencies around the world; and even though toll collection systems have existed for a long time, there is no standard design for these systems and the most common toll collection systems are Traditional Mainline Toll Plazas (TMTP), Hybrid Mainline Toll Plazas (HMTP), and All-Electronic Toll Collection (AETC) system. The HMTP has widely been deployed by many toll authorities such as in Florida, Illinois, New Jersey, and many other states. More details about these systems will be provided in the following chapters.

In this study, an extensive data collection was conducted that included a hundred mainline toll plazas located on approximately 750 miles of expressways in Florida. Multiple sources of data available online maintained by Florida Department of Transportation were considered to identify traffic, geometric and geographic characteristics of the locations, as well as investigation and determination of the most complete and accurate data. Different methods of observational Before-After and Cross-Sectional techniques were used to evaluate the safety effectiveness of applying different treatments on the expressways. The Before-After method includes Naïve Before-After, Before-After with Comparison Group, and Before-After with Empirical Bayesian (EB).

A set of Safety Performance Functions (SPFs) which predict crash frequency as a function of explanatory variables were developed at the aggregate level using crash data and the corresponding exposure and risk factors. Results of the aggregate traffic safety analysis can be used to identify the hazardous locations (hot spots) such as traditional toll plazas, and also to

predict crash frequency for untreated sites in the after period in the Before-After with EB method or derive Crash Modification Factors (CMFs) or Accident Modification Factor (AMF) for the treatment using the Cross-Sectional method. This type of analysis is usually used to improve geometric characteristics and mainly focus on discovering the risk factors that are related to the total crash frequency, specific crash type, and/or different crash severity levels. Both simple SPFs (with traffic volume only as an explanatory variable) and full SPFs (with traffic volume and additional explanatory variable(s)) were used to estimate the CMFs and only CMFs with lower standard error were recommended.

The use of the HMTP and AETC systems has demonstrated measured improvements in traffic operations and environmental issues. Also, it was proved that other treatments could improve safety at TMTP; for example, a study (Wong et al., 2006) evaluated the effects of a traffic guidance scheme for auto-toll lanes on traffic safety at toll plazas and they found that the overall lane-changing rate decreased significantly by 23 percent and the pooled conflict count decreased sharply by 44 percent; also the crash count decreased sharply by 38 percent. However, there is a lack of research that compares and evaluates the safety impacts of using different toll plaza types. So, there is an urgent need to assess the traffic safety effects of these facilities.

To the best of our knowledge, there were no studies that evaluated the safety impacts of using different toll collection systems. Therefore, the main goal of this dissertation is to compare and evaluate the safety impact of using different toll collection systems on expressways. So, the

results of this study would help officials to benefit from the extensive research in safety of expressways as it bridges the gap between research and practice, and to provide quantitative information on crash analysis and evaluation for decision making in planning, design, operation, and maintenance.

1.2 Research Objectives

This study seeks to fill some of the knowledge gap regarding the state of knowledge and state of practice in expressways safety. Specifically, it focuses on the traffic safety evaluation of toll collection systems on expressways such as Toll Plazas and High-Occupancy Toll lanes. Therefore, the main objective of this study is to model the crash occurrence at toll plazas to assess traffic safety on these facilities by developing Safety Performance Functions (SPFs) and Crash Modification Factors (CMFs) or Accident Modification Factors (AMFs). Also, another objective is to model and investigate the relationships between the crash frequency and several crash related factors such as roadway lighting, toll collection types, annual average daily traffic, and driver age.

1.2.1 Toll Collection Systems on Expressways:

The detailed objectives were achieved for this part by the following main procedures:

1. Collect data including all of the mainline toll plazas in Florida using multiple sources of data available online maintained by Florida Department of Transportation (FDOT).
2. Identify main contributing factors of crash frequencies on mainline toll plazas in Florida by crash frequency studies and geometric and traffic data.
3. Identify the locations with high risk at toll plazas using multiple analytical techniques.
4. Estimate crash risk evaluation models for the total crashes.
5. Analyze crash injury severity for the toll plazas by employing different modeling techniques.
6. Develop crash risk evaluation methods for each specific crash types (Rear End, and Lane Change Related Crashes) by considering their own features.
7. Develop models to examine the safety effectiveness of different designs of toll collection systems.
8. Develop models to investigate the crash characteristics and the relationships between the crash frequency and several crash related factors such as toll collection types, annual average daily traffic, and driver-age.

1.2.2 Adding Roadway Lighting on Expressways

The detailed objectives were achieved for this part by the following main procedures;

1. Collect data including all locations that have roadway lighting treatment in Florida.
2. Estimate crash risk evaluation models for the total crashes.
3. Analyze crash injury severity for these segments by employing different modeling techniques.
4. Develop crash risk evaluation methods for each specific crash types (Rear End, and Lane Change Related Crashes) by considering their own features.

To accomplish the above listed goals, the following objectives were achieved:

a. Different methods of Observational Before-After and Cross-Sectional techniques were used to evaluate the safety effectiveness of applying different treatments on expressways. The Before-After method includes Naïve Before-After, Before-After with Comparison Group, and Before-After with Empirical Bayesian. Moreover, Log-Linear models were developed to investigate the relationships between the crash frequency and several crash related factors such as toll collection types, annual average daily traffic, and driver-age.

b. Develop models to evaluate the safety effectiveness of the conversion from Traditional Mainline Toll Plaza (TMTP) design to Hybrid Mainline Toll Plazas (HMTP) system.

c. Develop models to evaluate the safety effectiveness of the conversion from TMTP or HMTP systems to All-Electronic Toll Collection (AETC) system.

d. Develop crash risk evaluation models for different designs of hybrid mainline toll plazas.

e. Estimate crash risk evaluation model to Identify the locations with high risk at the hybrid mainline toll plazas (diverge and merge) areas before and after the HMTP.

f. Evaluate the safety impact of the implementation of High-Occupancy Toll (HOT) lanes on safety performance of expressways.

g. Investigate the safety effectiveness of the implementation of roadway lighting on safety performance of expressways.

1.3 Dissertation Organization

The dissertation is organized as follows: following this Chapter, a thorough review of literature is provided; the review covers the methodologies and findings used in the previous traffic safety studies of Toll plazas, HOT-Lanes and roadway lighting as well as the use of different analytical techniques. Chapter 3 presents methodology; while Chapter 4 presents data

collection and its sources. Following with Chapter 5 presents the findings of the safety effectiveness of the conversion from TMTP design to HMTP system. The evaluation of the safety effectiveness of the conversion from TMTP or HMTP systems to AETC system is provided in Chapter 6. Followed by Chapter 7, which develops crash risk evaluation models for different designs of HMTP, as well as estimating crash risk evaluation model to identify the locations with high risk (diverge and merge) upstream and downstream of the toll plaza. Investigating the safety effectiveness of the implementation of roadway lighting on safety performance of expressways is illustrated in Chapter 8. While Chapter 9 evaluates the safety impact of the implementation of HOT-Lanes on safety performance of expressways. The final chapter of this dissertation, Chapter 10 concludes the research efforts, findings, and discusses future recommendations.

CHAPTER 2: LITERATURE REVIEW

2.1 General

This chapter provides a review of literature of the traffic safety on expressways; especially, toll collection systems, HOT-Lanes, and highway lighting related papers. These papers were summarized from the data aspect, methodology part and results. Previous studies and the current data indicated that certain locations at traditional toll plazas are more likely to be over-involved in traffic crashes than other areas on the expressway, however, there are limited studies evaluating traffic safety at these facilities.

2.2 Expressways

Expressways (Toll Roads) play a pivotal role in meeting the world's transportation needs. The use of toll road systems has risen dramatically in the United States in recent years. In Florida, toll roads have almost doubled since 2000. Moreover, many other countries' experience with expressways is rather limited to date, and also in the past decades there has been growing interest in their potential benefits and a relatively large increase in toll road construction. This interest has created a need for data regarding the safety effect of the toll collection systems. Although expressways offer high level of service, and well-maintained roadways, traditional toll facilities may pose great risks to drivers and workers. Figure 2-1 shows crash risk to drivers and workers at TMTP. Traditional toll plaza systems require vehicles to rapidly decelerate, navigate through different fare transaction options, and then accelerate and merge with traffic.

These confusing maneuvers constitute safety challenges and form hazardous locations (hot spots) on toll roadways (Abuzwidah et al., 2014).

Figure 2-1: Crash risk on drivers and workers at TMTP (NBC-NEWS- KS-Turnpike, 2014)

During the April 2006 hearing in Washington, D.C., investigators for the U.S. National Traffic Safety Board (NTSB) revealed that the most dangerous locations on the highway are toll plazas. In the same year, the NTSB reported that 49 percent of all crashes on expressways in Illinois occurred at toll plazas, and three times as many people died on them as in crashes on the rest of the same roadways. Also, 30 percent of all crashes on the Pennsylvania Turnpike happened at toll plazas and 38 percent of all collisions on New Jersey toll highways are toll plaza incidents (NTSB, 2006). In Florida, about 32 percent of the total crashes that occurred

on Orlando expressway system were located at the traditional mainline toll plazas (Mohamed et al., 2000).

2.2.1 Toll Collection Systems

There are many types of toll collection systems around the world; these systems vary in type, size, and design. Even though toll plazas have been implemented for a long time, there are no widely accepted design standards for these facilities' uniformity or safety with the only standards developed by individual toll operators based on their experience (Yang et al., 2014) (Abuzwidah, 2011) (Brown et al., 2006); Figures 2-2 to 2-4 show examples of different toll plaza signage designed based on toll agencies' experience.

Highway authorities have continued to use the updated technologies to improve the toll collection systems, starting with the automatic coin machines (ACM), and end up with All-Electronic Toll Collection (AETC) systems. AETC enables non-stop toll charges via automatic vehicle identification (AVI) transponders. This system is widely recognized as a smart and successful Intelligent Transportation Systems (ITS) application that reduces transaction time, improves throughput, and solves many economic and environmental problems.

Figure 2-2: Toll Plaza sign developed based on Toll agency's experience (IDOT, 2014)

Figure 2-3: Toll Plaza sign developed based on toll agency's experience (NJDOT, 2014)

Figure 2-4: Toll Plaza sign developed based on toll agency's experience (Source: CFX, 2014)

According to the Manual on Uniform Traffic Control Devices (MUTCD, 2014), the signposting distances and the influence area of the mainline toll plaza covers 1 mile before and 0.5 mile after the centerline of the mainline toll plaza (McDonald, and Stammer, 2001) (Schaufler, 1997); Figures 2-5 to 2-6 show signage locations before toll plazas.

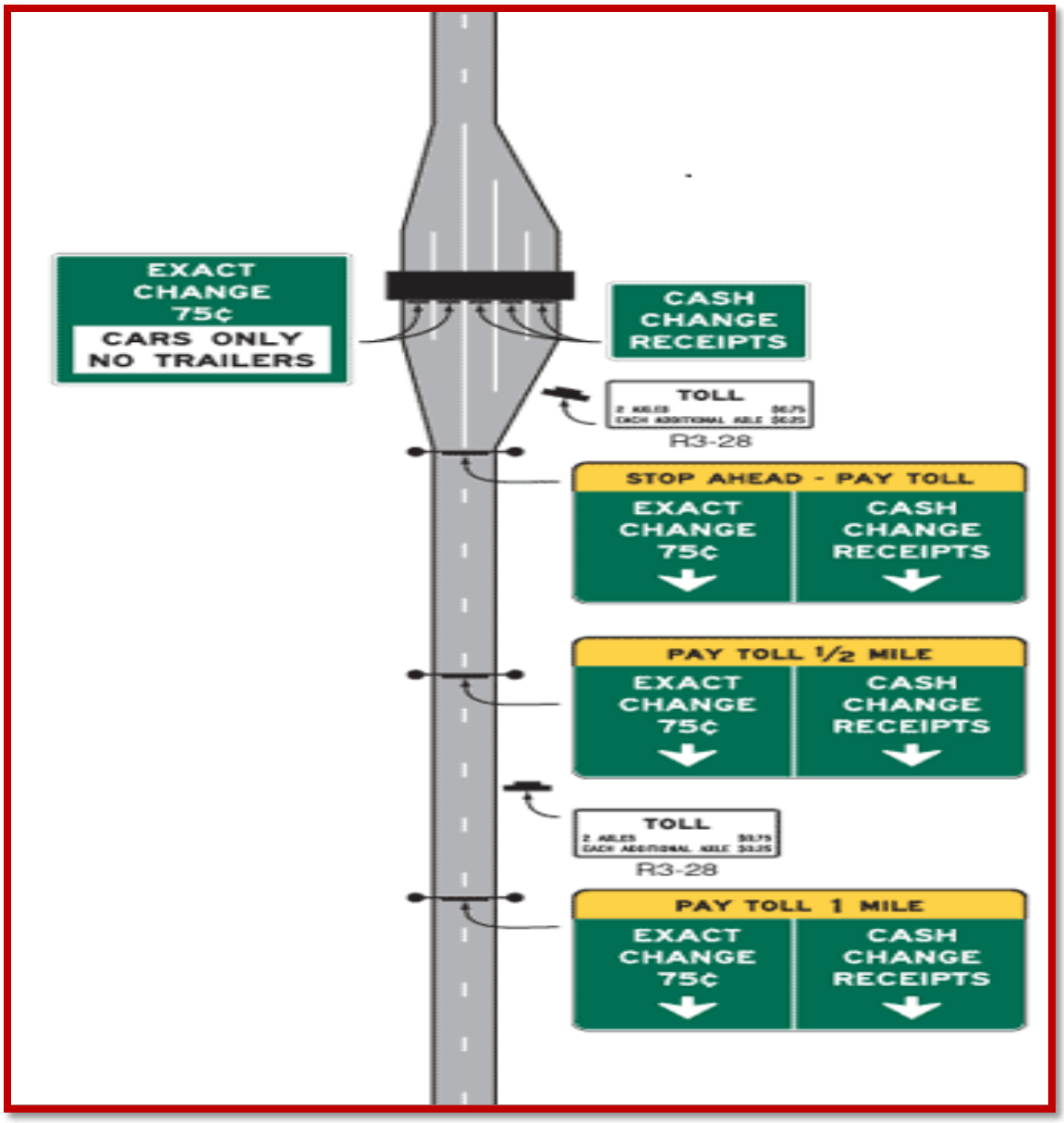


Figure 2-5: Advance signage for conventional toll plaza (Source: MUTCD, 2014)

The literature also showed that different toll collection systems have been adopted by different toll agencies around the world *(*Mohamed et al., 2000) (Schaufler, 1997).

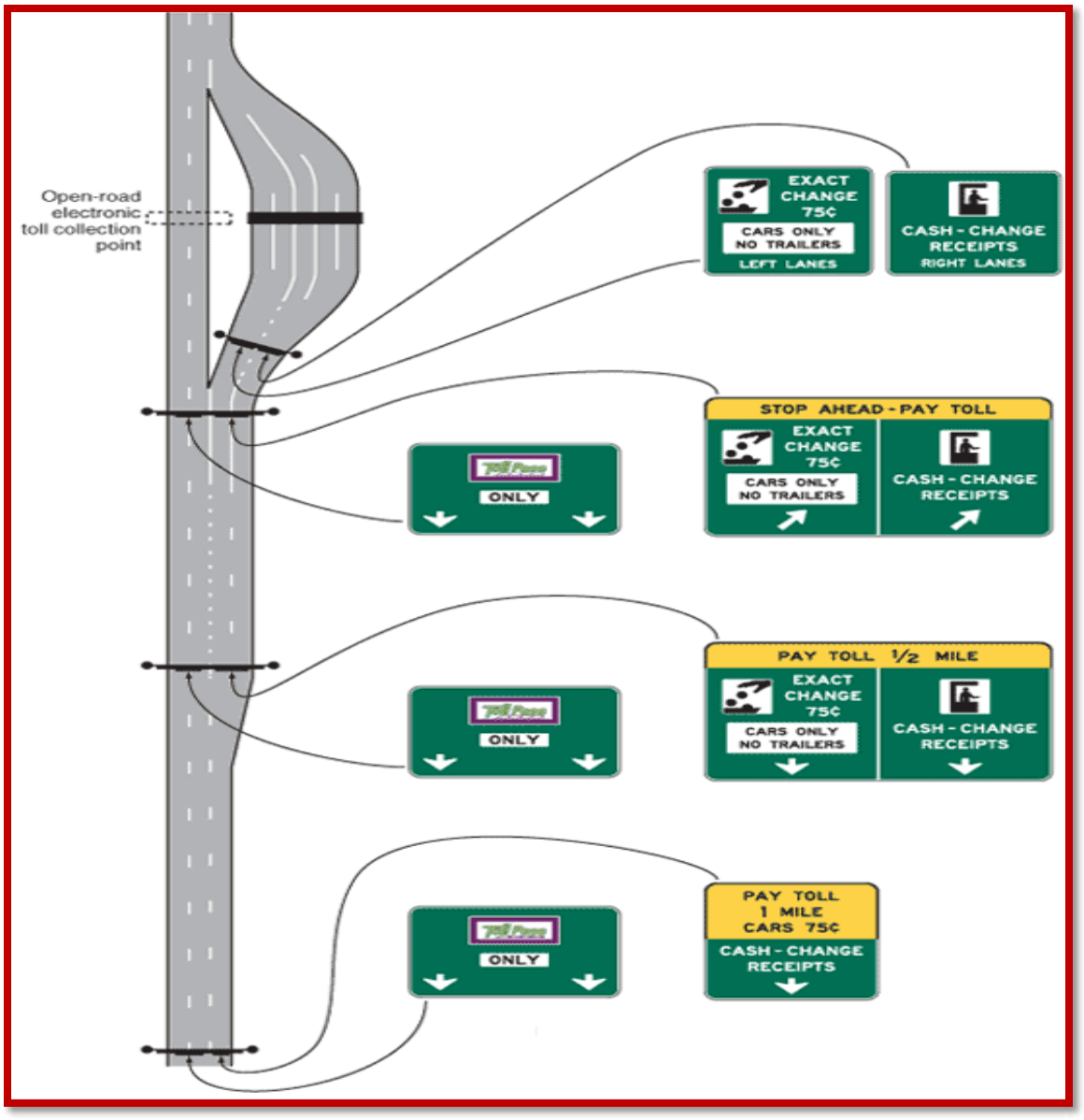


Figure 2-6: Advance signage for Hybrid Mainline Toll Plaza (Source: MUTCD, 2014)

However, the safety studies of toll collection systems are very limited, so there is an urgent need to study traffic safety issues of using different toll collection systems. The most common toll collection systems can be summarized as follows:

1. **Traditional Mainline Toll Plaza** (TMTP); this design require vehicles to rapidly decelerate, navigate through different fare transaction options, and then accelerate and merge with traffic. These confusing maneuvers constitute safety challenges and form hazardous locations high risk locations on expressways; Figure 2-7 and 2-8 show the TMTP.

Figure 2-7: Traditional Toll Plaza (Source: FHWA, 2014)

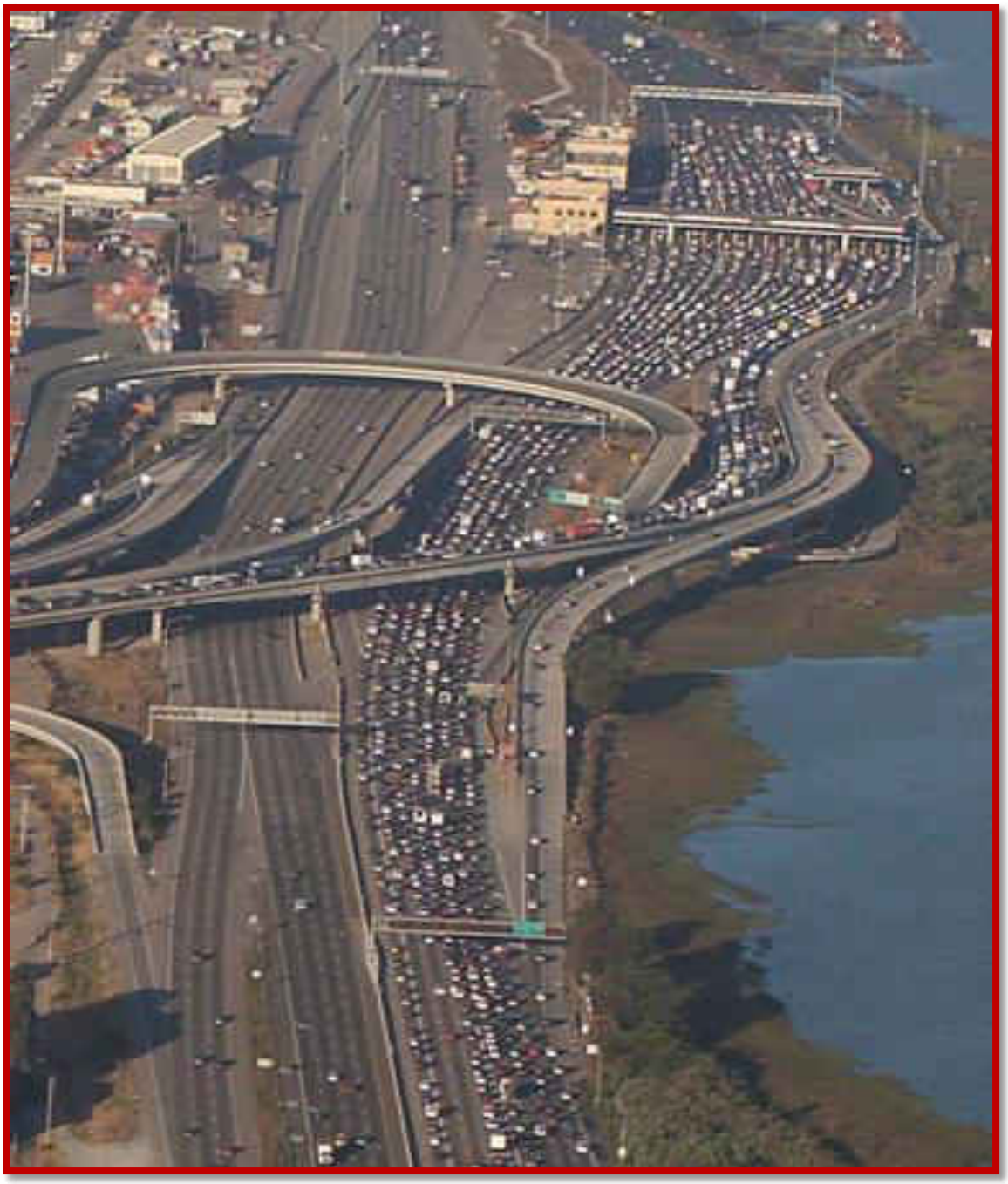


Figure 2-8: Traditional Toll Plaza at Bay Bridge- San Francisco (Source: FHWA, 2014)

2. **Hybrid Mainline Toll Plaza** (HMTP); this system retrofits existing tollbooths with express open Electronic Toll Collection (ETC) lanes; Figures 2-9 and 2-10 show ETC System at TMTP.

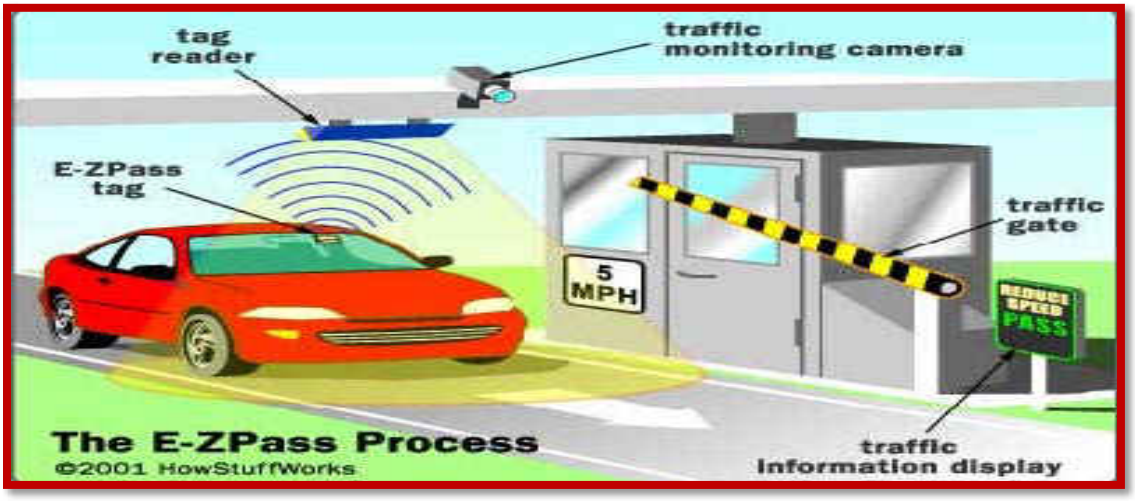


Figure 2-9: The E-ZPass Process at a Toll Booth (Source: FHWA-Ch8, 2014)

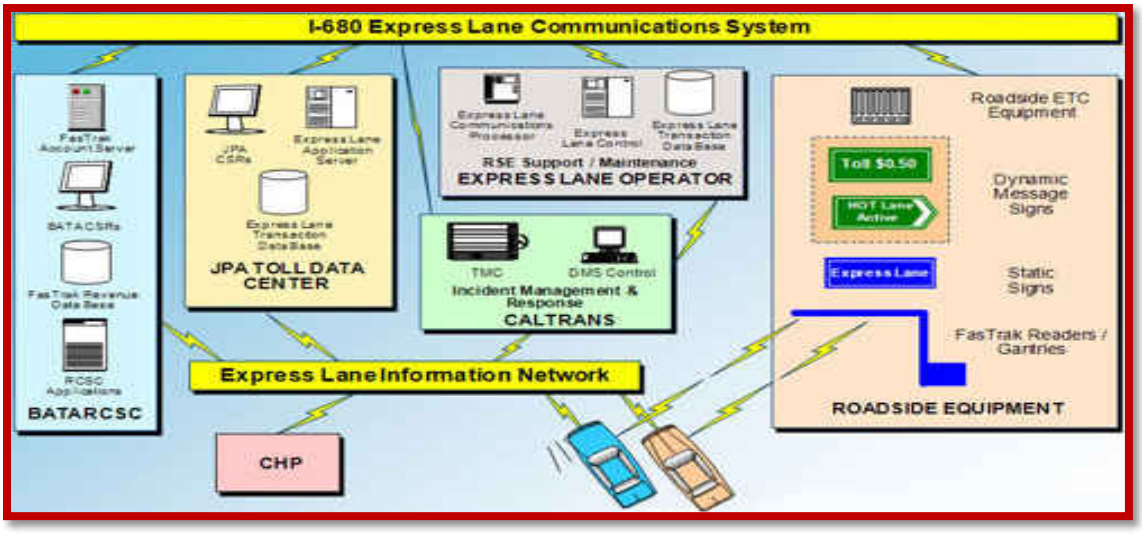


Figure 2-10: Electronic Toll System Architecture (Source: FHWA-Innovative Program, 2014)

The HMTP design is allowing more than 81 percent (FL-Turnpike, 2014) of the vehicles in Florida to travel at full speeds using electronic transponders or license plate recognition technology in an open road environment with fewer diverge and merge maneuvers before and after the toll plaza; Figure 2-11 shows diverge and merge areas before and after the HMTP.

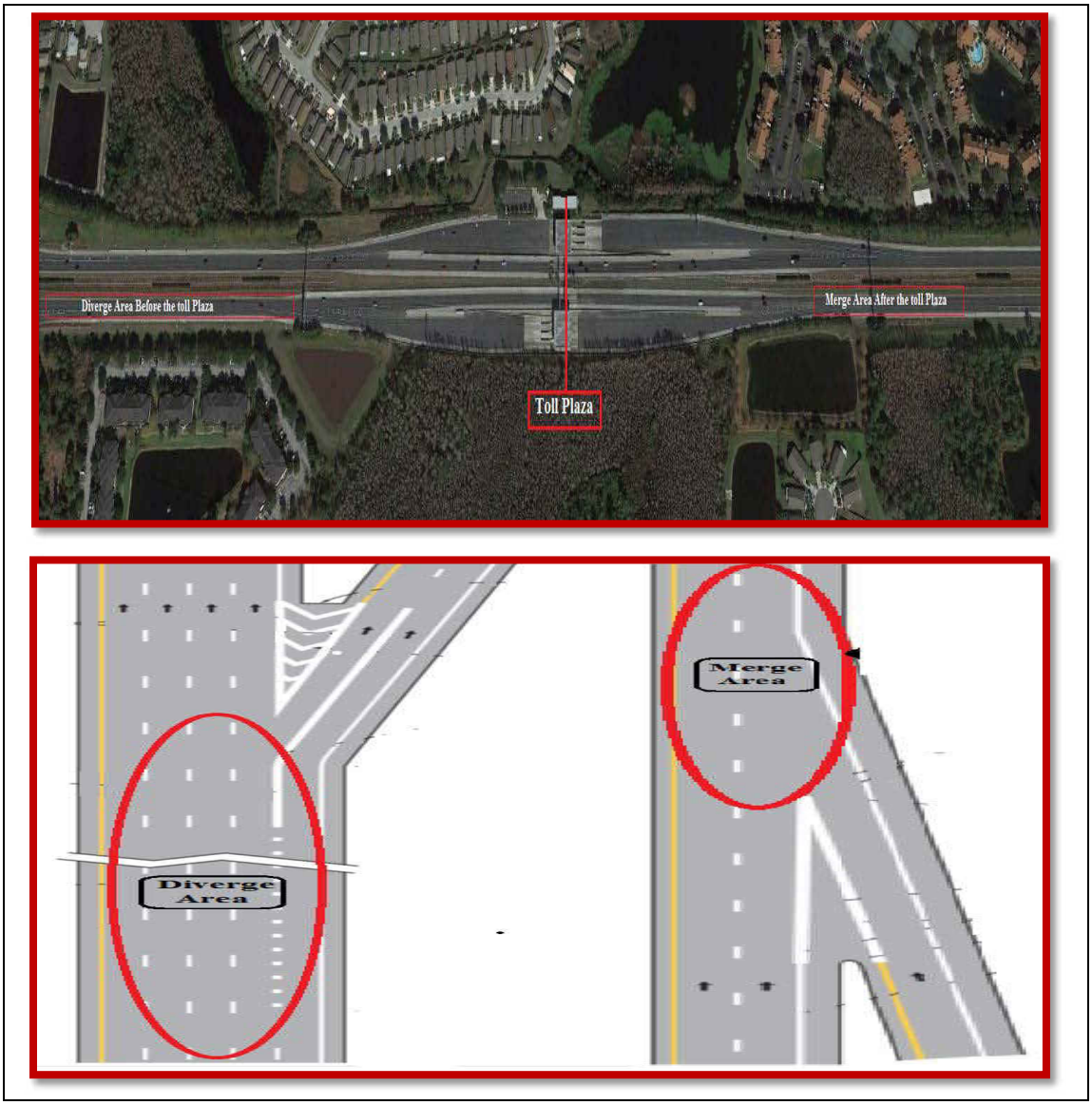


Figure 2-11: Diverge and merge areas for HMTP (Source: FHWA, 2014)

The HMTP design combines either express Open Road Tolling (ORT) lanes on the mainline and separate traditional toll collection to the side, or traditional toll collection on the mainline and separate ORT lanes to the side (FL-Turnpike, 2014). A study (Klodzinski et al., 2007) concluded that the addition of ORT to a mainline toll plaza in Florida reduces delays by almost 50 percent for cash users and about 55 percent for automatic coin machine users. Another study (Levinsin and Odlyzko, 2008) found that the throughput of manual collection lanes can be increased from 350 - 400 vehicles per hour per lane (vphpl) up to 2200 vphpl when upgraded to express ETC lanes; Figure 2.12 and 2-13 show different designs of HMTP.

Figure 2-12: HTP the ORT in the mainline (Source: CFX, 2014)

Figure 2-13: HTP the ORT on the side (Source: Google earth, 2014)

The conversion from traditional toll system to HMTP also was proven to significantly reduce emissions (Venigalla, and Krimmer, 1987). The HMTP is widely deployed by many toll authorities such as in Florida, Illinois, New Jersey, and many other states.

3. **All-Electronic Toll Gantry or All-Electronic Toll Collection** (AETC); this system is completely barrier-free that replaces all tollbooths with regular express ETC lanes to change the toll plaza to be similar to regular segments; Figure 2-14 and 2-15 show All-Electronic Toll Collection (AETC) system. The AETC system allows driving straight through an open road without needing to change lanes, stop the vehicle, or even slow down to pay a toll.

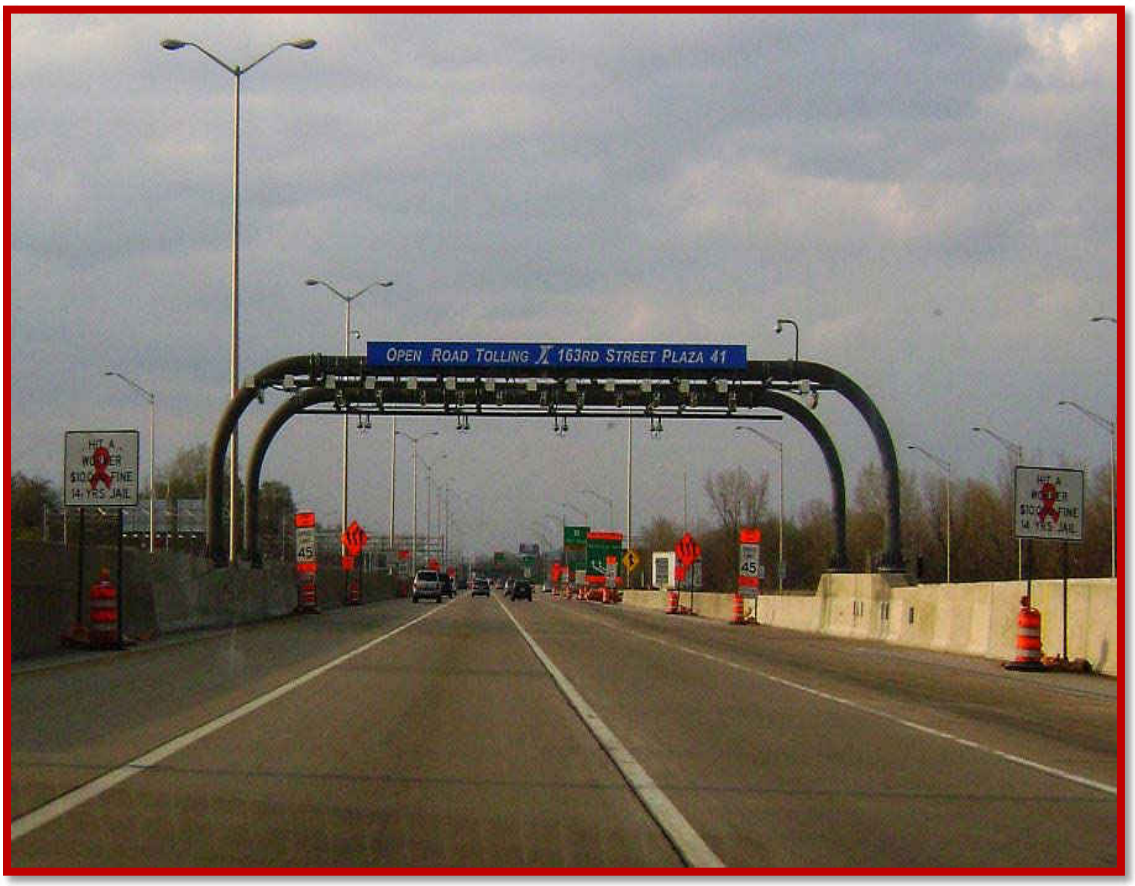


Figure 2-14: All-Electronic Toll Collection system (Source: FHWA, 2014)

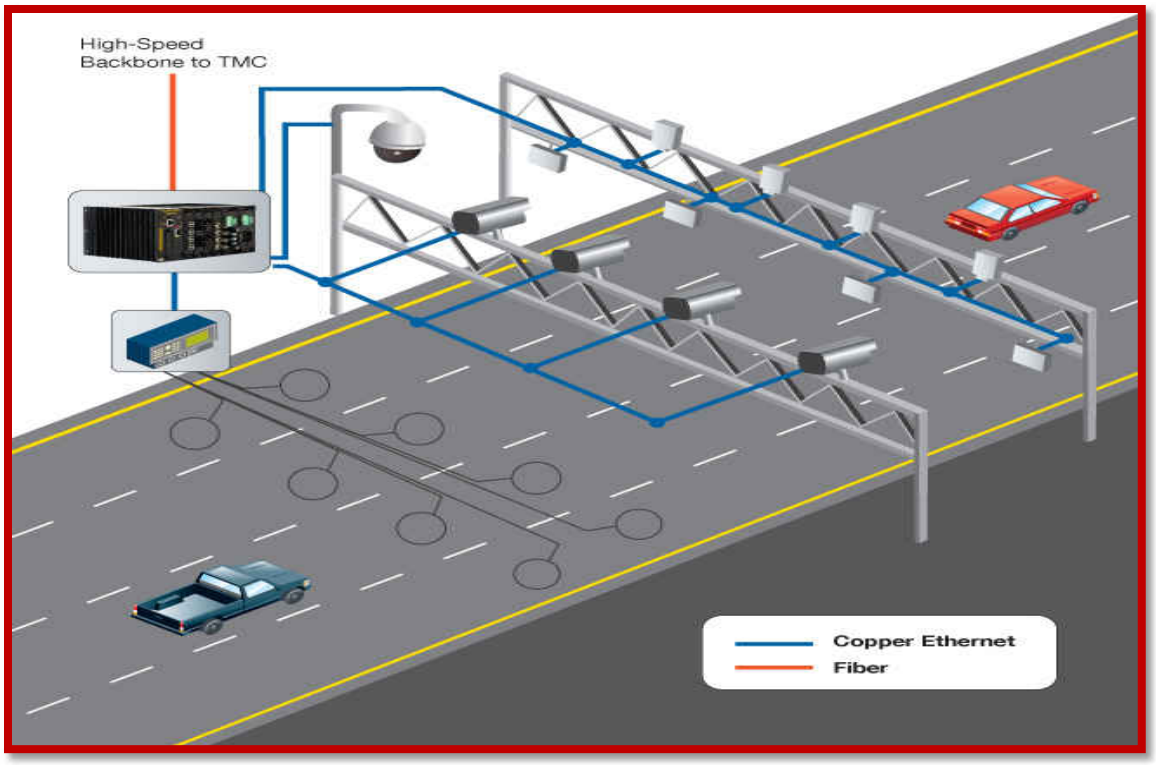


Figure 2-15: Electronic Toll Collection system at ORT (Source: SIEMENS, 2014)

The payment will be done automatically, instantly and accurately by using the automatic toll collection transponder known as prepaid transponder (FL-Turnpike, 2014); Figure 2.14 shows the AETC system.

However, there are some obstacles to the use of the HMTP and AETC systems in many countries because these systems require good arrangements between the tolling agencies and the department of motor vehicles database. These arrangements are needed to identify and bill drivers who do not have the prepaid transponder. This processing is called Toll-By-Plate program, which is an image based electronic toll collection system that uses photographic

images of the vehicle's license plate to identify the customers responsible for payments and bill them (FL-Turnpike, 2014) . For example, the Florida Turnpike is taking some steps to significantly increase the automatic toll collection users, by charging monthly documentation fees of $2.50 and offering less toll amount for the prepaid transponder users.

Overall, the use of the HMTP and AETC systems has demonstrated measured improvements in traffic operations and environmental issues. A recent study (Abuzwidah et al, 2014) found that the conversion from Traditional Mainline Toll Plaza (TMTP) to HMTP system resulted in an average crash reduction of 47 percent, 46 percent and 54 percent for total crashes, fatal-and-injury crashes and property damage only crashes, respectively. Moreover, they found that the use of the HMTP system also significantly reduced rear-end crashes and lane-change-related crashes by an average of 65 percent and 55 percent, respectively.

Another study (Yang et al., 2014) found that the removal of barrier toll plazas and applying the HMTP design in Garden State Parkway in New Jersey was a very beneficial countermeasure towards improving safety of toll roads. Also they concluded that the treatment resulted in an estimated reduction of 42.1 percent in crash occurrence at toll plazas, and the estimated crash cost was reduced by 40.1 percent at these facilities. Also, a study (Sze et al., 2008) proved that some simple and quick treatments could improve safety at TMTP. Another study (Wong et al., 2006) evaluated the effects of a traffic guidance scheme for auto-toll lanes on traffic safety at TMTP and they found that the overall lane-changing rate decreased

significantly by 23 percent and the pooled conflict count decreased sharply by 44 percent; also the crash count decreased sharply by 38 percent. However, there is a lack of research that compares and evaluates the safety impacts of using different toll plaza types. So, there is an urgent need to assess the traffic safety effects of these facilities.

2.3 Roadway Lighting

Roadway Lighting (RL) is designed, fabricated and installed for expected societal and safety benefits at night. Determination of the value of lighting is hard to quantify, because its value rests not simply upon its tangible implementation and operation costs but on its expected benefits, which are inherently difficult to estimate (Rea et al., 2009).

The literature showed that highway lighting can improve safety by an average 20 percent (Schwab et al., 1982) (Fisher. 1977). However, this statement must be carefully qualified in light of the potential biases that are inherent to study the effect of the treatment. First, and foremost, these estimates may be biased because of other safety measures closely associated with the implementation of lighting (Beyer, and Ker 2009). Moreover, these statistics give no indication of where and when lighting might or might not affect safety. But, it appears for example that lighting has little benefit in areas where there is limited chance of vehicle-vehicle or vehicle-pedestrian conflict (Rea et al., 2009).

Major efforts have been done by National Cooperative Highway Research Program (NCHRP) to assess the possible role of lighting in safety. In the former effort (Donnell. Et al., 2009)

(Bullough. et al., 2009a and b), large statistical samples of roadway lighting presence and crash data were assembled and analyzed to evaluate the impacts of highway lighting on traffic safety. These studies developed many statistical models; this approach attempted to control for traffic volume, posted speed limits, and roadway geometric characteristics that have not been considered in past studies of the impacts of highway lighting on traffic safety.

In Florida, there are more than 750 miles of expressways (toll roads). These roads vary in classification (urban, sub-urban, or rural) and the highway lighting condition. To the best of our knowledge, there are no specific studies that evaluated the safety impacts of installing the highway lighting on the expressways. Therefore, another goal of this dissertation is to evaluate the traffic safety effectiveness of the implementation of the highway lighting on expressways.

2.4 High-Occupancy Toll (HOT-Lanes)

The increasing number of cities throughout the world is dealing with similar problems such as traffic safety, demand of highway travel, congestion, limited ability etc. However, construction of new highways is not keeping pace with growing demand. One of these strategies of the U.S. Department of Transportation is to expand freeway capacity by adopting several solutions (U.S.DOT, 2014). One of these solutions is the Managed Lanes program; the Managed Lanes have different meanings to different DOTs. And the term is commonly thought of as High-Occupancy Toll (HOT) lanes, also known as Express Lane or priced lanes. The "Managed Lanes" also includes exclusive or special use lanes such as (express, bus-only, or truck-only lanes) *(*FHWA. 2014*)*.

The concept of providing HOT Lanes on the highway corridor reflects a growing national trend where urban areas are converting regular or HOV lanes into HOT facilities to enhance mobility and offer more choices for motorists and transit users. In other words, High-occupancy toll lanes are special toll lanes that offer drivers choices to pay a higher toll to bypass heavy congestion in regular toll lanes. The toll is varying, depending on traffic condition in the express lane. As the traffic demand increases, the toll is increased “i.e. dynamic tolling" to maintain the highway speeds (FT, 2014).

By driving up prices, traffic is expected to go back to free lanes, reducing congestion on the express lanes. Actually, charging a higher price during a period of high demand is a concept not exclusive to transportation. This method is used by other industries (i.e. electric utility, airlines, rental cars, and hotels) where rates are higher during peak usage times and peak seasons. So, it can be considered that the HOT-Lanes are first-class lanes within the highway.

The Florida Department of Transportation (FDOT. 2014) is advancing sections of the I-95 and SR-589 by adopting the HOT-Lanes system to help travelers get home or to work faster with less stress at those areas. In 2007, the FDOT completed the Managed Lanes Comprehensive Traffic and Revenue Study. This study evaluated the potential operations of the corridor with the implementation of two tolled express lanes in each direction (95 Express, 2013). They

determined that this implementation could improve travel time by saving up to 38 minutes during peak periods.

This study was based on the continuous express lanes throughout Miami-Dade, Broward, and Palm Beach Counties. The system known as 95-Express occurred on the I-95 corridor in Miami-Dade County (Phase 1 the northbound lanes opened December, 2008 and the southbound lanes opened January, 2010); Figure 2-16 shows South Florida Express Lanes Network.

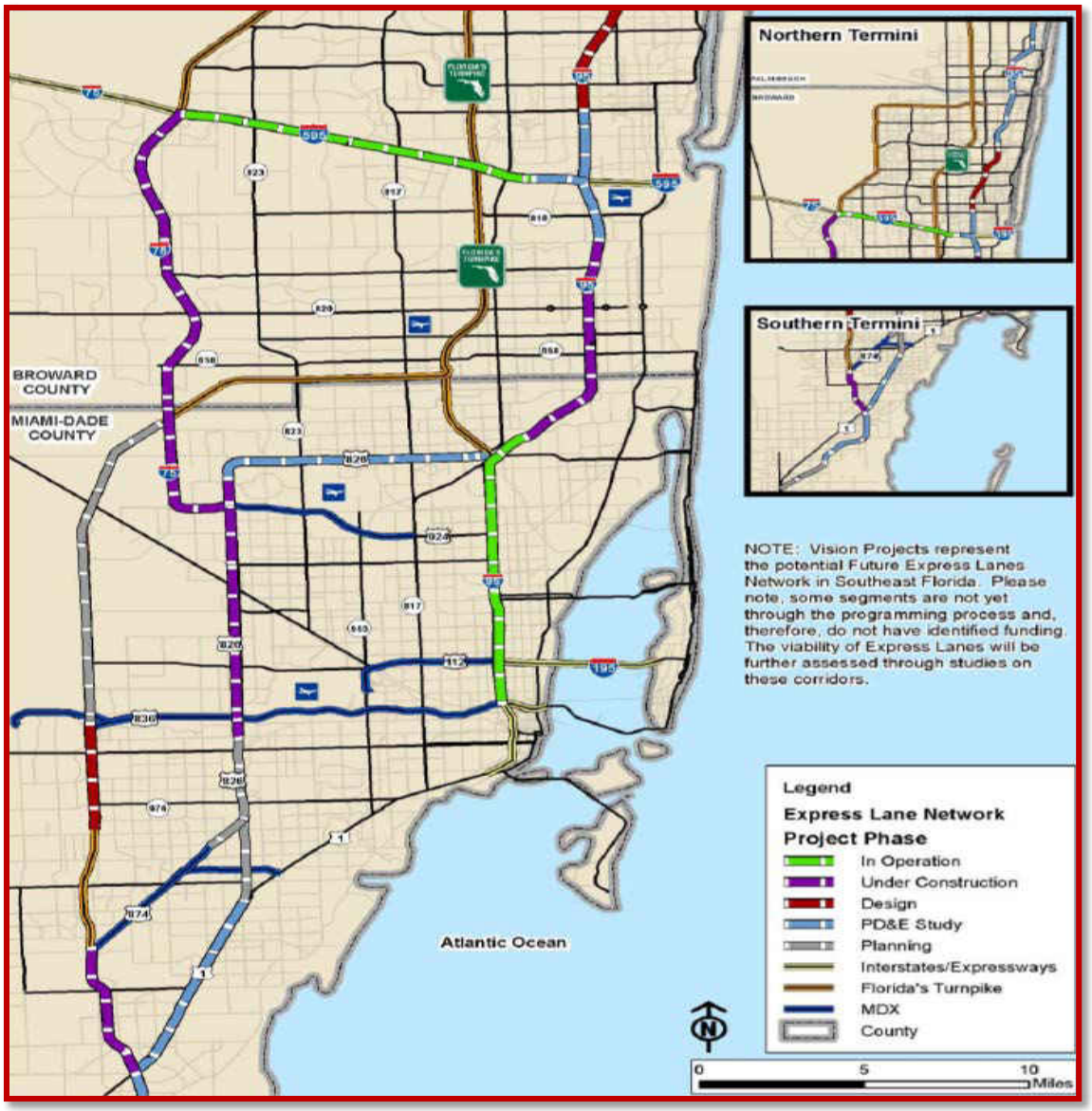


Figure 2-16: South Florida Express Lanes Network (Soucre: SCS, Inc. 2013)

The HOV lane on I-95 was converted into two managed HOT-Lanes in each direction. In this scheme, users are charged a variable fee to drive in these lanes between the I-395 and the Golden Glades interchange. The goal of this system is to maintain a speed of 45 mph in the

Express Lanes. Buses and high-occupancy vehicles with three or more passengers are allowed to use the HOT-Lanes for free (FL-Turnpike, 2014).

Since the opening of the I-95 Express Lanes commuters have experienced a number of benefits (SCS, Inc. 2013). The study found that the system improved throughput, it showed that from December 2008 to January 2009, there was a 9.5 percent increase in average weekday traffic volume throughput and a 15.7 percent increase during the PM peak period (4pm to 7pm).

Moreover, they found that a shift in travel modes has also occurred as a result of this system, and the ridership on the 95 Express bus route increased by an average of 33.5 percent between June 2007 and June 2009; also there were a significant improvement of the travel speeds after applying the HOT-Lanes. The travel speed increased during peak periods from 20 MPH to a monthly average of 63 MPH. Drivers in the General Purpose Lanes (GPL) (free lanes) also experienced a significant peak period increase. That may be attributed to the fact that the bus and carpool users increased while the total trips decreased.

In 2005, HOV-Lanes on I-394 in Minnesota were converted to HOT-Lanes. A previous study (Cao et al. 2012) evaluated the effect of HOV-to-HOT lane conversion on traffic safety using before-and-after method. They found that total crashes were reduced by 5.3 percent after the conversion and they concluded that the benefits were practically important when compared to the tolls collected. Likewise, many other HOT-Lanes are in full operation in the following

States: California (I-15), Colorado (I-25), Houston (I-10) and (US 290), Utah (I-15), and Washington (SR-167) (Cao et al., 2012). In addition, many other countries adopted a peak-hour toll to reduce traffic congestion. The drivers can pay tolls electronically by enrolling in the prepaid transponders, which is read by an electronic reader and deducts the toll from their balance. Some of these countries adopted another program called variable pricing which was applied to some highways to charge tolls based on demand and peak-hour.

For example, in 2006 this program was applied in Stockholm, Sweden (Graham, 2013). This implementation resulted in a significant drop (more than 20 percent) of traffic in those highways (Franklin, 2012). Moreover this program significantly reduced the crashes due to reduction in traffic volume and a shift in transport mode from single-occupant driver vehicles to mass transit system.

This concept has been very successful in other metropolitan areas throughout the U.S by solving several traffic operations and environmental problems, as well as giving drivers more choices to reach their final destinations quickly with less stress (FHWA). However, there is an urgent need to evaluate the safety impacts of HOV-to-HOT lane conversion to reach a clear conclusions on the effect of the high-occupancy toll lanes on traffic safety.

2.5 Crash Frequency Studies

2.5.1 Statistical Techniques of Analyzing Crash Frequency

Researchers have developed various methods, incorporated different types of data, and concluded varieties of countermeasures to improve traffic safety conditions. They put many efforts using different statistical techniques such as Bayesian statistical techniques (Empirical Bayes (EB) and Full Bayesian (FB)) and Cross-Sectional technique to analyze crash frequency data; also in trials that reveal the contributing factors that are associated with crash frequency on highway segments.

For example, a previous study (Lord and Mannering, 2010) summarized the variety methodological alternatives that were used in crash frequency studies; strengths and weaknesses of these modeling techniques have been assessed. They found that many researchers have put great effort in innovative methodological approaches to account for these formidable problems in data characteristics to help understand the factors that affect number of crashes. In this section, mainly modeling techniques utilized in the effect of treatments on traffic safety studies have been discussed: Observational before-after and Cross-Sectional techniques as well as Negative Binomial (NB) and log-linear models.

2.5.2 Crash Prediction Models

A study (Srinivasan et al. 2013) examined the safety effect of converting the signals to composite LED bulbs. An empirical Bayes before-after method was used for the evaluation

and Crash Modification Factors (CMFs) were estimated for three and four leg intersections for eight different crash types. Another study (Persaud et al. 2013) evaluated SPFs of passing relief lanes using Empirical Bayes before-after method and cross-sectional method. Based on their results, state-specific CMFs were established for passing lanes. Moreover, (Simpson and Troy, 2013) tried to evaluate safety effectiveness of intersection conflict warning system named "Vehicle Entering When Flashing" (VEWF) at stop-controlled intersections. CMFs were provided for all sites of study and each category using Empirical Bayes before-after Evaluation.

A recent study (Bauer and Harwood, 2013) evaluated the safety effect of the combination of horizontal curvature and longitudinal grade on rural two-lane highways. Safety prediction models for fatal-and-injury and PDO crashes were evaluated and CMFs representing safety performance relative to level tangents were developed from these models. Another study (Zeng and Schrock, 2013) compared safety effectiveness of ten shoulder design types between the winter and non-winter periods. For this study, a cross-sectional approach was applied to develop SPFs for the winter and non-winter periods.

Following the previous studies, Kim et al. 2013 developed a four-step procedure for SPFs using categorical impact, and clustering analysis. They claimed that their procedure can easily predict crash frequency more accurately. Moreover, (Nordback et al. 2013) presented for the first time specific SPFs of bicycles for Colorado. The developed SPFs demonstrated that

intersections with more cyclists have fewer collisions per cyclist, illustrating that cyclists are safer at intersections with a larger number of cyclists. A study also (Lan and Srinivasan, 2013) focused on the safety performance on discontinuing late night flash operation at signalized intersections. The study also compared between Empirical Bayes and Full Bayes.

2.5.3 Crash Modification Factors or Accident Modification Factors

Crash Modification Factors are known also as Crash Reduction Factors, Collision Modification Factors or Accident Modification Factors (CMFs or AMFs), all of which have the same definition. Crash Modification Factors (CRFs) function in a very similar way as they represent the expected reduction in number of crashes for a specific treatment. The proper calibration and validation of Crash Modification Factors will provide an important tool to practitioners to adopt the most suitable cost effective countermeasure to reduce crashes at hazardous locations.

2.5.4 Development of Crash Modification Factors

There are different methods to estimate CMFs; these methods vary from a simple Before and After study and Before and After study with comparison group to a relatively more complicated methods such Empirical Bayes, Full Bayes, and Cross-Sectional methods.

2.5.4.1 The simple (naïve) before-after study

This method compares numbers of crashes before and after the treatment is applied. The main assumption of this method is that the number of crashes before the treatment would be expected without the treatment. This method tends to overestimate the effect of the treatment because of the regression to the mean problem (Hauer, 1997).

2.5.4.2 The before-after study with comparison group

This method is similar to the simple before and after study; however, it uses a comparison group of untreated sites to compensate for the external causal factors that could affect the change in the number of crashes. This method also does not account for the regression to the mean as it does not account for the naturally expected reduction in crashes in the after period for sites with high crash rates.

2.5.4.3 The Empirical Bayes before-after study

The Empirical Bays (EB) method can account for the regression to the mean issue by introducing an estimate for the mean crash frequency of similar untreated sites using SPFs. Since the SPFs use AADT and sometimes other characteristics of the site, these SPFs also account for traffic volume changes which provide a true safety effect of the treatment (Hauer, 1997).

2.5.4.4 The Full Bayes before and after study

The Full Bays (FB) is similar to the EB of using a reference population; however, it uses an expected crash frequency and its variance instead of using point estimate, hence, a distribution of likely values of crash frequency is generated.

2.5.4.5 Cross-Sectional Studies

It should be noted that the CMF for certain treatments (e.g. median width) can only be estimated using the Cross-sectional method, but not Before-After method. This is because it is difficult to isolate the effect of the treatment from the effects of the other treatments applied at the same time using the Before-After method (Harkey et al., 2008).

The method is used in the following conditions (AASHTO, 2010): 1) the date of the treatment installation is unknown, 2) the data for the period before treatment installation are not available, and 3) the effects of other factors on crash frequency must be controlled for creating a Crash Modification Function (CMFunction).

2.5.5 Log-Linear Model

Several studies have used the log-linear model in traffic crash research. Lee et al. (2005) investigated the potential of using a log-linear model to quantify safety benefits of ramp metering.

The model estimates potential crash in real time as a quantitative measure of freeway safety, based on short-term variation in traffic flow. The model was applied to a section of I-880 as well as a hypothetical freeway section. The results demonstrated that the ALINEA ramp metering strategy can reduce the total crash potential by 5-37% compared to the no-control case.

Lee et al. (2003) estimated the real-time likelihood of freeway crash occurrence using a log-linear model based on the crash frequency analysis. To formulate the log-linear model, the continuous traffic parameters such as the density and coefficient of variation in speed were categorized resulting in loss of information due to categorization. Abdel-Aty, et al. (1998) also used log-linear models to study the relationship between the driver age and several important crash related factors and circumstances such as injury severity, collision types, average daily traffic (ADT), roadway character, speed ratio, alcohol involvement, and crash location.

Kim et al. (1995a) applied the model using crash type, seat-belt use, and injury severity variables to find the relationship among these three factors. Kim et al. (1995) estimated a model to investigate the role of driver characteristics and behavior in the causal sequence leading to more severe injuries. They found that driver behavior of alcohol or drug use and lack of seat belt use greatly increase the odds of more severe crashes and injuries.

2.6 Summary

Even though toll plazas are shorter segments on expressways, the literature showed that 30 to 49 percent of all crashes on expressways occurred at these facilities. This has made the expressway authorities work hard to relieve these issues. They applied several treatments on their networks such as adding highway lighting, using advance Intelligent Transportation System to collect tolls such as Electronic Toll Collection (ETC) at Traditional Toll Plazas, implementing Open Road Tolling (ORT) or Hybrid Toll Plazas (HTP) design, and the latest application is using the All-Electronic Toll Collections (AETC) system. Moreover, with the hope of relieving congestion on freeways and generating revenue to support the transportation demand, High-Occupancy-Toll (HOT) lanes become popular design at many places around the world.

These treatments (HTP, AETC, and HOT-Lanes) were proven to be an excellent solution to several traffic operations as well as environmental and economic problems. Thus, these systems are scheduled to be implemented in many new places around the world. However, there is a lack of research that compares and evaluates the safety impacts of using these treatments. Therefore, there is an urgent need to evaluate the safety effectiveness of using these systems. The main goal of this dissertation is to develop traffic safety guidelines for these systems which would be useful for practitioners and roadway users. And providing for the first time an up-to-date safety effectiveness of using different toll collection systems, adding highway lighting on expressways, and the use of high-occupancy toll lanes.

Moreover, the results of this study would help officials to benefit from the extensive research in safety of expressways as it bridges the gap between research and practice, and to provide quantitative information on crash analysis and evaluation for decision making in planning and design before the new implementation.

CHAPTER 3: METHODOLOGY

3.1 Overview

Different methods of Observational Before-After and Cross-Sectional techniques were used to evaluate the safety effectiveness of applying different treatments on expressways. The Before-After method includes Naïve Before-After, Before-After with Comparison Group, and Before-After with Empirical Bayesian. Moreover, Log-Linear models were developed to investigate the relationships between the crash frequency and several crash related factors such as toll collection types, annual average daily traffic, and driver-age.

A set of Safety Performance Functions (SPFs) which predict crash frequency as a function of explanatory variables were developed at the aggregate level using crash data and the corresponding exposure and risk factors. Results of the aggregate traffic safety analysis can be used to identify the hazardous locations (hot spots) such as traditional toll plazas, and also to predict crash frequency for untreated sites in the after period in the Before-After with EB method or derive Crash Modification Factors (CMFs) or Accident Modification Factor (AMFs) for the treatment using the Cross-Sectional method.

This type of analysis is usually used to improve geometric characteristics and mainly focus on discovering the risk factors that are related to the total crash frequency, specific crash type, and/or different crash severity levels. Both simple SPFs (with traffic volume only as an explanatory variable) and full SPFs (with traffic volume and additional explanatory

variable(s)) were used to estimate the CMFs and only CMFs with lower standard error were recommended.

Crash Modification Factors (CMFs) or Functions (CMFunctions) express the safety consequences of some treatment or intervention that has been implemented on a roadway facility. A CRF (Crash Reduction Factor) is the percentage crash reduction after implementing a given treatment at a specific site. It is also known as "safety effectiveness" of the treatment. Both CMF and CRF are commonly applied in traffic safety field and they can be estimated by a simple formula: CMF = 1- (CRF/100). One of the main methodologies to examine the effect of highway and traffic engineering measures on safety is the 'observational study'. Observational studies can be categorized into two main groups; 1) Before-After and 2) the Cross-Sectional.

The Before-After study is more advantageous over the Cross-Sectional study since it can capture the safety implications of a certain improvement or operational change where many of the attributes (e.g. geometry and other site characteristics) of a study facility remain unchanged. In contrast, in the Cross-Sectional study, the safety implications of one group of entities having some common feature are compared to the safety of a different group of entities not having that feature. However, the method is determined based on data availability.

3.2 Observational Before-After Studies

As discussed earlier, one of the main methodologies to examine the effect of highway and traffic engineering measures on safety is the 'observational Before-After study'. There are four most commonly used approaches to perform an 'observational Before-After' study; 1) naïve Before-After study, 2) Before-After study with yoked comparison, 3) Before-After study with comparison group (CG) and 4) Before-After study with Empirical Bayes (EB) approach.

Generally, all Before-After studies are designed to answer questions about "What would have been the safety of the entity in the after period had treatment not been implemented?" and "What the safety of the treated entity in the after period was?" (Hauer, 1997)

In this dissertation, CMFs were estimated using naïve Before-After study (only for illustration), Before-After with comparison group, and Before-After with EB method (the last two approaches are more reliable). Moreover, the Cross-Sectional study was used for the treatments where data were not sufficient for the Before-After study.

3.2.1 Naïve Before-After Study

The naïve Before-After approach is the simplest approach. Crash counts in the before period are used to predict the expected crash rate and, consequently, expected crashes had the treatment not been implemented. This basic Naïve approach assumes that there was no change

from the 'before' to the 'after' period that affected the safety of the entity under scrutiny; hence, this approach is unable to account for the passage of time and its effect on other factors such as exposure, maturation, trend and regression-to-the-mean bias. Despite the many drawbacks of the basic Naïve Before-After study, it is still quite frequently used in the professional literature because; 1) it is considered as a natural starting point for evaluation, and 2) its easiness of collecting the required data, and 3) its simplicity of calculation. The basic formula for deriving the safety effect of a treatment based on this method is shown in Equation 3-1:

$$CMF = \frac{N_a}{N_b} \tag{3-1}$$

Where N_a and N_b are the number of crashes at a treated site in the after and before the treatment, respectively. It should be noted that with a simple calculation, the exposure can be taken into account in the Naïve Before-After study. The crash rates for both before and after the implementation of a project should be used to estimate the CMFs which can be calculated as:

$$\text{Crash Rate} = \frac{\text{Total Number of Crashes}}{\text{Exposure}} \tag{3-2}$$

Where the 'Exposure' is usually calculated in million vehicle miles (MVM) of travel, as indicated in Equation 3-3:

$$Exposure = \frac{\text{Pr}oject\ Section\ Length\ in\ Miles \times Mean\ ADT \times Number\ of\ Years \times 365\ Days}{1{,}000{,}000} \tag{3-3}$$

Each crash record would typically include the corresponding average daily traffic (ADT). For each site, the mean ADT can be computed by Equation 3-4:

$$\text{Mean ADT} = \frac{\text{Summation of Individual ADTs Associated with each Crash}}{\text{Total Number of Crashes}} \quad (3\text{-}4)$$

3.2.2 Before-After with Comparison Group

To account for the influence of a variety of external causal factors that change with time, the Before-After with comparison group study can be adopted. A comparison group is a group of control sites that remained untreated, and that are similar to the treated sites in trend of crash history, traffic, geometric and geographic characteristics. The crash data at the comparison group are used to estimate the crashes that would have occurred at the treated entities in the 'after' period had treatment not been applied. This method can provide more accurate estimates of the safety effect than a naïve Before-After study, particularly, if the similarity between treated and comparison sites is high. The Before-After with comparison group method is based on two main assumptions (Hauer, 1997):

1. The factors that affect safety have changed in the same manner from the 'before' period to 'after' period in both treatment and comparison groups, and
2. These changes in the various factors affect the safety of treatment and comparison groups in the same way.

Based on these assumptions, it can be assumed that the change in the number of crashes from the 'before' period to 'after' period at the treated sites, in case of no countermeasures had been implemented, would have been in the same proportion as that for the comparison group. Accordingly, the expected number of crashes for the treated sites that would have occurred in the 'after' period had no improvement applied ($N_{expected,T,A}$) follows (Hauer, 1997):

$$N_{expected,T,A} = N_{observed,T,B} \times \frac{N_{observed,C,A}}{N_{observed,C,B}} \quad (3\text{-}5)$$

If the similarity between the comparison and the treated sites in the yearly crash trends is ideal, the variance of $N_{expected,T,A}$ can be estimated from Equation 3-6:

$$Var(N_{expected,T,A}) = N_{expected,T,B}^{2}(1/N_{observed,T,B} + 1/N_{observed,C,B} + 1/N_{observed,C,A}) \quad (3\text{-}6)$$

It should be noted that a more precise estimate can be obtained in case of using non-ideal comparison group as explained in Hauer (1997), Equation 3-7:

$$Var(N_{expected,T,A}) = N_{expected,T,B}^{2}(1/N_{observed,T,B} + 1/N_{observed,C,B} + 1/N_{observed,C,A} + Var(\omega)) \quad (3\text{-}7)$$

$$\omega = \frac{r_c}{r_t} \quad (3\text{-}8)$$

where $r_c \cong \frac{N_{expected,c,A}}{N_{expected,c,B}}$ (3-9)

and $r_t \cong \frac{N_{expected,t,A}}{N_{expected,t,B}}$ (3-10)

The CMF and its variance can be estimated from Equations 3-11 and 3-12.

$$CMF = (N_{observed,T,A}/N_{expected,T,A})/(1 + (Var(N_{expected,T,A})/N_{expected,T,A}^{2})) \quad (3\text{-}11)$$

$$Var(CMF) = \frac{CMF^2[(1/N_{observed,T,A}) + ((Var(N_{expected,T,A})/N_{expected,T,A}^{2})]}{[1 + (Var(N_{expected,T,A})/N_{expected,T,A}^{2}]^2} \quad (3\text{-}12)$$

where,

$N_{observed,T,B}$ = the observed number of crashes in the before period for the treatment group;

$N_{observed,T,A}$ = the observed number of crashes in the after period for the treatment group;

$N_{observed,C,B}$ = the observed number of crashes in the before period in the comparison group;

$N_{observed,C,A}$ = the observed number of crashes in the after period in the comparison group;

ω = the ratio of the expected number of crashes in the 'before' and 'after' for the treatment and the comparison group;

r_c = the ratio of the expected crash count for the comparison group;

r_t = the ratio of the expected crash count for the treatment group.

There are two types of comparison groups with respect to the matching ratio; 1) the Before-After study with yoked comparison which involves a one-to-one matching between a treatment site and a comparison site, and 2) a group of matching sites that are few times larger than treatment sites. The size of a comparison group in the second type should be at least five times larger than the treatment sites as suggested by Pendleton (1991). Selecting matching comparison group with similar yearly trend of crash frequencies in the 'before' period could be a daunting task. In this study a matching of at least 4:1 comparison group to treatment sites was conducted. Identical length of three years of the before and after periods for the treatment and the comparison group was selected.

3.2.3 Before-After with Empirical Bayes

In the Before-After with Empirical Bayes method, the expected crash frequencies at the treatment sites in the 'after' period had the countermeasures not been implemented is estimated more precisely using data from the crash history of a treated site, as well as the information of what is known about the safety of reference sites with similar yearly traffic trend, physical characteristics, and land use. The method is based on three fundamental assumptions (Hauer, 1997):

1. The number of crashes at any site follows a Poisson distribution.
2. The means for a population of systems can be approximated by a Gamma distribution.
3. Changes from year to year from sundry factors are similar for all reference sites.

Figure 3-1 illustrates the conceptual approach used in the EB method (Source: Harwood et al., 2003).

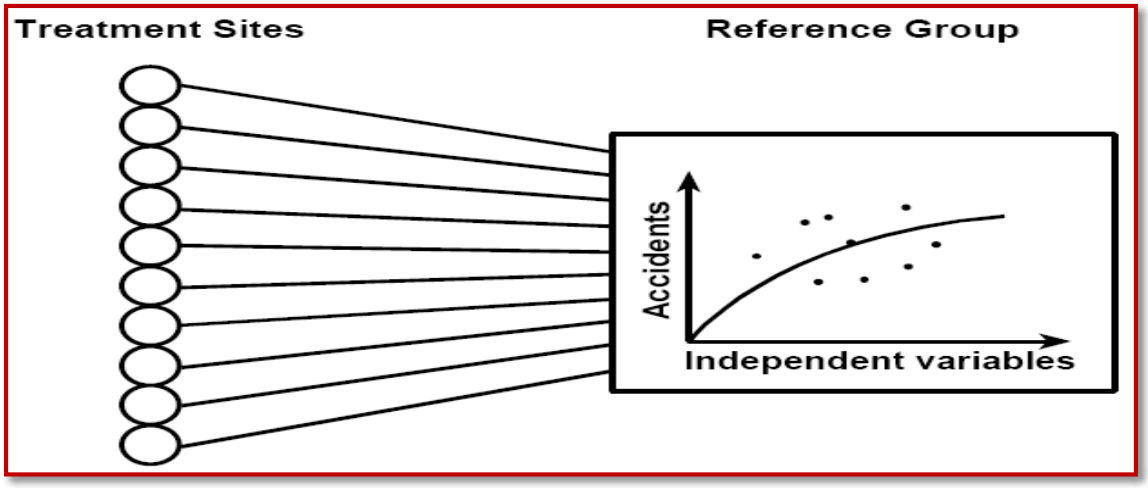


Figure 3-1: Conceptual Approach of the Empirical Bayesian Method (Harwood et al., 2003)

One of the main advantages of the Before-After study with Empirical Bayes is that it accurately accounts for changes in crash frequencies in the 'before' and in the 'after' periods at the treatment sites that may be due to regression-to-the-mean bias. It is also a better approach than the comparison group for accounting for influences of traffic volumes and time trends on safety. The estimate of the expected crashes at treatment sites is based on a weighted average of information from treatment and reference sites as given in (Hauer, 1997):

$$\hat{E}_i = (\gamma_i \times y_i \times n) + (1-\gamma_i)\eta_i \qquad (3\text{-}13)$$

where γ_i is a weight factor estimated from the over-dispersion parameter of the negative binomial regression relationship and the expected 'before' period crash frequency for the treatment site as shown in Equation 3-14:

$$\gamma_i = \frac{1}{1 + k \times y_i \times n} \tag{3-14}$$

where,

y_i = Number of average expected crashes of given type per year estimated from the SPF (represents the 'evidence' from the reference sites).

η_i = Observed number of crashes at the treatment site during the 'before' period

n = Number of years in the before period,

k = Over-dispersion parameter

The 'evidence' from the reference sites is obtained as output from the SPF. SPF is a regression model which provides an estimate of crash occurrences on a given roadway section. Crash frequency on a roadway section may be estimated using negative binomial regression models (Abdel-Aty and Radwan, 2000; Persaud, 1990), and therefore it is the form of the SPFs for negative binomial model is used to fit the before period crash data of the reference sites with their geometric and traffic parameters. A typical SPF will be of the following form:

$$y_i = e^{(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_n x_n)} \quad (3\text{-}15)$$

where,

β_i's = Regression Parameters;

x_1, x_2 = logarithmic values of AADT and section length, respectively;

x_i's ($i > 2$) = Other traffic and geometric parameters of interest.

Over-dispersion parameter, denoted by k is the parameter which determines how widely the crash frequencies are dispersed around the mean. The standard deviation (σ_i) for the estimate in Equation 3-16 is given by:

$$\hat{\sigma}_i = \sqrt{(1 - \gamma_i) \times \hat{E}_i} \quad (3\text{-}16)$$

It should be noted that the estimates obtained from equation 3-16 are the estimates for number of crashes in the before period. Since, it is required to get the estimated number of crashes at the treatment site in the after period; the estimates obtained from Equation 3-17 are adjusted for traffic volume changes and different before and after periods (Hauer, 1997; Noyce et al., 2006). The adjustment factors are given as below:

$$\rho_{AADT} = \frac{AADT_{after}^{\alpha_1}}{AADT_{before}^{\alpha_1}} \quad (3\text{-}17)$$

where,

ρ_{AADT} = adjustment factor for AADT;

$AADT_{after}$ = AADT in the after period at the treatment site;

$AADT_{before}$ = AADT in the before period at the treatment site;

α_1 = regression coefficient of AADT from the SPF.

$$\rho_{time} = \frac{m}{n} \tag{3-18}$$

where,

ρ_{time} = Adjustment factor for different before-after periods;

m = Number of years in the after period;

n = Number of years in the before period.

Final estimated number of crashes at the treatment location in the after period ($\hat{\pi}_i$) after adjusting for traffic volume changes and different time periods is given by:

$$\hat{\pi}_i = \hat{E}_i \times \rho_{AADT} \times \rho_{time} \tag{3-19}$$

The index of effectiveness (θ_i) of the treatment is given by:

$$\hat{\theta}_i = \frac{\hat{\lambda}_i / \hat{\pi}_i}{1 + \left(\hat{\sigma}_i^{\,2} \Big/ \hat{\pi}_i^{\,2} \right)} \tag{3-20}$$

where,

$\hat{\lambda}_i$ = Observed number of crashes at the treatment site during the after period.

The percentage reduction (τ_i) in crashes of particular type at each site *i* is given by:

$$\hat{\tau}_i = (1 - \hat{\theta}_i) \times 100\% \tag{3-21}$$

The Crash Reduction Factor or the safety effectiveness ($\hat{\theta}$) of the treatment averaged over all sites would be given by (Persaud et al., 2004):

$$\hat{\theta} = \frac{\sum_{i=1}^{m} \hat{\lambda}_i \Big/ \sum_{i=1}^{m} \hat{\pi}_i}{1 + \left(\text{var}(\sum_{i=1}^{m} \hat{\pi}_i) \Big/ (\sum_{i=1}^{m} \hat{\pi}_i)^2 \right)} \tag{3-22}$$

Where

m = total number of treated sites;

$$\text{var}(\sum_{i=1}^{k} \hat{\pi}_i) = \sum_{i=1}^{k} \rho_{AADT}^{\,2} \times \rho_{time}^{\,2} \times \text{var}(\hat{E}_i) \quad \text{(Hauer, 1997)} \tag{3-23}$$

The standard deviation ($\hat{\sigma}$) of the overall effectiveness can be estimated using information on the variance of the estimated and observed crashes, which is given by Equation 3-24.

$$\hat{\sigma} = \sqrt{\frac{\theta^2\left[\left(\text{var}(\sum_{i=1}^{k}\hat{\pi}_i)\Big/(\sum_{i=1}^{k}\hat{\pi}_i)^2\right)+\left(\text{var}(\sum_{i=1}^{k}\hat{\lambda}_i)\Big/(\sum_{i=1}^{k}\hat{\lambda}_i)^2\right)\right]}{\left[1+\left(\text{var}(\sum_{i=1}^{k}\hat{\pi}_i)\Big/(\sum_{i=1}^{k}\hat{\pi}_i)^2\right)\right]^2}} \quad (3\text{-}24)$$

where, $\text{var}(\sum_{i=1}^{k}\hat{\lambda}_i) = \sum_{i=1}^{k}\lambda_i$ (Hauer, 1997) (3-25)

Equation 3-25 is used in the analysis to estimate the expected number of crashes in the after period at the treatment sites, and then the values are compared with the observed number of crashes at the treatment sites in the after period to get the percentage reduction in number of crashes resulting from the treatment.

3.3 Cross-Sectional Studies

It should be noted that the CMF for certain treatments (e.g. median width) can only be estimated using the Cross-sectional method, but not Before-After method. This is because it is difficult to isolate the effect of the treatment from the effects of the other treatments applied at the same time using the Before-After method (Harkey et al., 2008).

The method is used in the following conditions (AASHTO, 2010): 1) the date of the treatment installation is unknown, 2) the data for the period before treatment installation are not available, and 3) the effects of other factors on crash frequency must be controlled for creating a Crash Modification Function (CMFunction).

The Cross-sectional method requires the development of crash prediction models (i.e. SPFs) for calculation of CMFs. The models are developed using the crash data for both treated and untreated sites for the same time period (3-5 years). According to the Highway Safety Manual (HSM, 2010), 10~20 treated and 10~20 untreated sites are recommended. However, the Cross-sectional method requires much more samples than the Before-After study, say 100~1000 sites (Carter et al., 2012). Sufficient sample size is particularly important when many variables are included in the SPF. This ensures large variations in crash frequency and variables, and helps better understand their inter-relationships. The treated and untreated sites must have comparable geometric characteristics and traffic volume.

The research developed a generalized linear model (GLM) with a negative binomial distribution (NB) using these crash data as it is the most common type of function which accounts over-dispersion. The model describes crash frequency in a function of explanatory variables including geometric characteristics, AADT and length of roadway segments as follows:

$$F_i = \exp(\alpha + \beta_1 * \ln AADT_i + \beta_2 * Length_i + \cdots + \beta_k * x_{ki}) \quad (3\text{-}26)$$

where,

F_i = crash frequency on a road segment i;

$Length_i$ = length of roadway segment i (mi);

$AADT_i$ = average annual daily traffic on a road segment i (veh/day);

x_{ki} = geometric characteristic k (i.e. treatment) of a road segment i ($k > 2$);

α = constant;

$\beta_1, \beta_2, \ldots, \beta_k$ = coefficient for the variable k.

In the above equation, length and AADT are control variables to identify the isolated effect of the treatment(s) on crash frequency. Since the above model form is log-linear, the CMFs can be calculated as the exponent of the coefficient associated with the treatment variable as follows (Lord and Bonneson, 2007; Stamatiadis et al., 2009; Carter et al., 2012):

$$CMF = \exp(\beta_k * (x_{kt} - x_{kb})) = \exp(\beta_k) \quad (3\text{-}27)$$

where,

x_{kt} = geometric characteristic k of treated sites;

x_{kb} = geometric characteristic k of untreated sites (baseline condition).

The above model can be applied to prediction of total crash frequency or frequency of specific crash type or crash severity. The standard error (SE) of the CMF is calculated as follows (Bahar, 2010):

$$SE = \frac{\exp(\beta_k * (x_{kt} - x_{kb}) + SE_{\beta_k}) - \exp(\beta_k * (x_{kt} - x_{kb}) - SE_{\beta_k})}{2} \quad (3\text{-}28)$$

where,

SE = standard error of the CMF;

$SE_{\beta k}$ = standard error of the coefficient β_k.

3.4 Safety Performance Functions (SPFs)

Data from the untreated reference group are used to first estimate a Safety Performance Function (SPF) that relates crash frequency of the sites to their traffic and geometrical characteristics. Generally, a Safety Performance Function (SPF) is a crash prediction model, which relates the frequency of crashes to traffic (e.g. Average Daily Traffic) and the roadway characteristics (e.g., number of lanes, width of lanes, width of shoulder, etc.).

There are two main types of SPFs in the literature: 1) 'Full' SPFs and 2) 'Simple' SPFs. 'Full' SPF is a mathematical relationship that relates both traffic parameters and geometric parameters as explanatory variables, whereas 'Simple' SPF includes Annual Average Daily

Traffic (AADT) as the sole explanatory variable in predicting crash frequency on a roadway entity. It is worth mentioning that the calibrated CMFs in the Highway Safety Manual (HSM) are based only on the simple 'SPF'.

As mentioned earlier that the weight in Equation 3-13 is calculated using the over-dispersion parameter obtained from the Negative Binomial (NB) model. In this project, 'Simple' and 'Full' SPFs will be developed for different roadway entities. Moreover, different SPFs will be estimated separately by land-use (rural/urban) for various crash type and severity levels.

3.4.1 Negative Binomial Models

Crash data have a gamma-distributed mean for a population of systems, allowing the variance of the crash data to be more than its mean (Shen, 2007). Suppose that the count of crashes on a roadway section is Poisson distributed with a mean λ, which itself is a random variable and is gamma distributed, then the distribution of frequency of crashes in a population of roadway sections follows a negative binomial probability distribution (Hauer, 1997).

$y_i|\lambda_i$ ~ Poisson (λ_i)

λ ~ Gamma (a,b)

Then, P(y_i) ~ Negbin (λ_i, k)

$$= \frac{\Gamma(1/k + y_i)}{y_i!\Gamma(1/k)} \left(\frac{k\lambda_i}{1 + k\lambda_i} \right)^{y_i} \left(\frac{1}{1 + k\lambda_i} \right)^{1/k} \quad (3\text{-}29)$$

where,

y = number of crashes on a roadway section per period;

λ = expected number of crashes per period on the roadway section;

k = over-dispersion parameter.

The expected number of crashes on a given roadway section per period can be estimated by Equation 3-30.

$$\lambda = \exp(\beta^T X + \varepsilon) \quad (3\text{-}30)$$

where,

β = a vector of regression of parameter estimates;

X = a vector of explanatory variables;

$\exp(\varepsilon)$ = a gamma distributed error term with mean one and variance k.

Because of the error term the variance is not equal to the mean, and is given by Equation 3-31.

$$\text{var}(y) = \lambda + k\lambda^2 \quad (3\text{-}31)$$

As $k \to 0$, the negative binomial distribution approaches Poisson distribution with mean λ. The parameter estimates of the binomial regression model and the dispersion parameter are estimated by maximizing the likelihood function given in Equation 3-32.

$$l(\beta,k) = \prod_i \frac{\Gamma(1/k + y_i)}{y_i!\Gamma(1/k)} \left(\frac{k\lambda_i}{1+k\lambda_i}\right)^{y_i} \left(\frac{1}{1+k\lambda_i}\right)^{1/k} \tag{3-32}$$

Using the above methodology negative binomial regression models were developed and were used to estimate the number of crashes at the treated sites.

3.5 Log-Linear Model

Past studies and current data have indicated that certain locations at toll plazas are more likely to be more risky than regular segments on the expressway. However, to the best of our knowledge there were no studies that investigated the association between traffic crashes and toll plaza types, AADT or driving maneuver variables among various age groups.

A log-linear model is a generalized linear model for Poisson-distributed data; it specifies how the size of a cell count depends on the levels of the categorical variables for that cell. The nature of this specification relates to the association and interaction structure among the variables (Christensen, 1990) (Abdel-Aty et al., 1998). The log-linear model describes the

association and interaction patterns among a set of categorical variables (Knoke, and Burke, 1980).

The estimates of parameters resulting from the model can be converted to estimate the odds ratio between variables. The formulation of a log-linear model with three variables and two-way interactions is as follows:

$$\log\ m_{ijk} = \nu + \lambda_i^x + \lambda_j^y + \lambda_k^z + \lambda_{ij}^{xy} + \lambda_{jk}^{yz} + \lambda_{ik}^{xz} \quad (3\text{-}33)$$

Where:

Log mijk = log the expected frequency of cell in which:

x=i, y=j, z=k;

υ = overall effect.

λ_i^x=effect due to the i^{th}level of x;

λ_j^y=effect due to the j^{th} level of y;

λ_k^z =effect due to the k^{th} level of z;

λ_{ij}^{xy} = interaction of x at the i^{th}level and y at the j^{th} level;

λ_{ik}^{xz} = interaction of x at the i^{th} level and z at the k^{th} level;

λ_{jk}^{yz} = interaction of y at the j^{th} level and z at the k^{th} level.

For instance, when the model contains the term λ_{ij}^{xy}, which is the effect due to the interaction of x being at level j, it also contains λ_i^x, the effect due to the i^{th} level of x, and λ_j^y, the effect due to the j^{th} level of y. A reason for including lower-order terms is that the statistical significance and practicable interpretation of a higher order term depends on how the variables are coded. Since this model contains an X–Y two-factor term, it permits association between X and Y, controlling for Z. It also permits an X–Z association, controlling for Y, and a Y–Z association, controlling for X (Abdel-Aty et al., 1998). By using eqn (1) for two cells, the log odds logit can be determined. And it helps understand how the independent variables affect the response variables (especially the toll plaza types); the logit models are constructed according to the response variables as follows:

$$\begin{aligned}\log\ (m_{ijk}/m_{i1k}) &= \left[\nu + \lambda_i^x + \lambda_j^y + \lambda_k^z + \lambda_{ij}^{xy} + \lambda_{jk}^{yz} + \lambda_{ik}^{xz}\right] \\ &\quad - \left[\nu + \lambda_i^x + \lambda_j^y + \lambda_k^z + \lambda_{ij}^{xy} + \lambda_{jk}^{yz} + \lambda_{ik}^{xz}\right] \\ &= \left[\left[\lambda_j^y - \lambda_i^x\right] + \left[\lambda_{ij}^{xy} - \lambda_{i1}^{xy}\right] + \left[\lambda_{jk}^{yz} - \lambda_{1k}^{yz}\right]\right] \qquad (3\text{-}34)\end{aligned}$$

Thus, for instance, in eqn (4), we are modeling the log of the odds that y=j instead of y=1, when x=I and z=k.

CHAPTER 4: DATA COLLECTION

An extensive data collection was conducted that included a hundred mainline toll plazas located on approximately 750 miles of expressways in Florida. Multiple sources of data available online maintained by Florida Department of Transportation were utilized to identify locations with treatments/upgrades, as well as their traffic, geometric and geographic characteristics.

These data sources included: Roadway Characteristics Inventory system (RCI), TRANSVIEW aerial mapping system, Five Years Work Program, Financial Management database, and Straight Line Diagrams (SLDs). Also, Google earth and the publication reports of Florida Turnpike and Central Florida Expressway authority were used to investigate and determine the most complete and accurate data each data source is described in detail in Section 4.1.

Crash data for eleven year period (2002-2012) was investigated to examine the safety impact by evaluating the crash history of before and after the implementation of the treatment. Crashes that occurred within the influence areas of treatments were extracted from the crash database maintained by FDOT called Crash Analysis Reporting (CAR) system. It should be noted that data in the period when locations were upgraded including six months before and six months after was excluded from the analysis.

4.1 Description of Data

4.1.1 Financial Management Database

Road facility construction projects are recorded in the Financial Management (FM) database. The database offers a search system named “Financial Project Search” as shown in Figure 4-1. Through this system, specific financial project and its relevant information can be identified.

Figure 4-1: Financial Project Search from the Financial Management Database (FDOT, 2014)

Also, the system provides a function to search financial projects by various conditions such as district, status, work types and year. The information provided in the FM database was too general in which other data sources have to be utilized to collect more information about the treated sites.

4.1.2 TRANSVIEW Aerial Mapping System

TRANSVIEW is a Geographical Database System provided by FDOT TranStat Department. The system was used to verify information collected from the FM. Figures 4-2 and 4-3 show a location with beginning and end mileposts for an identified project in the FM.

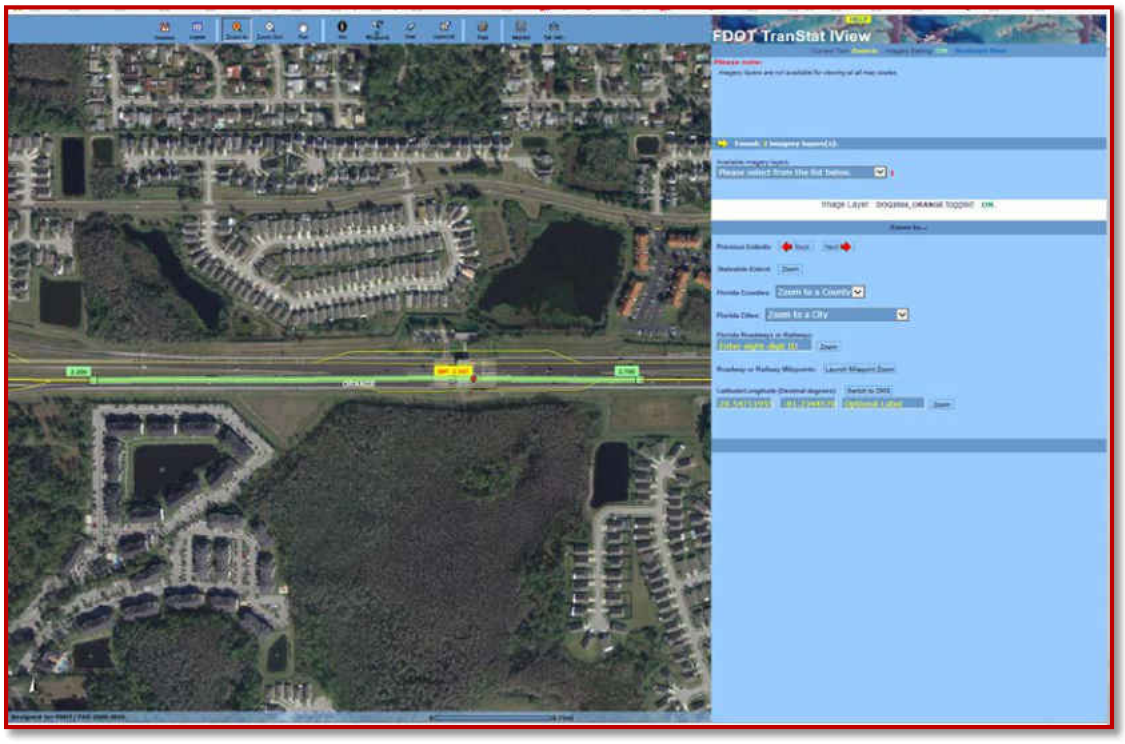


Figure 4-2: Example of TRANSVIEW Map (Source: FDOT, 2014)

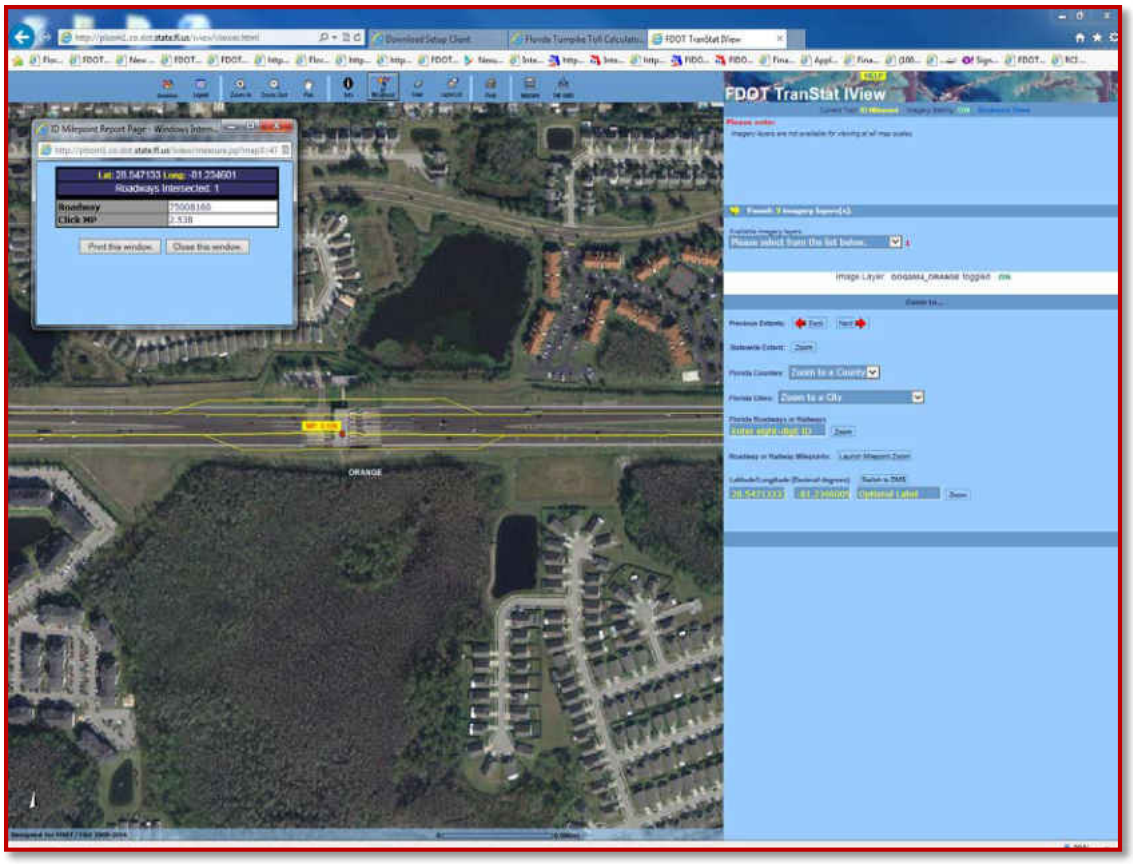


Figure 4-3: TRANSVIEW Map shows Roadway ID and its mileposts (Source: FDOT, 2014)

Although the treated site can be specified in the TRANSVIEW, it does not provide detailed historical geometry of the site. Therefore, Google Earth (GE) was used as an additional source to verify data collected from the FM. Google Earth provides historical satellite imagery layers for different years; Figure 4-4 shows an example of the historical satellite imagery layers for different years. This feature enabled us to compare the before and after geometrical characteristics more precisely. Although that Google Earth provided valuable information and

helped to identify various problems in the FM database, this process could be extremely tedious and time consuming.

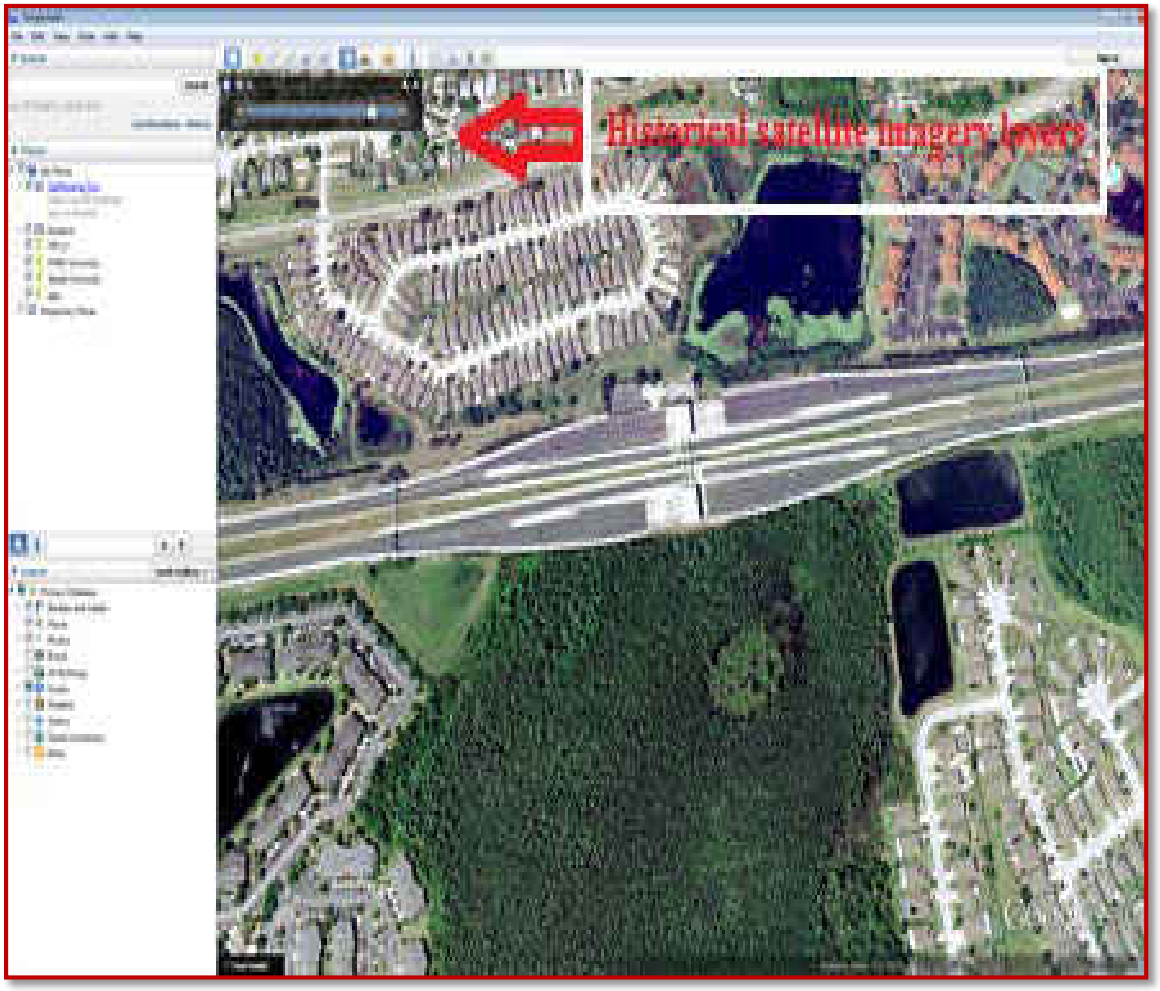


Figure 4-4: Historical satellite imagery layers for different years (Google Earth, 2014)

4.1.3 Video Log Viewer Application

Video Log Viewer Application was also used to check the validity and accuracy of the collected data. Figure 4-5 and 4-6 show screenshots of the results of two of the treated sites.

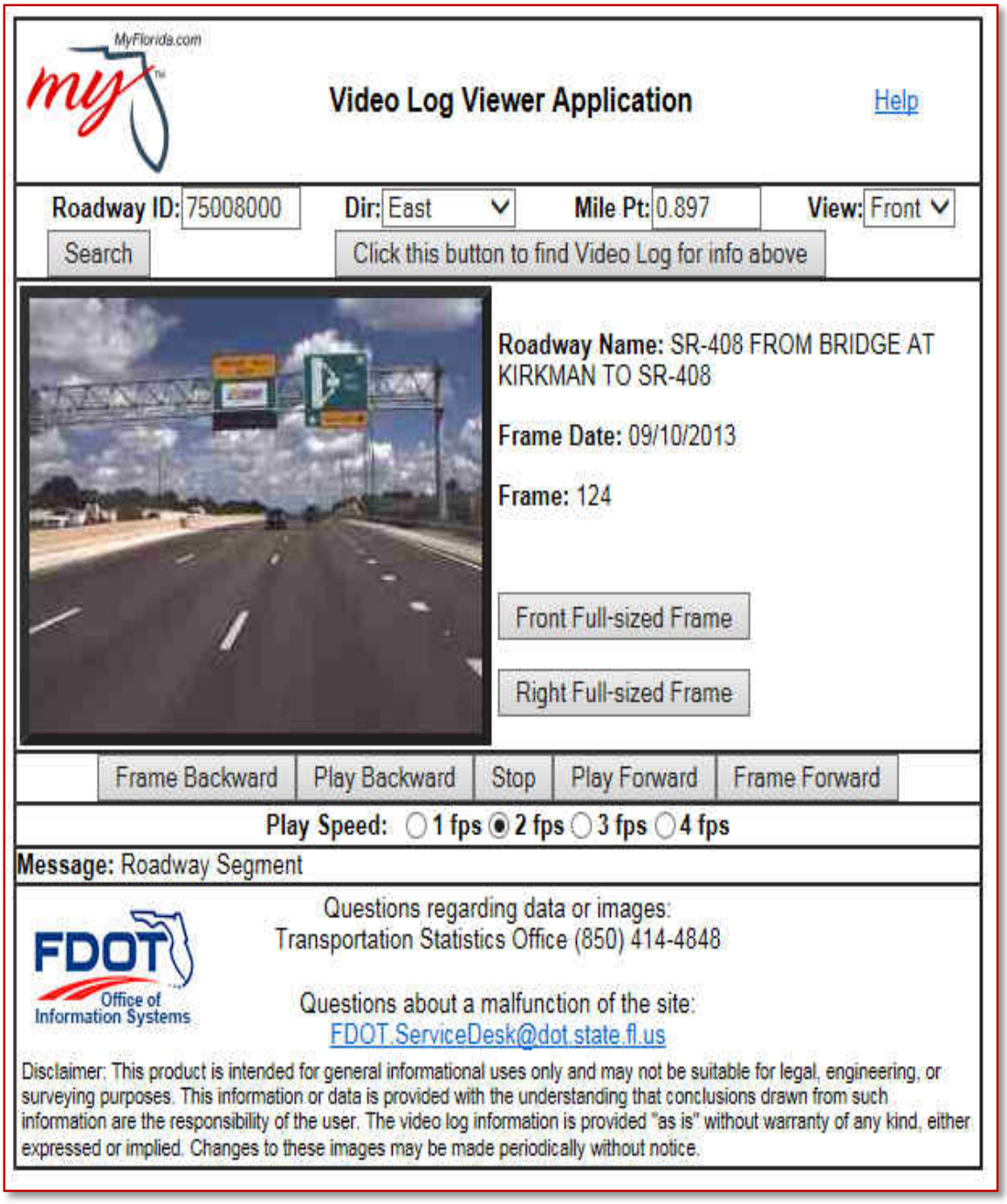


Figure 4-5: Screenshot from Video Log Viewer Application for HMTP (Source: FDOT, 2014)

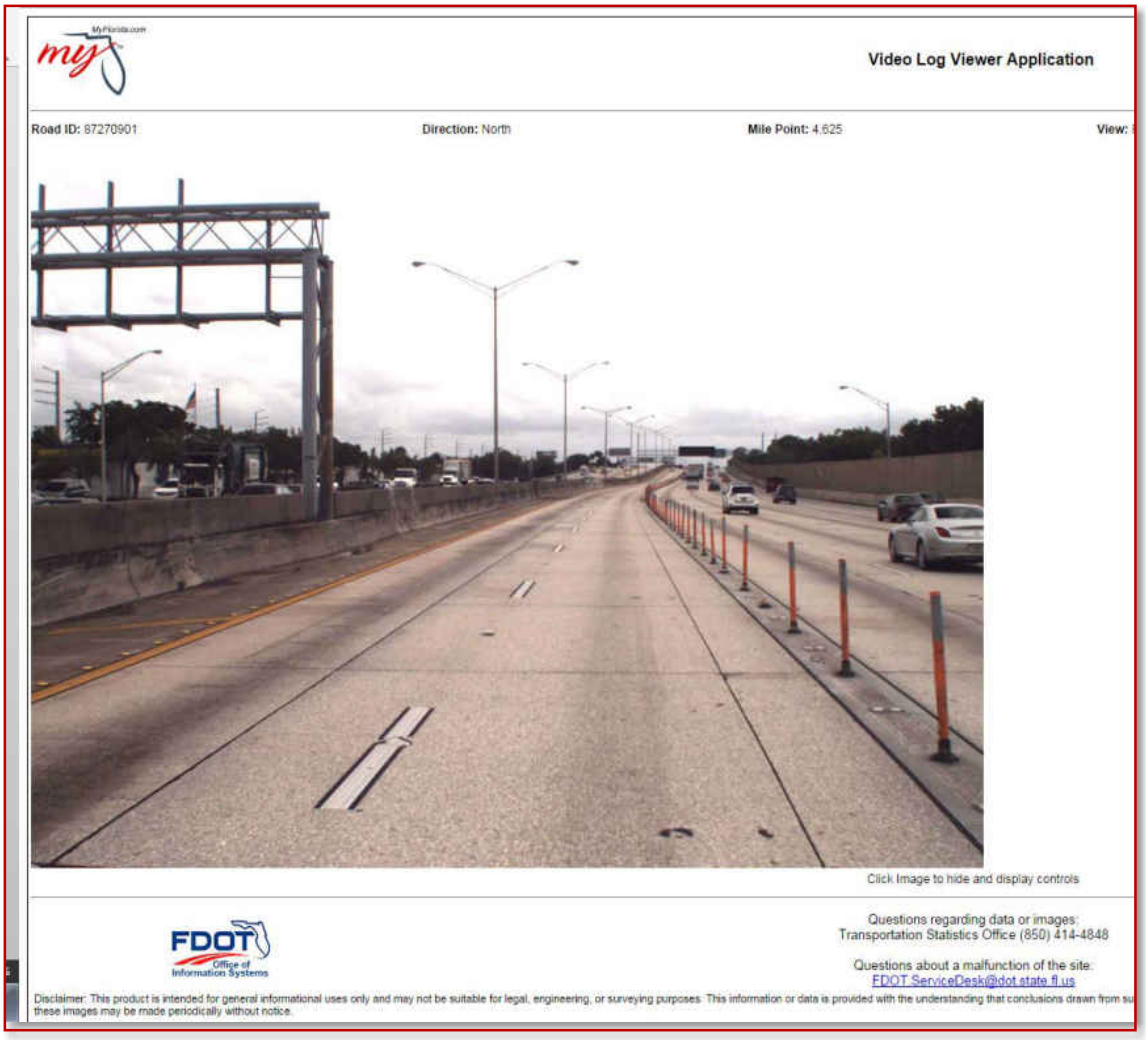


Figure 4-6: Screenshot from Video Log Viewer Application for HOT-Lanes (FDOT, 2014)

4.1.4 Roadway Characteristics Inventory (RCI)

The Roadway Characteristics Inventory (RCI) is mainly used to identify the type of road configuration, geometrics of roadway segments and intersections, e.g. overall surface lane width, number of lanes, shoulder type and width, median width, maximum speed limit and

other roadway and traffic characteristics. Figure 4 7 shows screenshot of Historical RCI Query List.

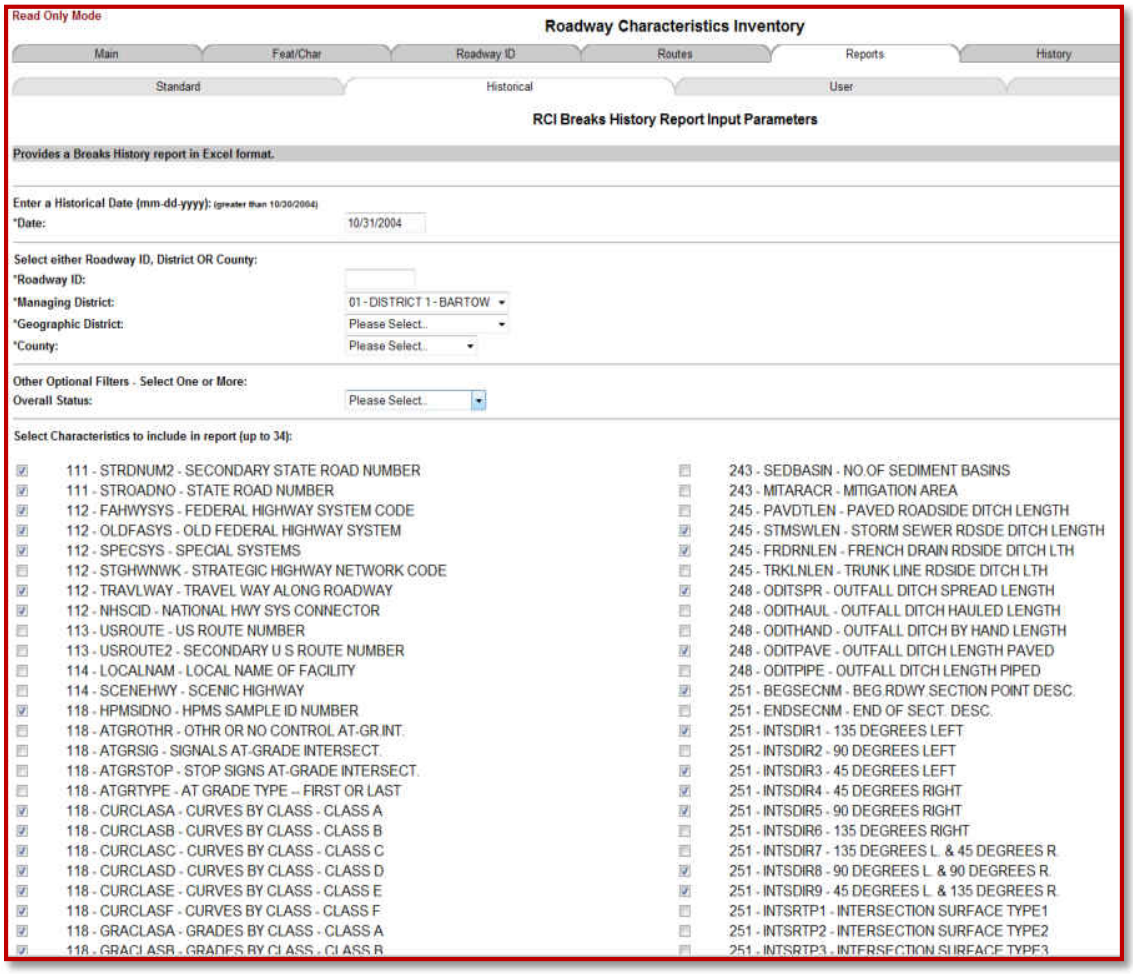


Figure 4-7: Screenshot of Historical RCI Query List (Source: FDOT, 2014)

The researcher identified the implemented treatments in the RCI to verify the data collected from the FM. It should be noted that RCI provides data only starting from 2004, and hence the identified treatment projects from 2000 to 2003 cannot be verified from RCI. Tables 4-1 and 4-2 examples of the major variables related to crash frequency (Source: RCI-FDOT).

Table 4-1: Example (1), Variables related to crash frequency in the RCI database

Variable	Variable Name	Description
111	STROADNO	State Road Number
113	USROUTE	US Route Number
118	TURNLANL	Turn Lane Left
118	GRACLASA	Grade by Class
118	GRACLASB	Grade by Class
118	GRACLASC	Grade by Class
118	GRACLASD	Grade by Class
118	GRACLASE	Grade by Class
118	GRACLASF	Grade by Class
118	TURNLANR	Turn Lane Right
118	TYPEOP	Type of Operation
120	TYPEROAD	Type of Road
121	FUNCLASS	Functional Classification
122	RDACCESS	Access Control Type
212	NOLANES	Number of Roadway Lanes
212	SURWIDTH	Total Through Lanes Surface Width
213	AUXLNTYP	Auxiliary Lane Type
213	AUXLWTH	Width of Auxiliary Lane
213	AUXNUM	Number of Auxiliary Lanes
214	SHLDTYPE 3	Highway Shoulder Type
214	SHLDTYPE	Highway Shoulder Type
214	SHLDTYPE 2	Highway Shoulder Type
214	SLDWIDTH	Highway Shoulder Width
214	SLDWIDTH 2	Highway Shoulder Width
214	SLDWIDTH 3	Highway Shoulder Width
215	MDBARTYP	Type of Median
215	MEDWIDTH	Highway Median Width
215	RDMEDIAN	Highway Median Type
216	BIKELNCD	Bicycle Lane

Table 4-2: Example (2), Variables related to crash frequency in the RCI database

Variable	Variable Name	Description
219	ISLDTYPE	Inside Shoulder Type
219	ISLDTYPE 2	Inside Shoulder Type
219	ISLDTYPE 3	Inside Shoulder Type
219	ISLDWDTH	Inside Shoulder Width
219	ISLDWDTH 2	Inside Shoulder Width
219	ISLDWDTH 3	Inside Shoulder Width
221	HRZCANGL	Horizontal Curve Central Angle
221	HRZDGCRV	Horizontal Degree of Curve
311	MAXSPEED	Maximum Speed Limit
313	DTEPKIMP	DTE Parking Restriction Implement
331	SECTADT	Section Average AADT
453	CRWALK24	No. of 24ft Crosswalks
453	CRWALK36	No. of 36ft Crosswalks
453	CRWALK48	No. of 48ft Crosswalks
453	CRWALK60	No. of 60ft Crosswalks
453	CRWALK72	No. of 72ft Crosswalks
455	PAVTMARK	Number of raised pavement markers
456	CL	Centerline
456	EL	Edge Line
457	FINPROJ	Financial Project No.

4.2 Data Collection for the analysis

In this study, each roadway segment (treated or untreated segments) has uniform geometric characteristics within the road section (e.g. Toll plaza, HOT-Lanes, and Roadway Lighting). A segment is represented by roadway ID, and beginning and end mile points. But segments do not necessarily have equal length.

4.2.1 Mainline Toll Plazas

Traditional Mainline Toll Plaza (TMTP) systems require vehicles to rapidly decelerate, navigate through different fare transaction options, and then accelerate and merge with traffic. Unlike TMTP, Electronic Toll Collection (ETC) technologies allow vehicles to pass through the toll plaza without interruption as tolls are charged electronically. Thus, Hybrid Mainline Toll Plaza (HMTP) that retrofits existing tollbooths with express open ETC lanes are widely deployed in many states. Figures 4-8 ~ 4-11 show designs and guide signs for mainline toll plazas.

Figure 4-8: Traditional Mainline Toll Plaza (TMTP) (Source: FHWA, 2014)

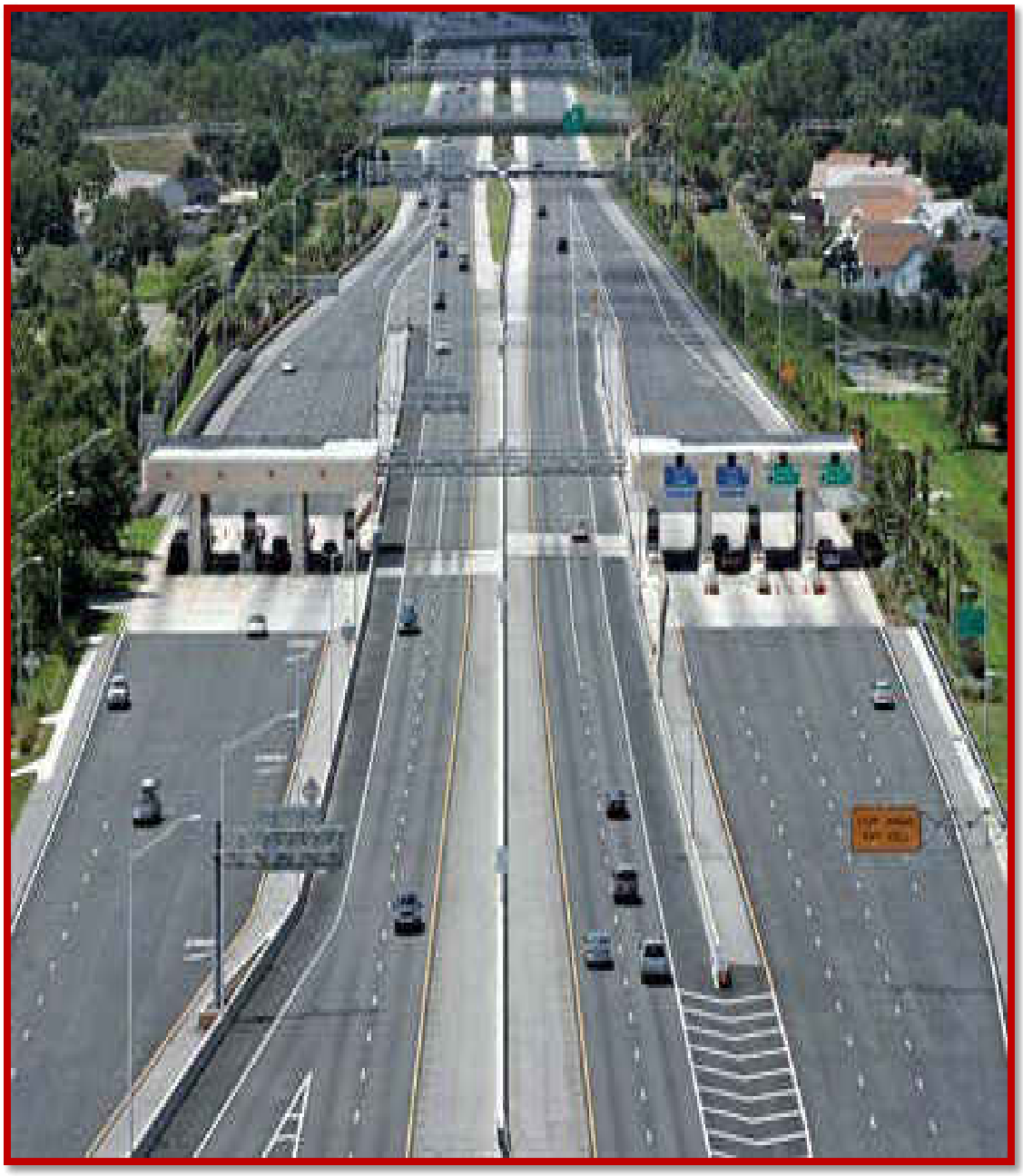


Figure 4-9: Hybrid Mainline Toll Plaza (HMTP) (Source: CFX, 2014)

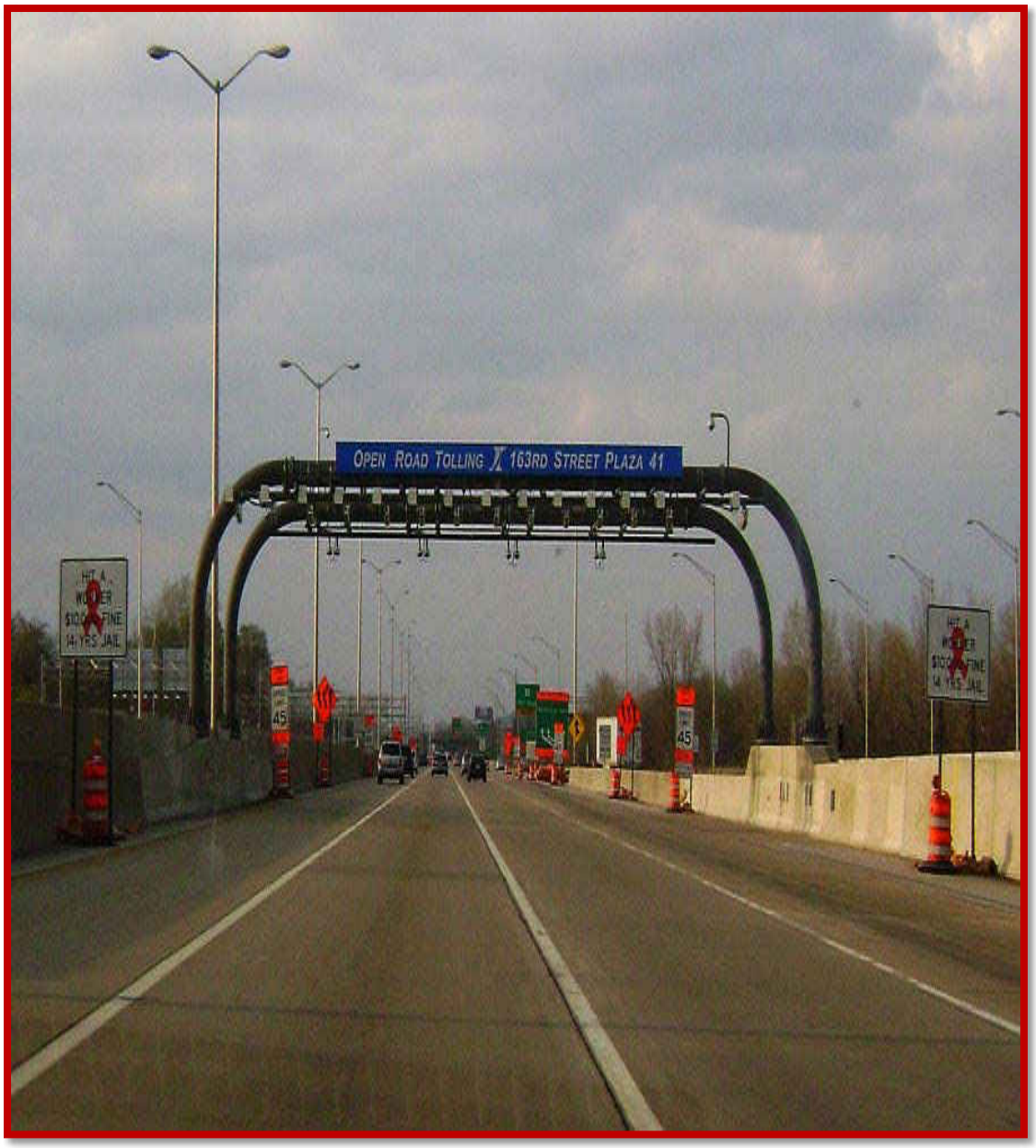


Figure 4-10: All Electronic Toll Collection (AETC) (Source: FHWA, 2014)

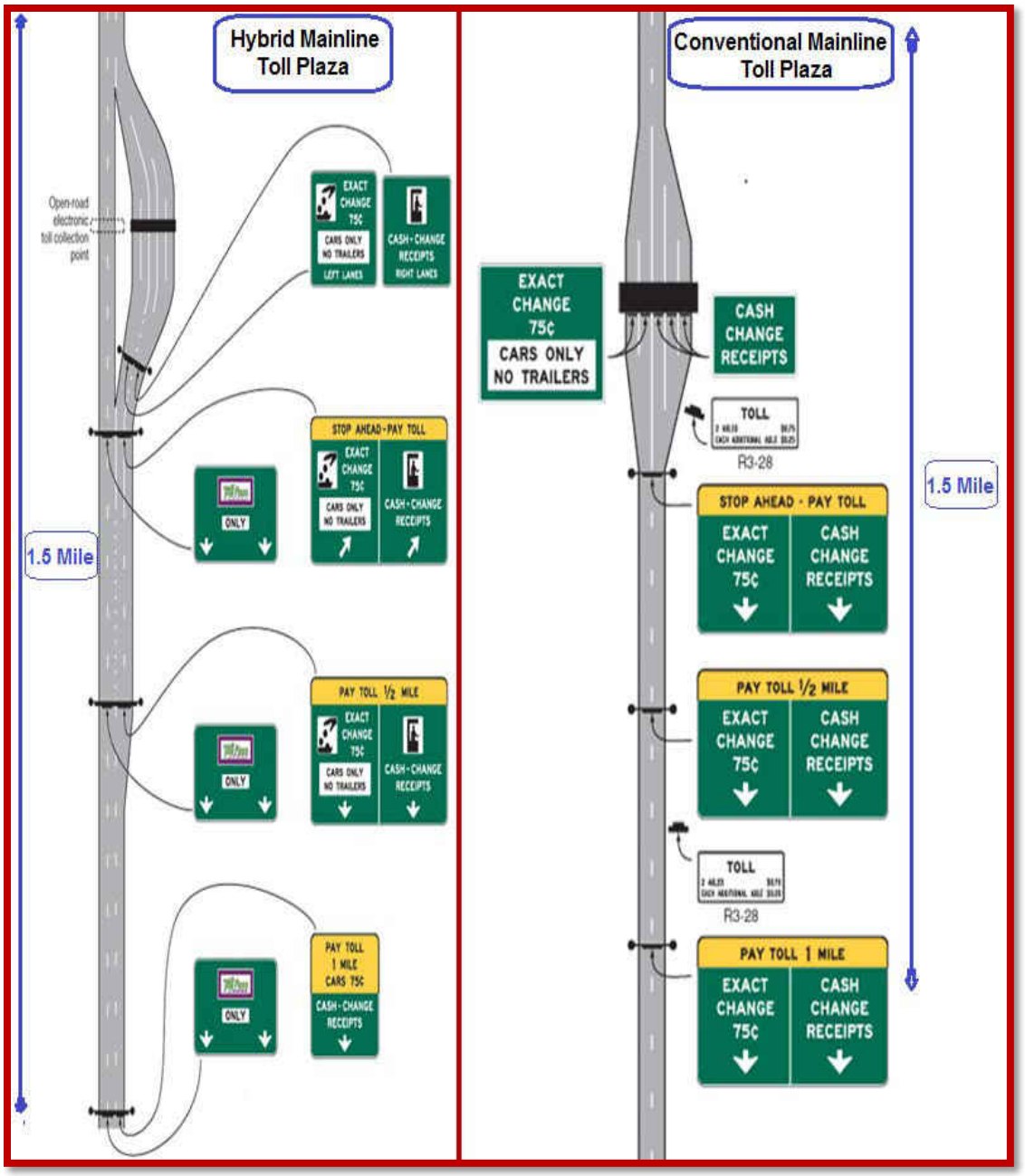


Figure 4-11: Advance Signage for Conventional and HMTP (Source: FHWA, 2014)

Data was collected from hundred Mainline Toll Plazas (two directions) located on approximately 750 miles of toll roads in the State of Florida. There were thirty sites converted

from TMTP to HMTP. Forty two untreated sites that have TMTP design were also identified as reference sites. Reference sites are different from the comparison sites - reference sites are broader than the comparison sites with more variation AADT, roadway characteristics and crash history. Data from twenty eight HMTPs which design has not been changed since they were built was used to evaluate the quality of the calibrated SPFs, CMFs and Crash Modification Functions (CMFunctions). Numbers of treated and untreated sites, and HMTPs without design change are shown in Table 4-3.

Crash data for three years before and three years after the implementation of the treatment in 2002-2012 were used to examine the safety impact of converting TMTP to HMTP. According to the Manual on Uniform Traffic Control Devices (MUTCD), the signposting distances and the influence areas of the mainline toll plaza cover 1 mile before and 0.5 mile after the centerline of the mainline toll plaza. Crashes that occurred within the influence areas of toll plazas were extracted from the CAR database. It should be noted that the crash data in the period six months before and after the conversion of TMTP to HMTP were excluded from the analysis.

Table 4-3: Numbers of Sites for Mainline Toll Plaza

	Sites converted from TMTP to HMTP	Reference (Untreated) sites of TMTP	HMTPs without design change
Number of Sites	30	42	28

CHAPTER 5: HYBRID MAINLINE TOLL PLAZA

5.1 Converting Traditional Mainline Toll Plaza to Hybrid Mainline Toll Plazas system.

5.1.1 Summary of the Chapter

Traditional mainline toll plazas on expressways may have both safety and operational challenges. While many studies demonstrated the operational and environmental impacts of the conversion from traditional toll plazas to a barrier-free system (Open Road Tolling), there is a lack of research that quantifies the safety benefits of new tolling systems. This study evaluated the safety effectiveness of the conversion from Traditional Mainline Toll Plaza (TMTP) design to Hybrid Mainline Toll Plaza (HMTP) system. HMTP combines both an Open Road Tolling (ORT) on the mainline and separate traditional toll collection to the side.

Various observational before-after studies were applied on ninety-eight mainline toll plazas (two directions) located on approximately 750 miles of toll roads in the State of Florida; thirty of them were upgraded to HMTPs. The multivariate Empirical Bayes (EB) method produced the best crash modification factors with low standard errors, and its results indicated that the conversion from TMTP to HMTP system resulted in an average crash reduction of 47 percent, 46 percent and 54 percent for total crashes, fatal–and-injury crashes and property damage only crashes, respectively. The use of HMTP system also significantly reduced rear end crashes and lane change related crashes by an average of 65 percent and 55 percent, respectively.

Overall, the use of HMTP system was proven to be an excellent solution to several traffic operations, environmental and economic problems. The results of this study proved that the safety effectiveness across all locations that were upgraded to HMTP was significantly improved.

5.1.2 Objective

While many studies demonstrated the operational and environmental benefits of the conversion from traditional toll plazas to HMTP, there is a lack of research that quantifies the safety impact of new tolling systems. Therefore, this section of the dissertation aims to evaluate the impact of the conversion of the traditional mainline toll plaza to HMTP on crash frequency, crash types and severity.

5.1.3 Data description

Multiple sources of data available online maintained by Florida Department of Transportation (FDOT), were considered to identify the traffic, geometric and geographic characteristics of the locations as well as investigation and determination of the most complete and accurate data. Data from 100 sites of Mainline Toll Plazas (two directions) located on approximately 750 miles of toll roads in the State of Florida was used. These sites were classified as the following: 30 sites were converted from traditional to HMTP design. A total number of 42 untreated sites were also identified as a reference sites. Reference sites are different than the comparison sites; the reference sites are broader than the comparison sites with more variation in AADT,

roadway characteristics and crash history. An additional 28 sites were identified where the HMTP system was implemented from the beginning; these 28 sites were not included in the analysis. However, they were used to evaluate the quality of the safety performance functions (SPFs), Crash Modification Factors or Accident Modification Factor (AMFs) and Crash Modification Functions (CMFs).

Crash data for eleven years period (2002-2012) was investigated to examine the safety impact by evaluating the crash history of three years before and three years after the implementation of the treatment. According to the Manual on Uniform Traffic Control Devices (MUTCD), the signposting distances and the influence area of the mainline toll plaza covers 1 mile before and 0.5 mile after the centerline of the mainline toll plaza. Crashes that occurred within the influence areas of toll plazas were extracted from the crash database maintained by FDOT called Crash Analysis Reporting (CAR) system. It should be noted that data in the period when toll plazas were upgraded to HMTPs including six months before and six months after was excluded from the analysis.

5.1.4 Analysis and results

5.1.4.1 Naïve Before-After study:

This approach was applied to 30 sites of mainline toll plazas that were upgraded to HMTP. The crash modification factors were estimated based on crash rates for both individual and all

locations combined and the Poisson test of significance was performed. The total crash rate across all locations was reduced from 29.59 crashes per million vehicle miles (MVM) in the 'before' period, to 13.91 crashes per MVM after the implementation of HMTP, representing about 53 percent reduction in the crash rate; this reduction was statistically significant. Same approach was applied to the property damage only as well as Fatal-and-Injury crashes, and the results showed that HMTP significantly reduced these levels of severity by 57.2 and 54.3 percent, respectively. The use of HMTP design significantly reduced rear end and lane change related crashes (i.e. sideswipe, lost control, overturned and angle crashes) as well by 69 and 59 percent, respectively.

Data from sixteen treated sites compared with data from sixteen untreated sites (these sites have similar characteristic such as geometric and AADT) were used in this approach. The crash modification factors were estimated for both individual and all sites combined using crash experience data from 16 comparison sites (traditional MTPs). Crash data of three years before and three years after the treatment was used. The safety effectiveness from HMTP across all locations combined was significantly improved by reducing the total crashes (all severity) by 48 percent with standard error of 9.42 percent. The statistical significance of the estimated safety effectiveness was calculated as:

$$Abs\left(\frac{\text{Safety } \textit{Effectiveness}}{\text{SE (Safety } \textit{Effectiveness})}\right) = \frac{48}{9.42} = 5.1 \qquad (5\text{-}1)$$

Since Abs [Safety Effectiveness/SE (Safety Effectiveness)] is ≥ 1.96, it can be concluded that the treatment effect is significant at the 95 percent confidence level. Same steps were applied to the property damage only (PDO) and Fatal-and-Injury crashes. The safety effectiveness across all locations combined was significantly improved by 55 and 45.2 percent with a standard error of 8.43 and 9.43 percent, respectively.

The (Abs) was statistically significant for both (Abs= (4.79 and 6.52) ≥ 1.96) at the 95 percent confidence level as well. Similar to the collision types, the treatment indicated a significant reduction for the rear end and lane change related crashes. The reductions were 65.3 and 57.4 percent, respectively. The values of (Abs) were statistically significant at the 95 percent confidence level for both types of crashes. These results were consistent with our previous findings in (Abuzwidah, 2011), that the use of Hybrid Mainline Toll Plaza system significantly reduces the number of crashes.

5.1.4.2 Before-After with the Empirical Bayes:

Data from 42 reference sites that have no treatment implemented from 2002 to 2012 were used in the Empirical Bayes analysis to develop Safety Performance Functions (SPFs) for mainline toll plazas.

5.1.4.3 Safety Performance Functions:

Generally, SPF is a crash prediction model, which relates the frequency of crashes to traffic and the roadway characteristics. There are two main types of SPFs in the literature: 1) 'Full' FSPFs and 2) 'Simple' SSPFs. 'Full' SPF is a mathematical relationship that relates both traffic and geometric parameters as explanatory variables, whereas 'Simple' SPF includes Annual Average Daily Traffic (AADT) as the sole explanatory variable in predicting crash frequency on a roadway entity. The Negative Binomial (NB) regression models for safety evaluation were developed for total crashes, severity levels and type of crashes.

A 'Simple' and 'Full' SPFs were developed for the mainline toll plaza. Table 5-1 summarizes the estimated models' parameters for the 'Full' SPFs. It should be noted that the results of the 'simple' SPFs were slightly different than the 'Full' SPFs. The (AIC) values of the NB models in 'Full' SPFs are smaller than the (ACI) values in the 'simple' SPFs. It is worth noting that a smaller (AIC) means that the model fit better for the same dataset.

The analysis showed that log (AADT), speed Limit and a downstream plaza dummy variable were the most significant variables in the final models. It is worth noting that the length of diverge and merge areas were considered in the analysis. The signs for the parameter estimates were as expected for all crash categories. For example, the coefficients for the traffic volume were positive indicating that an increase in traffic volumes leads to an increase in Total, F+I and all types of crashes at the mainline toll plazas. The coefficients for speed limit were

negative in total crashes indicating that increase in speed limit is associated with fewer crashes. But, it was positive in the F+I crashes indicating that increase in speed limit is associated with more severe crashes. This may be attributable to the fact that the variance of speeds will increase between ETC lanes and the cash lanes at the same toll plaza (approach). This speed's variations most likely would contribute to more severe crashes.

For the crash types, the coefficients for Downstream were negative in the rear end and lane change related crashes 'indicating that downstream location is associated with fewer crashes in these categories than the upstream. More research might be needed to investigate the differences between the two locations such as traffic and geometric characteristics. It is worth noting that at Hybrid Mainline Toll Plaza the upstream section is associated with diverge and potential sudden lane changing while downstream area of the plaza would involve merge of traffic from the regular and open tolling lanes.

The EB before-after evaluation of HMTP was used to predict the expected crash frequency at treated sites assuming the HMTP had not been implemented. The expected crash frequency was compared with the number of observed crashes in the period after HMTP had been implemented. The results showed that almost all the treated sites had a significant safety improvement.

To compute the safety impacts of the treatment, Crash Modification Factors and Functions (CMFs) were estimated using different approaches for the total crashes, severity levels and the collision types. Crash Modification Factors expresses the safety consequences of some treatment or intervention that has been implemented on a roadway facility. A CMF greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after the implementation of a given countermeasure.

Table 5-1: Estimates of Coefficients for 'Full' Safety Performance Functions

Severity Levels						
NB model - Total Crashes				**NB model - (F+I) Crashes**		
Parameter	**Estimate**	**Std.Err**	**P > ChiSq**	**Estimate**	**Std.Err**	**P > ChiSq**
Intercept	-9.2609	1.0614	<.0001	-9.0152	1.1002	<.0001
Log of AADT	1.3271	0.1950	<.0001	1.1128	0.1844	<.0001
Speed limit	-0.0240	0.0104	0.0210	0.0048	0.0105	0.0474
Dispersion	0.4695	0.1034		0.2807	0.0872	
AIC	308.6199			303.2229		
NB model - PDO Crashes						
Parameter	**Estimate**	**Std.Err**	**P > ChiSq**			
Intercept	-10.4611	2.5545	<.0001			
Log of AADT	1.4220	0.2738	<.0001			
Speed limit	-0.0387	0.0131	0.0032			
Dispersion	0.5756	0.1471				
AIC	312.6152					
Crash Types						
NB model - Rear End Crashes				**NB model - Lane Change related Crashes**		
Parameter	**Estimate**	**Std.Err**	**P > ChiSq**	**Estimate**	**Std.Err**	**P > ChiSq**
Intercept	-9.7686	2.2221	<.0001	-11.0950	2.9216	0.0001
Log of AADT	1.1572	0.2208	<.0001	1.2329	0.2907	<.0001
Downstream	-0.4605	0.2119	0.0298	-0.5511	0.2726	0.0432
Dispersion	0.2684	0.1072		0.3242	0.1730	
AIC	277.6112			267.2759		

Table 5-2 presents comparisons between the Crash Modification Factors (CMFs) resulted from different methods (CG and EB (FSPF and SSPF)) for (All treated sites combined) based on the standard errors. It can be seen that the results from the Before-After with comparison group are almost identical to the multivariate EB/FSPF. The Before-After with comparison group and univariate EB/SSPF, provided higher standard errors than the multivariate EB/FSPF. Therefore, for the total crashes it is recommended to use the crash modification factor resulted from EB/FSPF CMF= 0.53(±0.05) for the hybrid mainline toll plaza treatment.

Table 5-2: Comparison between the CMFs results for all locations combined for (HMTP)

Crash Category	**Method**					
	Before-After with Comparison Group		**EB Before-After**			
			Univariate EB SSPF*		**Multivariate EB FSPF***	
	CMF (Safety Effectiveness)	S.E.*	**CMF** (Safety Effectiveness)	S.E.*	**CMF (Safety Effectiveness)**	S.E.*
Total Crashes	0.52 (48%)	0.09 (9.42%)	0.54 (46.40%)	0.08 (7.9%)	**0.53 (47.30%)**	**0.05 (5.39%)**
F+I	0.55 (45.2%)	0.09 (9.43%)	0.51 (49%)	0.09 (9.2%)	**0.54 (46.2%)**	**0.07 (6.62%)**
PDO	0.45 (55%)	0.08 (8.43%)	0.47 (53%)	0.07 (7.2%)	**0.46 (54.2%)**	**0.06 (6.22%)**
Rear End	0.35 (65.3%)	0.10 (10%)	0.33 (67.13%)	0.08 (8.4%)	**0.34 (65.6%)**	**0.06 (6.4%)**
Lane change related*	0.43 (57.3%)	0.11 (11.13%)	0.46 (54.4%)	0.09 (9.13%)	**0.45 (55.4%)**	**0.09 (9%)**

S.E* = Standard Error
SSPF*='Simple' SPF & FSPF*='Full' SPF.
Lane change related* = (i.e. sideswipe, lost control, overturned and angle crashes)

Similarly for F+I and PDO crashes, the comparison group method returned closer results to the multivariate EB/FSPF with slightly higher standard error. Thus, for the F+I and PDO crashes it is recommended to use CMF=0.54(±0.07) and CMF=0.46(±0.06), respectively. Similarly for the rear end and Lane change related crashes, based on the lowest standard error resulted from EB/FSPF the best CMFs are 0.34(±0.06) and 0.45(±0.09), respectively.

The results shown in Table 5-3 conclude that there is a linear relationship between the crash modification factors CMFs, and the natural logarithm of the annual average daily traffic (AADT). This relation can be used to develop Crash Modification Function for all severity levels based on the locations' AADTs. Linear models were developed between the CMFs, AADTs and some other variables. Log (AADT) was the most significant variable in the final models. The results showed an acceptable value of R-square (0.6363, 0.6825 and 0.731) for the Total, PDO and Fatal-and-Injury crashes, respectively.

The CMF functions are as follows:

1- Total Crashes: CMF= 0.0541*Ln (AADT) (5-2)

2- Fatal and Injury Crashes: CMF= 0.0401*Ln (AADT) (5-3)

3- Property damage only Crashes: CMF= 0.047*Ln (AADT) (5-4)

Where

CMF= Crash Modification Function

Ln (AADT) = Natural logarithm of the annual average daily traffic

Table 5-3: Estimates of Coefficients for Crash Modification Functions

Linear model for CMF of Total Crashes			
Parameter Estimates			
Variable	**Parameter Estimate**	**Standard Error**	**Pr -value**
Log of AADT	**0.05411**	0.00765	<.0001
Linear model for CMF of Fatal and Injury Crashes			
Parameter Estimates			
Variable	**Parameter Estimate**	**Standard Error**	**Pr -value**
Log of AADT	**0.04010**	0.06240	0.0021
Linear model for CMF of PDO Crashes			
Parameter Estimates			
Variable	**Parameter Estimate**	**Standard Error**	**Pr -value**
Log of AADT	**0.04720**	0.008230	0.0011

To evaluate the quality of the SPFs and CMFs, we applied them at individual and combined locations levels for 28 sites. These sites had HMTP system from the beginning of construction and were not included in the SPFs and CMFs analyses. Crash data of three years in the after period were used. The procedure is as follows:

1. Calculate the expected number of crashes at each location using the SPFs assuming the treatment had not been implemented.
2. Multiply the expected crash frequencies by the CMFs presented in Table 5-2 and in equations (5-2 TO 5-4) for individual and combined sites levels.

3. Compare the results with the observed crashes at these sites.

The results showed that the best crash modification factors for all crash categories were produced from multivariate FSPFs/EB method. Similarly we applied the crash modification functions and they gave slightly higher errors than the crash modification factors. Therefore, for practitioners it is recommended to use the multivariate EB - CMFs, and for future research, researcher may build on the Crash Modification Functions.

5.2 Conclusions

This section aimed at evaluating the Safety Effectiveness of upgrading traditional mainline toll plazas to Hybrid Mainline Toll Plaza (HMTPs). Data from 98 sites located on approximately 750 miles of toll roads in the State of Florida were used; thirty of them were upgraded to HMTPs. Crash data from a period of eleven years (2002-2012) were used by evaluating three years of crash data before and three years after the implementation of HMTPs.

The Safety Effectiveness of HMTPs was estimated using 'Observational Before-After studies' including: Naïve before-after, before-after with comparison group and Empirical Bayes approaches. Negative binomial (NB) regression models were used to develop the mainline toll plazas' specific Safety Performance Functions (SPFs). The analysis focused on total crashes, property damage only crashes, fatal-and-injury crashes and crash types.

The analysis showed that the best crash modification factors for all crash categories were produced from multivariate FSPFs/EB method, and its results indicated that the conversion from traditional mainline toll plaza design to HMTP system resulted in an average crash reduction of 47 percent, 46 percent and 54 percent for total crashes, fatal–and-injury crashes and property damage only crashes, respectively. The use of HMTP design also significantly reduced rear end crashes and lane change related crashes (i.e. sideswipe, lost control, overturned and angle crashes) as well by an average of 65 percent and 55 percent, respectively.

Overall, the use of hybrid mainline toll plaza design was proven to be an excellent solution to several traffic operations, environmental and economic problems. The results of this study proved that the safety effectiveness across all locations that were upgraded to hybrid mainline toll plaza was significantly improved. Choosing locations for the toll plazas that have safe distances from the interchanges and finding ways to increase the percentage of ETC users are potential means of reducing lane changes at these facilities. For practitioners it is recommended to use the multivariate EB- CMFs results, and for future research, researchers may build on the crash modification functions that were developed in this study.

CHAPTER 6: ALL-ELECTRONIC TOLL COLLECTION SYSTEM

6.1 Converting TMTP or HMTP to All-Electronic Toll Collection system

6.1.1 Summary of the Chapter

Traditional mainline toll plaza (TMTP) is considered the most high risk location on the toll roads. Conversion from TMTP or Hybrid Mainline Toll Plaza (HMTP) to an All-Electronic Toll Collection (AETC) system has demonstrated measured improvement in traffic operations and environmental issues. However, there is a lack of research that quantifies the safety impacts of these new tolling systems. This study evaluated the safety effectiveness of conversion from TMTP or HMTP to AETC system. An extensive data collection was conducted that included hundred mainline toll plazas located on more than 750 miles of toll roads in Florida. Various observational before-after studies including the Empirical Bayes method were applied.

The results indicated that the conversion from the TMTP to an AETC system resulted in an average crash reduction of 77, 76, and 67 percent for total, fatal-and-injury and Property Damage Only (PDO) crashes, respectively; for rear end and Lane Change Related (LCR) crashes the average reductions were 81 and 75 percent, respectively. The conversion from HMTP to AETC system enhanced traffic safety by reducing crashes by 23, 29 and 19 percent for total, fatal-and-injury, and PDO crashes respectively; also, for rear end and LCR crashes, the average reductions were 15 and 21 percent, respectively.

Overall, this section provided an up-to-date safety impact of using different toll collection systems. The results proved that the AETC system significantly improved traffic safety for all crash categories; and changed toll plazas from the highest risk on Expressways to be similar to regular segments.

6.1.2 Data description

All-Electronic Tolling (AETC) is expanding on the Florida Turnpike (FT). Since spring 2011 FT started removing the TMTP and HMTP and adopting the AETC system and the Toll-By-Plate (TBP) program. After successfully adopting this system in Miami-Dade County's toll plazas in spring 2011, it was scheduled to be done in other FT facilities. For example, Fort Lauderdale and Tampa Bay scheduled for spring 2014 and summer 2014, respectively.

Data from 100 sites of Mainline Toll Plazas (two directions) located on approximately 750 miles of toll roads in the State of Florida was used. These toll plazas were classified based on the type of design (i.e. TMTP, HMTP, or AETC), and whether if the location was a reference site, treated site or the treatment was applied from the beginning. Figure 6-1 shows All-Electronic Toll Collection system.

Figure 6-1: All-Electronic Toll Collection (AETC) (Source: Google Earth, 2014)

Crash data for an eleven-year period (2003-2013) was investigated to examine the safety impact by evaluating crashes for a period of two years before and two years after the treatment. Crashes that occurred within the influence areas (1 mile before and 0.5 mile after the centerline of the mainline toll plaza) were extracted from the crash database maintained by FDOT known as a Crash Analysis Reporting (CAR) system. Although eleven years of crash data was available, it should be noted that different toll plazas had different upgrading period. Thus, data in the period when toll plazas were being upgraded in addition to six months after were excluded from the analysis.

6.1.3 Analysis and results

6.1.3.1 Before-After with Comparison Group

Data including all of the available treated sites (16 locations affected by the AETC system) in Florida was used in this approach. These locations were compared with data from the same number of untreated sites (comparison sites that have similar characteristics as the treated sites). The crash modification factors were estimated for both individual and all sites combined using crash data from a group of traditional MTPs as well as another group of hybrid MTPs. Crash data from the before and after treatment was used. The safety effectiveness from AETC across all locations combined was significantly improved by reducing the total crashes (all severity) by 77.6 percent from the base case TMTP with standard error of 8.32 percent, and 26.2 percent reduction of the total crashes from the HMTP with standard error of 9.8 percent. The statistical significance of the estimated safety effectiveness was calculated as:

$$Abs\left(\frac{\text{Safety } \textit{Effectiveness}}{\text{SE (Safety } \textit{Effectiveness})}\right) = \frac{77.6}{8.32} = 9.32 \;\; \geq 1.96 \qquad (6\text{-}1)$$

Since the *Abs* [safety effectiveness / standard error of the safety effectiveness)] is ≥ 1.96, it can be concluded that the treatment effect is significant at the 95 percent confidence level. The same steps were applied to the Property Damage Only (PDO) and Fatal-and-Injury crashes, and the safety effectiveness across all locations combined was significantly improved by 70.2

and 74.7 percent from the base case TMTP with a standard error of 10 and 9.8 percent, respectively. Also, by using the HMTP as base case, the safety effectiveness across all locations combined was significantly improved by 21 and 27.4 percent for PDO and Fatal-and-Injury crashes, respectively.

Similarly for the collision types, the treatment indicated significant reductions for the rear end and lane change related crashes. Using the TMTP as base case, the reductions were 81.6 and 75.4 percent, respectively. And the conversion from HMTP to AETC system reduced the rear end and lane change related crashes by 15 and 22 percent, respectively. The values of the safety effectiveness were statistically significant at the 95 percent confidence level for all crash categories.

6.1.3.2 Before-After with the Empirical Bayes

Data from 54 reference sites (i.e. HMTP) that have no AETC treatment was used in this approach. Crash data of three years was used to develop the Safety Performance Functions (SPFs) of the hybrid mainline toll plaza.

6.1.3.3 Safety Performance Functions

A Safety Performance Function (SPF) is generally known as a crash prediction model, which relates the frequency of crashes to traffic and the roadway characteristics. The SPF can be

developed using the Negative Binomial (NB) model formulation with the data from the reference sites. There were two types of SPFs that have been mainly used in the literature: 1) 'Full' SPFs and 2) 'Simple' SPFs. 'Full' SPF is a mathematical relationship that includes both traffic and geometric parameters as explanatory variables, whereas 'Simple' SPF includes Annual Average Daily Traffic (AADT) as the sole explanatory variable in predicting crash frequency on a roadway entity.

Even though the CMFs in the HSM were calculated based on the simple SPFs, better CMFs however resulted from using the Full SPF in the EB method (AASHTO, 2010). Actually, the simple SPF is an over-simplified function since crash frequency is affected by the traffic volume as well as other factors. A set of SPFs were used in this study including: 1) Traditional mainline toll plaza's specific SPFs from our previous study (Abuzwidah et al., 2014), and 2) Developing new Hybrid Mainline Toll Plaza's specific SPFs. These prediction models were used to predict the crashes at the AETC system to evaluate the safety effectiveness in the after period. The functional form of the SPF for fitting the NB regression models is shown in Equation (6-2) as follows:

$$N_{predicted} = \exp\left(\beta_0 + \beta_1 * \ln(AADT) + \beta_2 S + \beta_3 L\right) \quad (6\text{-}2)$$

Where,

$N_{predicted}$= Expected crash frequency without treatment,

β_i =coefficients,

AADT=Annual Average Daily Traffic,

S= Speed limit.

L= Location: dummy variable (i.e. Upstream of Toll Plaza =1 and Downstream of Toll Plaza =0.).

The Negative Binomial (NB) regression models for safety evaluation were developed for the type of crashes and injury levels. A 'Simple' and 'Full' SPFs were developed for the hybrid mainline toll plaza. Table 6-1 summarizes the estimated parameters for the 'Full' and 'Simple' SPFs. It should be noted that only models with smaller AIC values were selected. It is worth noting that a smaller AIC means that the model fit better for the same dataset.

The SPF models included many crash related factors. However, only log (AADT), speed limit, and the location (Upstream and Downstream of the toll plaza) came out to be significant in the final models of the total, F+I, and lane change related crashes. And only log (AADT) was significant in the final models of the PDO and rear end crashes. The signs for the parameter estimates were as expected for all crash categories.

Table 6-1: Estimates of Coefficients for HMTP Safety Performance Functions

Toll Plaza-Specific Full SPFs									
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Speed Limit**		**Dispersion**	**AIC**
		Esti*	**P-Value**	Esti*	**P-Value**	Esti*	**P-Value**	Esti*	**Value**
All	**All**	-11.8525	<.0001	1.1181	<.0001	0.0574	0.0215	0.3128	208.670
All	**F+I**	-14.8636	<.0001	1.2362	<.0001	0.0629	0.0269	0.2207	180.483
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Location***		**Dispersion**	**AIC**
LCRC*	**All**	-12.8711	<.0001	1.1993	<.0001	0.3455	0.0065	0.2028	100.618
Toll Plaza-Specific Simple SPFs									
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Dispersion**			**AIC**
		Esti*	**P-Value**	Esti*	**P-Value**	Esti*			**Value**
All	**PDO**	-9.1515	<.0001	1.1708	<.0001	0.3273			172.799
Rear End	**All**	-8.8567	<.0001	1.0746	<.0001	0.4450			165.867

Esti* =Estimate
LCRC*: Lane change related Crashes*** =** (i.e. sideswipe, angle crashes, etc.)
Location*: Dummy variable (i.e. Upstream of Toll Plaza =1 and Downstream of Toll Plaza =0.)

For example, the coefficients of the traffic volume were positive indicating that an increase in traffic volume leads to increase in all injury levels and all type of crashes at the hybrid mainline toll plaza. Also, the coefficients of the speed limit were positive in total and F+I crashes indicating that increase in speed limit is associated with more and severe crashes. This may be attributable to the fact that the variance of speeds is high between the ORT lanes and the cash

lanes at the same toll plaza approach. This speed variation is more likely to contribute to more severe crashes.

The coefficients for the upstream were positive in the lane change related crashes indicating that the upstream section is associated with more LCRC than the downstream of the toll plaza. More research might be needed to investigate the differences between the two locations such as traffic, geometric characteristics, and signage locations. It is worth noting that the upstream section of the hybrid mainline toll plaza is associated with diverge and potential sudden lane change. Moreover, drivers may be distracted when they prepare to pay, search for cash or cards, and selecting either cash or coin lane. While in the downstream area of the plaza, they just accelerate and focus on merging with traffic, especially if the acceleration lane has a good design and signage.

6.1.3.4 Crash Modification Factors

The EB before-after evaluation of AETC system was used to predict the expected crash frequency at the treated sites assuming the treatment had not been implemented. The expected crash frequency was compared with the number of observed crashes in the period after AETC system had been implemented. The results showed that almost all the treated sites had a significant safety improvement.

To compute the safety impacts of the treatment, Crash Modification Factors (CMFs) were estimated using different methods for the collision types and the injury levels.

Table 6-2 presents comparisons between the Crash Modification Factors (CMFs) resulted from EB method, using Full and Simple SPFs, based on the base case of the toll plaza (i.e. TMTP or HMTP); Therefore:

1. If the upgrade is from Traditional Mainline Toll Plaza to the All-Electronic Toll Collection system, it is recommended to use crash modification factor for the total crashes CMF= 0.23(±0.074). And for F+I and PDO crashes, it is recommended to use CMF=0.24(±0.09) and CMF=0.33(±0.08), respectively. Likewise, for the rear end and Lane change related crashes (all injuries), the best CMFs are 0.19(±0.10) and 0.25(±0.07), respectively.
2. If the upgrade is from Hybrid Mainline Toll Plaza to the All-Electronic Toll Collection system, it is recommended to use the crash modification factor for the total crashes CMF= 0.78(±0.09). And for F+I and PDO crashes, it is recommended to use CMF=0.71(±0.08) and CMF=0.81(±0.10), respectively. For the rear end and Lane change related crashes (all injuries), the best CMFs are 0.84(±0.08) and 0.79(±0.10), respectively.

It should be noted that the remaining crash percentages at the AETC locations are representing the regular crash rates at the regular segments on the toll roads.

The results showed that the conversion from TMTP to the AETC system resulted in higher improvement than the conversion from HMTP to the AETC system. This is maybe because of the reduction of the cash lanes users' percentage at the HMTPs. According to the Florida Turnpike (FL-Turnpike, 2014), more than 81 percent of the customers in Florida switched to prepaid electronic toll collection system (transponder). So, the Toll-By-Plate program will deal with less than 19 percent of the transactions.

In the long-term, however, the steps taken by the tolling agencies as well as the AETC lanes themselves will encourage more customers to switch to transponder usage as they more clearly see the mobility benefits provided to electronic toll users such as safety, toll discount, travel time and environmental benefits, etc. Thus, this percentage is expected to decrease significantly over the time.

In this study, the results from the comparison group and the Empirical Bayes method were very close to each other. However, the Empirical Bayes provided more reliable estimates of crash modification factors for all crash categories (i.e. lower standard error) than the comparison group method. It is clear that the upgrade from Traditional Mainline Toll Plaza to the All-Electronic Toll Collection system significantly improved traffic safety for all crash categories. Also, the upgrade from Hybrid Mainline Toll Plaza to the All- Electronic Toll Collection system enhanced traffic safety at these facilities.

Table 6-2: Comparison between the CMFs for all-locations combined for (AETC) system

Before-After with the Empirical Bayes Results								
Crash Category	**Upgrade to HMTP**		**Upgrade to AETC**					
	TMTP as a base case		**TMTP as a base case**		**HMTP as a base case**			
	'Full' SPF		**'Full' SPF**		**'Simple' SPF**		**'Full' SPF**	
	CMF S.E.*	S.Err.**	CMF S.E.*	S.Err.**	CMF S.E.*	S.Err.**	CMF S.E.*	S.Err.**
Total Crashes	0.53 (47.30%)	0.05 (5.39%)	0.23 (77.30%)	0.07 (7.44%)	-	-	0.78 (22.30%)	0.09 (9.31%)
F+I	0.54 (46.2%)	0.07 (6.62%)	0.24 (76.2%)	0.09 (8.72%)	-	-	0.71 (29.2%)	0.08 (8.12%)
PDO	0.46 (54.2%)	0.06 (6.22%)	0.33 (67.2%)	0.08 (7.92%)	0.81 (19.2%)	0.10 (9.64%)	-	-
Rear End	0.34 (65.6%)	0.06 (6.4%)	0.19 (81.6%)	0.10 (9.83%)	0.84 (15.6%)	0.08 (7.7%)	-	-
LCRC*	0.45 (55.4%)	0.09 (9%)	0.25 (75.4%)	0.07 (7%)	-	-	0.79 (21.4%)	0.10 (9.53%)

S.E.* =Safety Effectiveness
S.Err** = Standard Error
LCRC* =Lane change related crashes = (i.e. sideswipe, angle crashes, etc.)

Figure 6-2 shows the comparison between the total crash rates (number of crashes per 10,000 vehicle miles of travel (VMT)) over the years on the highway (SR-821) and the total crash rates at its toll plazas. These crash rates were estimated for the crashes that occurred on the

mainline of the highway, excluding the On-and-Off ramps. The highway was divided into segments based on the AADT values, and the crash rates were estimated for both the individual and all segments combined. Similarly for the toll plazas, it was calculated for the individual and all locations combined.

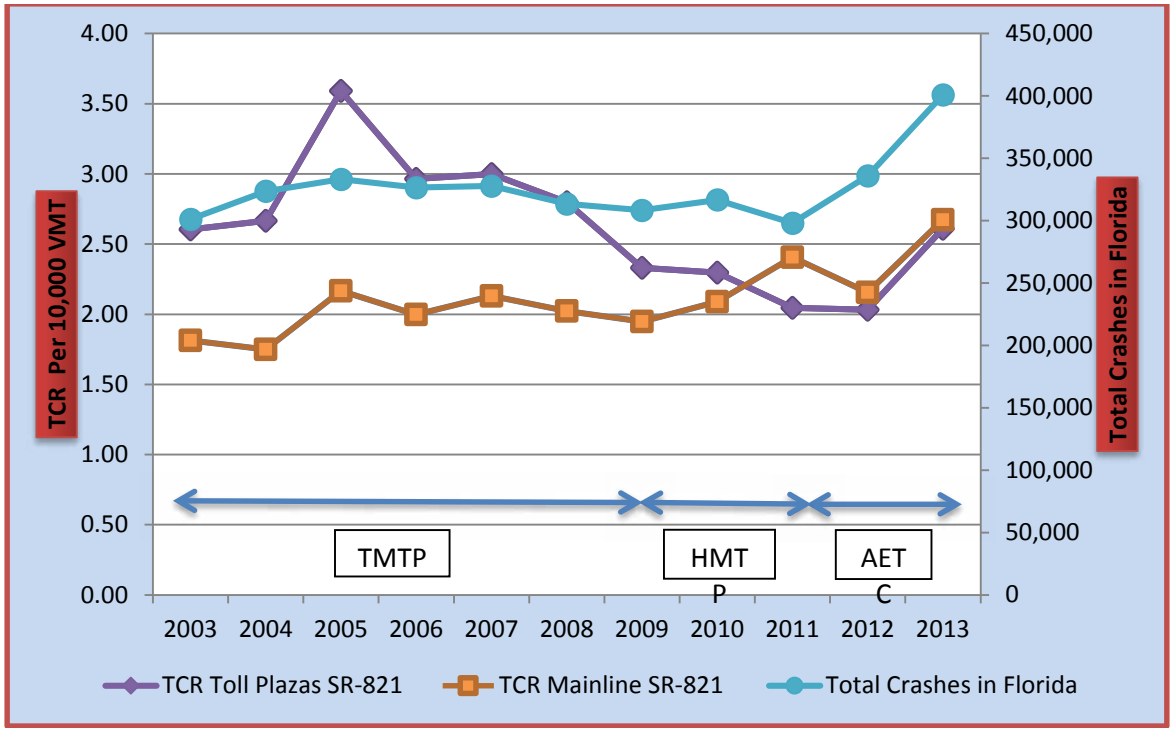


Figure 6-2: Comparison between the total crash rates on the SR-821 and its toll plazas.

Where:

TCR = Total Crash Rate per 10,000 VMT
TMTP = Traditional mainline toll plaza
HMTP = Hybrid Mainline Toll Plaza
AETC = All-Electronic Toll Collection

It is worth noting that the total crash number in Florida has increased substantially in 2013, due to the change of the policy of the crash reporting strategy. Traffic crashes in Florida are generally reported by the use of two forms commonly referred to as the "Long Form" and the "Short Form." A Long Form crash report is used when one or more of the following criteria are met (FDOT, 2014):

- Death or personal injury
- Leaving the scene involving damage to - vehicles or property
- Driving while under the influence.

The Short Form crash report is used to report all other types of traffic crashes. According to FDOT, effective July 1, 2012 new criteria has been applied to reduce the proportion of short form crashes by encouraging all of the law enforcement agencies that are using field data collection software to adopt a "long-form-only" reporting strategy. This strategy caused an increase of the long form crashes by approximately 25 percent in the 2013 crash data (FDOT, 2014).

This study proved that the AETC system has made the toll plaza exactly the same as regular segments on the roadway. Moreover, the results showed that the crash rate at these facilities has improved more than the rest of the same roadway.

6.2 Conclusions

All-Electronic Toll Collection (AETC) system is the future of toll collection, not just on Florida roads, but in many countries around the world. Even though the upgrade from the Traditional Mainline Toll Plaza (TMTP) to Hybrid Mainline Toll Plaza (HMTP) or to the AETC system has demonstrated measured improvements in traffic operations and environmental issues, there is a lack of research that quantifies the safety impacts of these new tolling systems.

Thus, the main objective of this study is to comprehensively evaluate the safety effects of upgrading from TMTP or HMTP to the AETC system. Data from a hundred sites located on approximately 750 miles of toll roads in Florida was used. Crash data from an eleven-year period (2003-2013) was used to evaluate the crash history of before and after the implementation of the AETC system.

The Safety Effectiveness of the AETC system was estimated using 'Observational Before-After studies' including: before-after with comparison group and before-after with Empirical Bayes. Negative binomial (NB) regression models were used to develop the hybrid mainline toll plaza's specific safety performance functions. These models were used to investigate different crash types and injury levels.

In this study, the results from the comparison group and the Empirical Bayes methods were very close to each other. However, the Empirical Bayes method provided more reliable

estimates of crash modification factors for all crash categories (i.e. lower standard error) than the comparison group method, and the main conclusions are as follows:

1. The conversion from TMTP to the AETC system resulted in an average crash reduction of 77 percent, 76 percent and 67 percent for total crashes, fatal-and-injury crashes and Property Damage Only (PDO) crashes, respectively. This conversion also significantly reduced rear end and Lane Change Related Crashes (LCRC) by an average of 81 percent and 75 percent, respectively.
2. The conversion from HMTP to the AETC system enhanced traffic safety by 23 percent, 29 percent and 19 percent for total crashes, fatal-and-injury crashes and PDO crashes, respectively. Also, this system significantly reduced rear end crashes and LCRC by an average of 15 percent and 21 percent, respectively.

To the best of our knowledge, there were no studies that evaluated the safety benefits of using the AETC system.

Thus, this section provided an up-to-date safety impact of using different toll collection systems. The results proved that the conversion from TMTP or HMTP to the AETC system significantly improved traffic safety for all crash categories, and changed toll plaza from a high risk location on the highway to a regular segment on the toll road. However, more data may be needed for future research, especially after all construction is complete and upgrades are made.

CHAPTER 7: EVALUATING DIFFERENT DESGINS OF HMTP

7.1 Effects of using different toll collection systems on safety performance of expressways

7.1.1 Summary of the Chapter

Expressways (toll roads) and freeways are considered as an important part of any successful transportation system, because they carry the majority of daily trips on the transportation network. Although toll roads offer a high level of service, traditional plazas still experience high crash rate, high percentage are severe. Therefore, this study examines for the first time the traffic safety impact of using different designs of the Hybrid Mainline Toll Plaza (HMTP). The HMTP is a plaza combines open road tolling for electronic toll collection and plaza structure for manual payment. In addition, this study helps understand the relationship between the crash frequency and several important crash-related factors and circumstances.

Crash data from a seven-year period was investigated, and a hundred mainline toll plazas in Florida were evaluated using multiple analytical techniques. The results of this section proved that there is a significant difference between the different designs of the HMTP. And there is an indication that the majority of crashes occurred at diverge-and-merge areas before and after the plaza. Moreover, the results indicated significant relationships between the crash frequency and toll plaza types, annual average daily traffic, and driver-age. This section has also proved that the HMTP and the All-Electronic Toll Collection (AETC) were associated with less number of crashes than the traditional mainline toll plazas by 44.7 and 72.6 percent,

respectively. For those agencies that cannot adopt the HMTP and the AETC systems, improving traffic safety at traditional toll plazas should take a priority.

7.1.2 Data description

Different tolling systems are expanding on the Florida expressways. In the past decade, many toll agencies converted traditional mainline toll plazas to either hybrid mainline toll plaza or all-electronic toll collection system. Multiple sets of data were used in this section. A hundred mainline toll plazas were selected. Crash data from seven-year period (2007-2013) were investigated. Crashes that occurred within the influence areas (1 mile before and 0.5 mile after the centerline of the mainline toll plaza) were extracted from the crash database. Although seven years of crash data was available, it should be noted that different toll plazas had different before and after periods. Thus, data in the period when toll plazas were being upgraded in addition to six months after were excluded from the analysis.

7.1.3 Analysis and results

7.1.3.1 Part I: Comparison between different designs of the hybrid mainline toll plaza

Data from 60 Hybrid Mainline Toll Plazas (HMTP) were used in part I of this section. Crash data from a three-year period after the implementation of the hybrid mainline toll plaza was investigated. Figure 7-1 shows different designs of the hybrid mainline toll plazas. Design 1

(D_1) combines express Open Road Tolling (ORT) lanes on the mainline and separate traditional toll collection to the side; while Design 2 (D_2) combines traditional toll collection on the mainline and separate ORT lanes to side.

A series of Negative Binomial (NB) models were fitted to establish the relationships between traffic and roadway characteristics, and crash frequency at the vicinity of HMTPs. Exploratory modeling indicated that the crash frequency is not significantly associated with traffic direction, number of entry and exit ramps, and distance to entry and exit ramps. Table 7-1 shows the parameter estimates of the final model.

Only log Annual Average Daily Traffic (AADT) and the type of design came out to be significant with the expected signs. The coefficient of AADT has a positive sign, which indicates that as AADT increases, the frequency of HMTP-related crashes increases.

This finding could be attributed to the fact that the AADT is considered as the exposure factor; more traffic at the HMTP would lead to higher chances of crash occurrence. This is expected, since higher AADT results in higher exposure of vehicles to weaving maneuvers (change lanes) before and after the toll plaza, which in turn would result in higher crash frequencies.

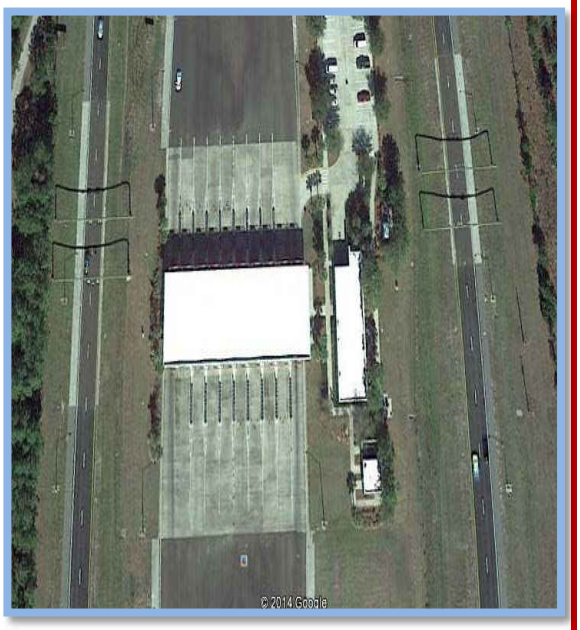
Design 1 (D_1) ORT in the mainline	Desgin 2 (D_2) ORT to the side
	
	

Figure 7-1: Different designs of the Hybrid Mainline Toll Plazas (Google Earth, 2014)

Table 7-1: Estimates of Coefficients for Different designs of the HMTP

Negative Binomial					
Analysis Of Maximum Likelihood Parameter Estimates					
Crash Type	Injury Level	Parameter	Estimates	Pr > ChiSq	AIC
All	All	Intercept	-16.755	<0.0001	168.653
		Log AADT	1.883	<0.0001	
		Design type*	0.169	0.0433	
		Dispersion	0.113		

Design type *= (D_1-and-D_2) dummy variable (i.e. D_1=0 and D_2=1.)

The design type was found to be significant; the effect of design 2 (D_2) of the HMTP was compared to the design 1 (D_1) (the base case). The parameter estimates given in Table 7-1 can be used to estimate the Incident Rate Ratios (IRR) by exponentiation of the regression coefficients Exp[β]. IRR value shows that the risk of crashes at D_2 was approximately 19 percent higher than at the D_1, given that all other variables are constant.

The increased crash risk at the D_2 may be explained by the fact that more than 81 percent of the vehicles in Florida are equipped with prepaid toll transponders (FL-Turnpike, 2014). Thus, the use of D_2 will cause more than 81 percent of the traffic to diverge and merge before and after the toll plaza; while in D_1 only 19 percent or less of the traffic (vehicles without transponders) will need to diverge and merge before and after the toll plaza.

The good news is that Florida Turnpike has scheduled all of the HMTPs that have D2 to be converted to All-Electronic Toll Collection. However, D2 could be a good temporary design depends on the percentage of vehicles with prepaid transponders. In the other words, it is dependent upon the percentage of the automatic tolling users. So, as this percentage increases, more traffic will need to diverge and merge; thus, this design becomes riskier. It should be noted that unfamiliar drivers could be confused and they may think that the Open Road Tolling lanes are in the mainline of the expressway as of design 1. So, in case of using design 2, an advanced warning system should be implemented before toll plaza.

7.1.3.2 Part II: Comparison between diverge-and-merge areas

Similar to part I, data from 60 hybrid mainline toll plazas was used in this approach. Crash data from a three-year period after the implementation of the hybrid mainline toll plaza was investigated. Table 7-2 shows the parameter estimates of the final model resulting from 120 observations. Sixty hybrid mainline toll plazas, each one has two locations, one before (Diverge) and one after (Merge) the Toll plaza (60*2=120 observations).

It should be noted that the data used in this part included only the mainline crashes, i.e. crashes that occurred at the toll booths were excluded. Figure 7-2 shows the diverge-and-merge areas that were investigated in this part of the analysis.

The log Annual Average Daily Traffic (AADT) and the location came out to be significant with the expected signs in the final model. The coefficient of AADT has a positive sign, which indicates that as AADT increases, the frequency of diverge-and-merge related crashes increases. This is expected, since higher AADT results in higher exposure of vehicles to weaving maneuvers (change lanes) before and after the toll plaza, which in turn would result in higher crash frequencies.

Table 7-2: Estimates of Coefficients of diverge and merge areas of the HMTP

Negative Binomial					
Analysis Of Maximum Likelihood Parameter Estimates					
Crash Type	Injury Level	Parameter	Estimates	Pr > ChiSq	AIC
All	All	Intercept	-20.6811	<0.0001	365.607
		Log AADT	2.2327	<0.0001	
		Location*	0.2103	0.0317	
		Dispersion	2.2667		

Location* = (diverge-and-merge) dummy variable (i.e. diverge=1 and merge=0.)

The location (diverge-and-merge) dummy variable (i.e. diverge=1 and merge=0) was found to be significant. Since the lengths are different between the (diverge-and-merge) areas, the frequency of crashes were controlled by the segments' lengths. The effect of diverge was compared to the merge (the base case), and the coefficient of the location was positive indicating that diverge section is associated with more crashes than the merge section. The Incident Rate Ratios (IRR) value shows that the risk of crashes at diverge area before the

HMTP was approximately 23 percent higher than at the merge area after the plaza, given that all other variables are constant.

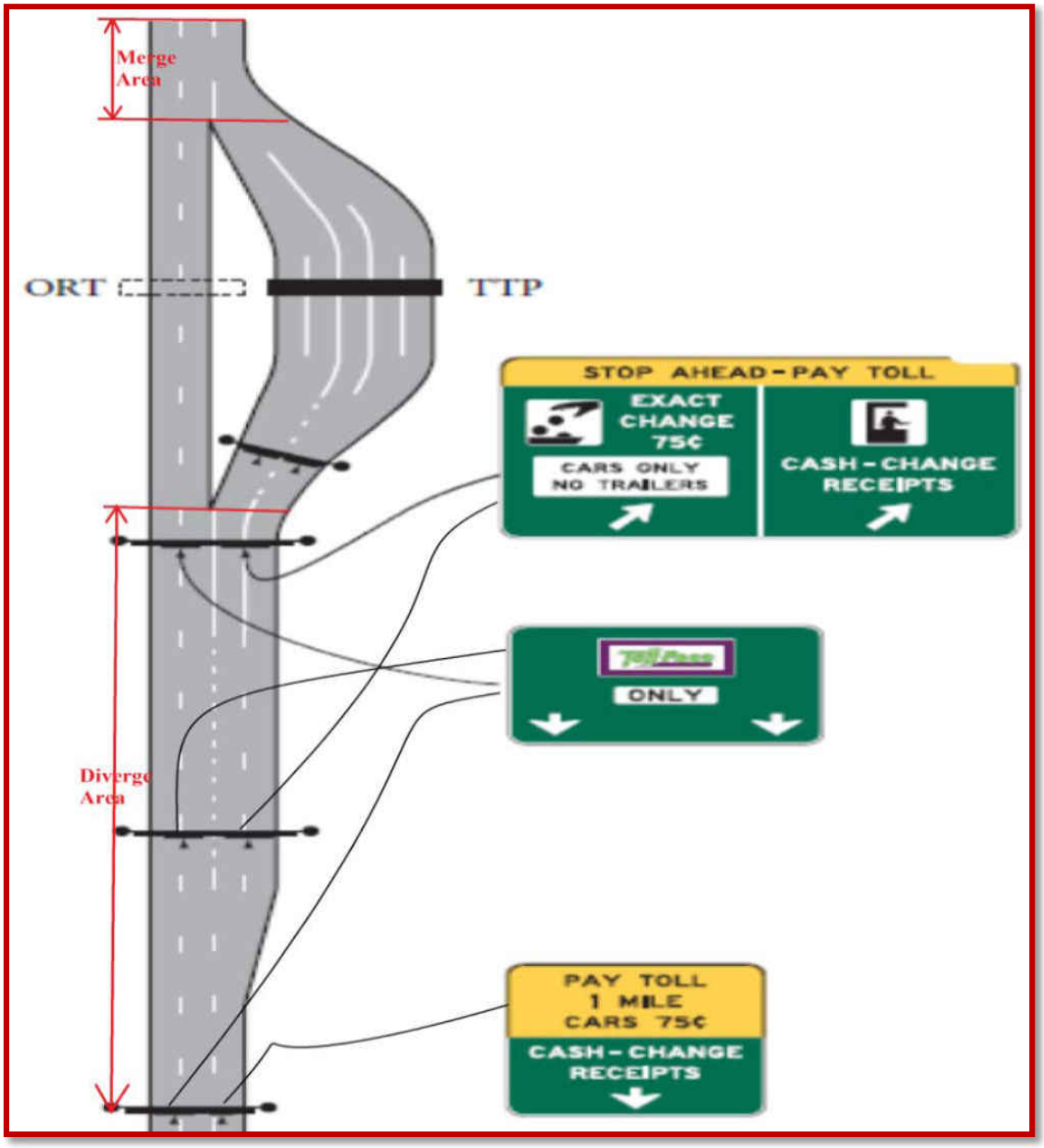


Figure 7-2: Diverge-and-merge areas before and after the HMTP (Source: MUTCD, 2014)

The increased crash risk at diverge area may be explained by the fact that diverge section of the hybrid mainline toll plaza is associated with potential sudden lane change. Moreover, drivers may be distracted when they prepare to pay, search for cash or cards, and selecting either the cash or coin lane. While in the merge area, drivers just accelerate and focus on merging with traffic, especially if the acceleration lane has a good design and signage.

However, choosing a good toll plaza location and finding ways to increase the percentage of prepaid transponder users are potential means of reducing lane changes at toll plazas. Adequate warning of no sudden lane change and good signage should be given on the approach to the diverge area. Offering toll discounts for prepaid transponder users and educating drivers can incentivize drivers to enroll in this system.

7.1.3.3 Part III: Log-Linear models:

Data including all types of toll plazas in Florida were used in this approach. A hundred mainline toll plazas, each one has two locations, one before and one after the toll plaza (100*2=200 segments). Several Log-linear models with different variables in each model were developed, and only the significant variables and best fit model was presented. The effects of AADT and crash related factors were examined, and interactions among them were considered. Crash data from a three-year period was used, and only crashes that occurred within the influence areas of the toll plazas were investigated. The final model was developed to

investigate the association between toll plaza types and both driver-age and the AADT. The three main effects and all three possible two-way interactions were included in this model.

It should be noted that in order for the model to fit the data in a proper way, the variables should be categorized. Thus, toll plaza types categorized to three categories, driver-age categorized to two categories, and the AADT categorized to two categories. These categories were as follows:

(1)" X = Toll Plaza Types: They were categorized into three levels and coded as follows:

i= level:

"1" = Hybrid Mainline Toll Plaza (HMTP)

"2" = All-Electronic Toll Collection (AETC)

"0" = Traditional Mainline Toll Plaza (TMTP) - (the base case).

(2) Y= driver-age: It was categorized into two levels and coded as follows:

j= level:

"1" = Young (15–30 years old)

"0" = Not young (Older than 30 years old) - (the base case).

(30 years old was selected as the cutoff point for age based on the literature (FDOT, 2014) (Kim et al., 1995), and criteria similar to those used by car insurance companies for

when drivers start to drive more carefully due changes in life style and their life cycle (FDOT, 2014).

(3) Z= Annual Average Daily Traffic (AADT): It was categorized into two levels based on the 50^{th} percentile and coded as follows:

k=level:

"1" = Low

"0" = High (the base case).

This is a three-variable model with variables x= (toll plaza types), y= (driver-age), and z= (AADT).

Normally, the G^2 goodness-of-fit statistic and p-value are used to determine the rejection or acceptance of the model. The larger value of G^2, the more evidence there is against the null hypothesis (H_o), where H_o=model fits the relationship and H_a=model does not fit the relationship. Hence, the smaller G^2 is better, but it depends on the degrees of freedom. The larger p-value (>0.05) indicates that the estimated model fits the relationship. The model contains all three main effects and all three possible two-way interactions. Table 7-3 shows the parameter estimates and odds ratios.

The values of the G^2=1.27, P-value=0.5311, and the DF=2 indicated that the model significantly fits the data. So, it can describe the associations between the variables by

computing the odds ratios. With the logit model, the parameters provide a measure of the magnitude and direction of effects of the independent variables on the response variable (Kim et al., 1995). The parameter estimates for individual and interaction terms and their odds ratios are presented in Table 7-3. Conceding the total number of crashes, the odds ratio is as follows:

- The odds ratio of hybrid mainline toll plaza (level 1) is 0.553 (Safety Effectiveness = 100-55.3=44.7 percent) from the base case traditional mainline toll plaza (level 0). Also, the odds ratio of the level 2 = all-electronic toll collection is 0.274 (Safety Effectiveness = 100-27.4=72.6 percent) from the base case traditional mainline toll plaza, given that all other variables are constant. These results proved that the HMTP and the AETC are much safer than the traditional mainline toll plaza, and this is consistent with the previous finding (Abuzwidah et al, 2014) (Yang et al., 2014).

- The estimate of driver-age is negative, so it gives odds of less than one. The decrease of the crash risk of this age group for total crashes at all types of toll plazas may be explained by the fact that the proportion of the young drivers is less than the middle age and older (age >30). This is same for the interaction of (AETC (level 2)* young age).

- The odds of (HMTP * young age) is 3.2 percent higher than the base cases. This may be explained by the literature that very young and young drivers probably have less driving experience, and with low AADT they tend to speed and commit driving violations (Kim et al., 1995); especially with the risk of diverge-and-merge before and after the hybrid mainline toll plaza. This fact was clear for the total crashes at all types of toll plazas, the

odds ratio of the interaction (young age * Low AADT) is 9.5 percent more than the base case (older than 30* high AADT), so this might explain their involvement in crashes.

Table 7-3: the Estimate of Log-Linear Model

Model Summary					
Response			TPT × Driver-age × AADT		
Source			DF	Chi-Square	Pr > ChiSq
TPT*			2	6.36	0.0257
Driver-age			1	2.23	0.1124
TPT × driver-age			2	4.69	0.0581
AADT			1	1.22	0.3153
TPT × AADT			2	0.33	0.8368
Driver-age × AADT			1	1.77	0.1664
Likelihood Ratio			2	1.27	0.5311
Analysis of Maximum Likelihood Estimates					
Parameter		Estimate& (Odds ratio)	Standard Error	Chi-Square	Pr > ChiSq
TPT*	1	- 0.5922 (0.553)	0.1335	5.79	0.0192
	2	- 1.2935 (0.274)	0.2112	0.22	0.5442
Driver-age	Young	-0.0754 (0.927)	0.1324	2.23	0.1245
TPT × Driver-age	1 Young	0.0321 (1.032)	0.1415	0.06	0.6523
	2 Young	-0.3822 (0.682)	0.2505	4.12	0.0352
AADT	Low	0.0223 (1.022)	0.1107	1.22	0.2532
TPT × AADT	1 Low	-0.5229 (0.593)	0.1532	0.00	0.8851
	2 Low	-0.9795 (0.375)	0.1907	0.28	0.4211
Driver-age × AADT	Young Low	0.0915 (1.095)	0.1292	1.77	0.1237

TPT*= Toll Plaza Types (i.e. TMTP (0), HMTP (1), and AETC (2))

- The low AADT has odds 2.2 percent higher than the high AADT. This is because at low AADT, the speed is usually high. So, drivers are more likely to make a sideswipe, hit the tollbooths and/or lost control.

7.2 Conclusions

Expressways (toll roads) and freeways are considered an important part of any successful transportation system, because they are carrying the majority of daily trips on the transportation network. Although toll roads offer a high level of service, traditional plazas still experience many crashes, many of which are severe. Therefore, this study examines for the first time the traffic safety impact of using different designs, and diverge-and-merge areas of the Hybrid Mainline Toll Plazas (HMTP). HMTP is a plaza that combines open road tolling for electronic toll collection and plaza structure for manual payment. Also, this study helps understand the relationship between the crash frequency and several important crash-related factors and circumstances such as toll plaza types, traffic volume, and driver-age.

Crash data from a seven-year period was investigated, and a hundred mainline toll plazas were evaluated using multiple analytical techniques. The current data has indicated that certain designs and locations at toll plazas are more likely to experience traffic crashes than regular segments of the expressways.

The Incident Rate Ratios (IRR) value shows that the risk of crashes at design 2 (D_2) of the hybrid mainline toll plaza was approximately 19 percent higher than at the design 1 (D_1), given that all other variables are constant. The increased crash risk at D_2 may be explained by the fact that more than 81 percent of the vehicles in Florida are equipped with prepaid toll transponders (FL-Turnpike, 2014). Thus, the use of D_2 will cause more than 81 percent of the traffic to diverge and merge before and after the toll plaza. While in D_1, only 19 percent or less of the traffic (vehicles without transponders) will need to diverge and merge before and after the toll plaza. However, D2 could be a good temporary design depends on the percentage of vehicles with prepaid transponders. In the other words, it is dependent upon the percentage of the automatic tolling users. So, as this percentage increases, more traffic will need to diverge and merge; thus, this design becomes riskier. It should be noted that unfamiliar drivers could be confused and they may think that the Open Road Tolling lanes are in the mainline of the expressway as of design 1. So, in case of using design 2, an advanced warning system should be implemented before toll plaza.

Another finding is there is an indication that the majority of crashes occurred at diverge and merge areas before and after the HMTP. The IRR value shows that the risk of crashes at diverge areas were approximately 23 percent higher than at the merge areas, given that all other variables are constant. The increased crash risk at diverge areas may be explained by the fact that diverge sections before the hybrid mainline toll plazas are associated with potential sudden lane change. Moreover, drivers may be distracted when they prepare to pay, search for cash or

cards, and selecting either the cash or coin lane, while in the merge area they just accelerate and focus on merging with traffic, especially if the acceleration lane has a good design and signage.

The results indicated significant relationships between the crash frequency and toll plaza types, annual average daily traffic, and driver-age. This means all of these three variables significantly affect the frequency of toll plazas-related crashes. Moreover, it was found that the HMTP and the All-Electronic Toll Collection (AETC) were associated with less number of crashes than at the traditional mainline toll plaza by 44.7 and 72.6 percent, respectively. Therefore, HMTPs and AETCs are much safer than the traditional mainline toll plazas. For those agencies that cannot adopt the HMTP and the AETC systems, improving traffic safety at traditional toll plazas should take a priority.

CHAPTER 8: HIGHWAY LIGHTING STUDY

8.1 Safety Effectiveness of Adding Highway Lighting

Highway Lighting (HL) is designed and implemented for expected societal and safety benefits at night. However, estimating the expected benefits of lighting is hard to quantify. Therefore, the main goal of this section is to evaluate the safety effectiveness of the implementation of highway lighting on the Night-Time crashes on expressways. However, major efforts have been done in this section by evaluating the treatment impact on different types of roads and comparing the results with the treatment impact on expressways. This section was divided into three approaches, 1) Evaluating the safety effectiveness of adding lighting to expressways, 2) Evaluating the safety effectiveness of adding lighting to all road types with all number of lanes, and 3) Compare the results and provide recommendations.

8.1.1 Adding Lighting to Expressways

Cross-Sectional method was used in this approach to evaluate the effect of adding highway lighting on the safety performance of expressways. The data was carefully selected and only expressways with 4-lanes were chosen for two main reasons, 1) There were enough treated and reference segments for this type of roads, and 2) Expressways in the urban areas have more number of lanes, so it was not possible to find reference sites and in the same time in the urban areas these roads are usually built with lighting from the beginning.

The Cross-sectional method requires the development of crash prediction models (i.e. SPFs) for the calculation of CMFs. The models are developed using the crash data for both treated and untreated sites for the same time period. However, as mentioned in the methodology Chapter, the Cross-Sectional method requires much more samples than the Before-After study, say 100~1000 sites (Carter et al., 2012). Sufficient sample size is particularly important when many variables are included in the SPF. This ensures large variations in crash frequency and variables, and helps better understand their inter-relationships. In the Cross-sectional models, a total number of 22 treated segments and 155 untreated segment located on expressways were used.

A set of SPFs using NB distribution were developed to estimate CMFs for the treatment at a specific road type and setting. SPFs describe night-time crash frequency as a function of explanatory variables including the presence of adding lighting, AADT and length of roadway segments as follows:

$$F_i = \exp(\alpha + \beta_1 * Adding\_Lighting_i + \beta_2 * Length_i) * AADT_i^{\beta_3} \quad (8\text{-}1)$$

where,

F_i = Night-Time crash frequency on a road segment i;

$Lighting_i$ = presence of adding lighting on a road segment i (= 1 if the Lighting of a segment i is implemented, = 0 if the Lighting of a segment i is not implemented);

$Length_i$ = length of a road segment i (mi);$AADT_i$ = average annual daily traffic on a road segment i (veh/day);

α = constant;

β = coefficients for variables.

Then CMFs were calculated using the following equation:

$$CMF = \exp(\beta_1 * (1-0)) = \exp(\beta_1) \quad (8\text{-}2)$$

The above model can be applied to for prediction of the total crash frequency or frequency of a specific crash type or severity. The standard error (SE) of the CMF is calculated as follows (Bahar, 2010):

$$SE = \frac{\exp(\beta_k * (x_{kt} - x_{kb}) + SE_{\beta_k}) - \exp(\beta_k * (x_{kt} - x_{kb}) - SE_{\beta_k})}{2} \quad (8\text{-}3)$$

where,

SE = standard error of the CMF;

$SE_{\beta k}$ = standard error of the coefficient of the variable (*Adding_Lighting*).

The results of SPFs for four-lane expressways by severity (injury/non-injury) and crash type are shown in Table 8-1. All the factors are statistically significant at a 95 percent confidence level.

Table 8-1: Adding Lighting Specific SPFs for C-S method (Expressways 4-lanes)

Night-Time Crashes										
Crash Type	**Severity levels**	**Intercept**		**Log(AADT)**		**Adding Lighting**		**Length**		**Over Dispersion Parameter (K)**
		Estimate	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	**Estimate**	**P-Value**	
All types	All	-15.2163	0.0072	1.6695	0.0058	-0.3103	0.04410	0.6642	<.0001	0.9829
	Non- Injury	-12.1816	0.0002	1.4952	<.0001	-0.2305	0.03612	0.7245	<.0001	0.9545
	F+I	-14.3123	0.0372	1.4698	0.0108	-0.3508	0.0081	0.5541	<.0001	0.8579
	Severity Level 3-5	-13.7642	0.0079	1.3766	0.0037	-0.3205	0.0325	0.9864	0.0035	1.3201
Rear- end	All	-18.5910	0.0001	1.7573	0.0001	-0.2113	0.0502	0.4688	0.0051	1.6434
Angle	All	-22.4649	0.0881	2.2235	0.0558	-0.2833	0.0525	0.4825	0.0095	4.8505
Single	All	-17.6425	0.0033	2.3655	0.0024	-0.4122	0.0564	0.7251	0.0356	2.0318
All other	All	-12.6492	0.00432	1.7682	<.0001	-0.2365	0.0015	0.4266	0.0021	2.1446

Table 8-2: Recommended CMFs for Adding Lighting (Expressways 4-lanes)

Night-Time Crashes			
Cross-Sectional method			
Crash Type	**Severity Levels**	**CMF** (Safety Effectiveness)	Standard Error
All types	**F+I**	**0.73** (27%)	0.09
	Non- Injury	**0.79** (21%)	0.10
	Injury Level 3-5	**0.73 (27%)**	0.09
	All Severity	**0.70** (30%)	0.11
Rear End	**All**	**0.81** (19%)	0.09
Angle	**All**	**0.75** (25%)	0.12
Single	**All**	**0.66** (34%)	0.14
All other	**All**	**0.78** (22%)	0.13

8.1.2 Adding Lighting to all road types with all number of lanes

An Observational Before-After method was used in this approach and the analysis divided as follow:

1. Before-After with a comparison group, this method was applied to the 45 and 33 treated sites for all road types with all number of lanes and urban 4-lane/6-lane principal and

minor arterials, respectively. The safety effectiveness of adding lighting was estimated for individual sites and averaged over all sites using the crash data from 45 and 33 comparison sites, respectively, with similar roadway characteristics and AADT; and

2. Before-After with EB method, a total of 230 and 164 roadway segments were identified as reference sites for all road types with all number of lanes and urban 4-lane/6-lane principal and minor arterials, respectively. Roadway characteristics and crash data were collected from FDOT databases. Simple and full SPFs with Negative Binomial (NB) distribution were developed using these data.

Tables 8-3 and 8-4 present the best SPFs for different crash types and severity levels: 1) All crashes, 2) Non-Injury crashes, 3) Fatal and Injury (F+I), 4) Severity Levels (3 to 5) crashes, 5) Rear End Crashes, 6) Angle crashes, 7) All Single Vehicle Run-off Road crashes, and 8) All other crashes. CMFs were estimated for different crash types and severity levels using their respective SPFs. All variables shown in SPFs are significant at a 90% confidence level.

Table 8-3: Adding Lighting SPFs (All Road Types with All Number of Lanes)

Night-Time Crashes										
		Intercept		Log(AADT)		Speed Limit		Length		Over Dispersion Parameter (K)
Crash Type	Severity levels	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	
All types	All	-4.8170	0.0016	0.3473	0.0214	0.0422	<.0001	0.1565	<.0001	0.7831
	Non- Injury	-7.866	<.0001	0.5529	0.0005	0.0442	0.0003	0.1400	<.0001	0.8033
	F+I	-6.2509	<.0001	0.4509	0.0034	0.0396	0.0013	0.1551	<.0001	0.8984
	Severity Level 3-5	-3.7382	0.0279	0.3766	0.0277	-	-	0.1824	<.0001	1.0227
Rear-end	All	-10.5845	<.0001	0.8627	<.0001	0.0279	0.0250	0.1254	<.0001	0.6053
Angle	All	-10.9692	<.0001	0.7679	<.0001	0.0465	0.0012	0.1208	<.0001	0.5952
Single	All	-4.3031	<.0001	-	-	0.0642	<.0001	0.1408	<.0001	0.9322
All other	All	-2.0503	0.0003	-	-	0.0402	<.0001	0.1616	<.0001	0.5833

Table 8-4: Adding Lighting SPFs (Urban 4-lane/6-lane Principal and Minor Arterials)

Night-Time Crashes										
		Intercept		Log(AADT)		Speed Limit		Length		Over Dispersion Parameter (K)
Crash Type	Severity levels	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	
All types	All	-4.3123	0.0372	0.4262	0.0308	0.0203	0.0488	0.1641	<.0001	0.4579
	Non- Injury	-2.1816	0.0032	-	-	0.0569	<.0001	-	-	1.3945
	F+I	-5.6659	0.0169	0.4930	0.0278	0.0242	0.0277	0.1617	<.0001	0.4672
	Severity Level 3-5	-1.1384	0.0474	-	-	0.0273	0.0153	0.1558	<.0001	0.4337
Rear-end	All	-8.5910	0.0084	0.7973	0.0110	-	-	0.1688	<.0001	0.6434
Angle	All	-8.4649	0.0041	0.7680	0.0068	-	-	0.1525	<.0001	0.1505
Single	All	-4.6611	0.0002	-	-	0.0597	0.0118	0.1797	0.0003	1.0939
All other	All	-1.4051	0.0266	-	-	0.0496	0.0001	-	-	1.1446

For all road types with all number of lanes, adding lighting has a positive effect on reduction in night-time crashes for all crash types and severity levels except for the non-injury crashes as shown in Table 8-5. The CMFs for all types of roads were compared with the CMFs in the HSM for fatal-and-Injury (F+I) and non-injury crashes and they comparable to a large extent. However, the results extend to severity levels and crash types beyond the HSM. The Before-After with EB method provided lower standard errors of CMFs than the Before-After with CG method. Therefore, CMFs from the EB method are recommended for the CMFs for the crash types and severity levels.

Table 8-5: CMFs for Adding Lighting (All Road Types with All Number of Lanes)

Night-Time Crashes									
		Before-After with CG		**Before-After with EB**				**HSM**	
Crash Type	**Severity Levels**	**CMF**	**SE***	**Simple SPF**		**Full SPF**		**CMF**	**SE**
				CMF	**SE**	**CMF**	**SE**		
All types	**F+I**	0.60	0.15	0.57	0.13	0.63	0.12	**0.72**	**0.06**
	Non- Injury	0.87	0.24	0.82	0.19	0.84	0.18	**0.83**	**0.07**
	Injury Level 3-5	0.93	0.30	**0.89**	**0.17**	0.91	0.19	N/A	N/A
	Total Crashes	0.72	0.12	0.63	0.11	**0.68**	**0.09**	N/A	N/A
Rear End	**All**	0.65	0.21	0.61	0.15	**0.67**	**0.14**	N/A	N/A
Angle	**All**	0.68	0.24	**0.64**	**0.18**	0.67	0.19	N/A	N/A
Single	**All**	0.75	0.27	**0.72**	**0.18**	0.77	0.21	N/A	N/A
All other	**All**	0.67	0.16	0.70	0.10	**0.72**	**0.08**	N/A	N/A

Note: The values in **bold** are recommended CMFs.
SE* = Standard Error of the CMF

It is clear that the treatment has positively affect the night time crashes for the urban 4-lane/6-lane principal and minor arterials, by reducing all crash types and severity levels as shown in Table 8-6. The Before-After with EB method (using full SPFs) provided lower standard errors than the Before-After with CG method. Therefore, it is recommended to use CMFs from the EB method.

Table 8-6: CMFs for Adding Lighting (Urban 4-lane/6-lane Principal and Minor Arterials)

Night-Time Crashes							
		Before-After with CG		Before-After with EB (Full SPF)		HSM	
Crash Type	**Severity Levels**	**CMF**	**SE***	**CMF**	**SE***	**CMF**	**SE**
All types	**F+I**	0.70	0.11	**0.68**	0.05	N/A	N/A
	Non- Injury	0.74	0.09	**0.76**	0.08	N/A	N/A
	Injury Level 3-5	0.75	0.15	**0.77**	0.09	N/A	N/A
	All Severity	0.72	0.11	**0.74**	0.10	N/A	N/A
Rear-end	**All**	0.73	0.18	**0.62**	0.12	N/A	N/A
Angle	**All**	0.77	0.14	**0.82**	0.10	N/A	N/A
Single	**All**	0.60	0.13	**0.63**	0.09	N/A	N/A
All other	**All**	0.71	0.12	**0.82**	0.12	N/A	N/A

Note: The values in bold are recommended CMFs.
SE* = Standard Error of the CMF

8.1.3 Comparison of the developed CMFs and CMFs in previous studies (i.e. HSM)

Table 8-7 presents and compares the CMFs for Adding Lighting to urban 4-lane/6 lanes Principal and minor arterials and CMFs for adding lighting to 4-lanes expressways, as well as CMFs for adding lighting to all road types in the HSM.

Table 8-7: CMFs for Adding Lighting (Urban 4-lane Principal and Minor Arterials)

Night-Time Crashes							
		Expressways 4-Lanes		**Urban 4-lane Principal and Minor Arterials**		**All Types of road**	
		Cross-Sectional Method		**Before-After with EB (Full SPF)**		**HSM**	
Crash Type	**Severity Levels**	**CMF**	**SE***	**CMF**	**SE***	**CMF**	**SE**
All-Types	**F+I**	0.73	0.09	0.68	0.05	0.72	0.06
	Non- Injury	0.79	0.12	0.76	0.08	0.83	0.07
	Injury Level 3-5	0.73	0.08	0.77	0.09	N/A	N/A
	All-Severity	0.70	0.11	0.74	0.10	N/A	N/A
Rear-End	**All**	0.81	0.09	0.62	0.12	N/A	N/A
Angle	**All**	0.75	0.12	0.82	0.10	N/A	N/A
Single	**All**	0.66	0.10	0.63	0.09	N/A	N/A
All-other	**All**	0.78	0.13	0.82	0.12	N/A	N/A

Note: The values in bold are recommended CMFs.
SE* = Standard Error of the CMF

8.2 Conclusion

Although the literature showed that highway lighting could result in both crash and crime reduction by an average of 20 to 30 percent, respectively (FHWA, 2014). However, there is a lack of research that evaluates the safety impacts of adding highway lighting to different road types. Thus, there is a need to assess the traffic safety effects of this treatment. Therefore, the main goal of this section is to evaluate the safety effectiveness of the implementation of highway lighting on the Night-Time crashes on expressways. This section was divided into three approaches, 1) Evaluating the safety effectiveness of adding lighting to expressways, 2) Evaluating the safety effectiveness of adding lighting to all road types with all number of lanes, and 3) Compare the results and provide recommendations.

The results showed that for urban 4-lane/6-lane principal and minor arterials, adding lighting has a positive effect on crash reduction for the night-time crashes (all crash types and severity levels). Similar to all road types with all number of lanes, the safety was improved and the Before-After with EB method (using full SPFs) provided lower standard errors than the Before-After with CG method. Moreover adding roadway lighting has significantly improved traffic safety on the 4-lanes expressways by reducing the night-time crashes by an approximately 35 percent.

Overall, the Crash Modification Factors developed in this section would help officials to benefit from the extensive research in adding highway lighting to the road network, especially

on expressways by providing quantitative information on crash analysis and evaluation for decision making in planning, design, operation, and maintenance.

CHAPTER 9: HIGH-OCCUPANCY TOLL (HOT) LANES STUDIES

9.1 Introduction

The increasing number of cities throughout the world is dealing with similar problems such as traffic safety, demand of highway travel, congestion, etc. However, construction of new highways is not keeping pace with growing demand. In 2006, the U.S. Department of Transportation initiated an Urban Partnership Agreement (UPA) with cities to implement complementary and synergistic strategies to relieve urban congestion.

One of these strategies is to expand freeway capacity by adopting several solutions (DOT. 2014). One of these solutions is the Managed Lanes program; this program has different meanings to different agencies. And the term is commonly thought of as High-Occupancy Toll (HOT) lanes, also known as Express Lanes or value priced lanes *(*FHWA. 2014*).* The "Managed Lanes" also includes exclusive or special use lanes such as (express, dynamic tolling, bus-only, or truck-only lanes).

The concept of providing HOT Lanes on the highway corridor reflects a growing national trend where urban areas are converting regular or HOV lanes into HOT facilities to enhance mobility and offer more choices for motorists and transit users. In other words, High-occupancy toll lanes are special toll lanes that offer drivers choices to pay a higher toll (dynamic tolls) to bypass heavy congestion in regular toll lanes. The toll is varying, depending on traffic condition in the express lane. As the traffic demand increases, the toll increases "i.e. "dynamic

tolling" to maintain the highway speeds (FT, 2014). By driving up prices, traffic is driven back into the General-Purpose Lanes (GPL) or (Free-Lanes), easing congestion on the express lanes. Actually, charging a higher price during a period of high demand is a concept not exclusive to transportation. This method is used by other industries (i.e. electric utility, airlines, rental cars, and hotels) where rates are higher during peak usage times and peak seasons. So, it can be considered that the HOT-Lanes are first-class lanes within the highway. Figure 9-1 and Tables 9-1, 9-2 show useful information and examples of HOT-Lanes projects across the United States.

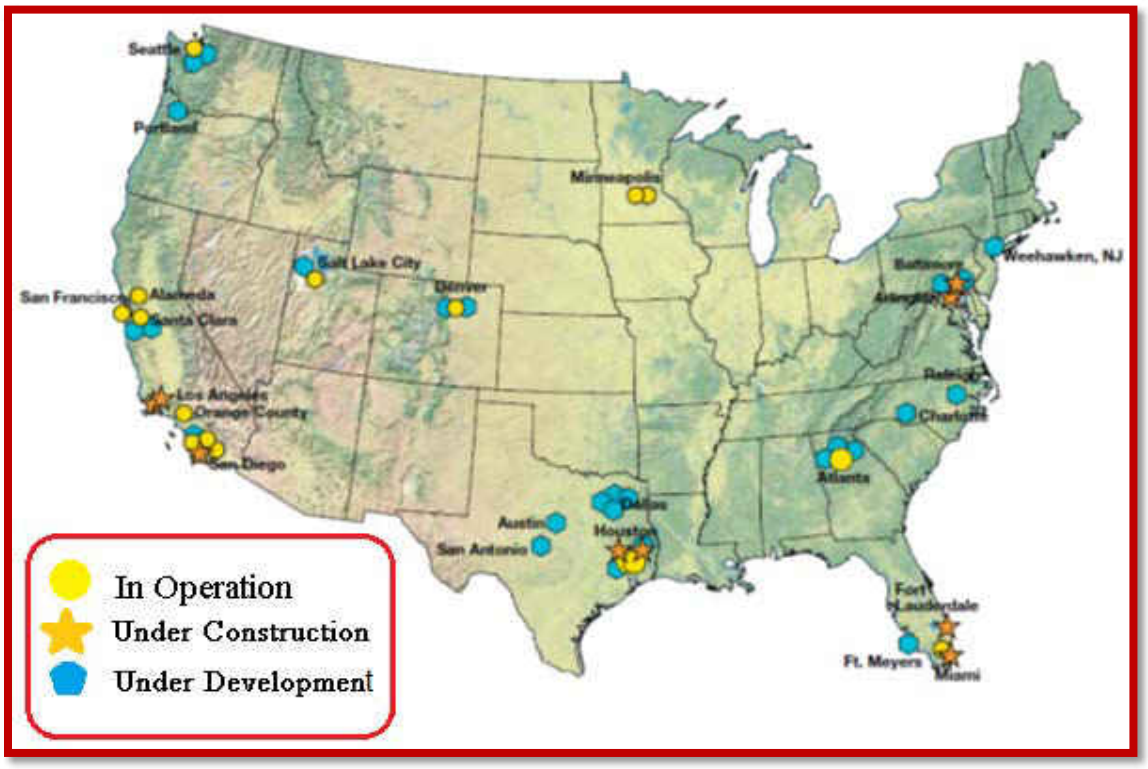


Figure 9-1: HOT lanes across the United States (Source: WSDOT - FAPS, 2012)

Table 9-1: Examples of existing HOT-Lanes projects.

HOT Lanes in the U.S. include:	
SR 237 Express Lanes in Silicon Valley	http://www.vta.org/expresslanes/
I-85 Express Lanes in Atlanta, Georgia	http://www.peachpass.com/
I-680 Express Lanes in Oakland, California	http://www.680expresslane.org/I-680.asp
I-35 W Express Lanes in Minneapolis, MN	http://www.dot.state.mn.us/upa/
I-95 Express Toll Lanes in Miami, Florida	http://www.95express.com/
SR-167 HOT Lanes Pilot in Seattle, Washington	http://www.wsdot.wa.gov / Tolling/SR167HotLanes/default.htm
I-25 Express Lanes in Denver, Colorado	http://www.coloradodot.info /travel/tolling/i-25-hov-express-lanes
I-15 Express Lanes Pilot in Salt Lake City, Utah	http://www.udot.utah.gov/expresslanes/
I-394 in Minneapolis, Minnesota	http://www.mnpass.org/
I-15 Express Lanes in San Diego, California	http://fastrak.511sd.com/
HOT Lanes on the I-10 Katy Freeway in Houston, Texas	https://www.hctra.org/
SR-91 Express Lanes in Orange County, California	http://www.91expresslanes.com/

Table 9-2: Examples of U.S. locations where HOT Lanes are in development or on Schedule for construction.

U.S. locations where HOT Lanes are in development or on Schedule for construction:	
Orlando: Interstate-4 HOT-Lanes known as I4-ULTIMATE is expected to start construction in 2015. (Source: FDOT)	http://www.i4ultimate.com/ http://i4ultimate.com/project-info/future-i-4/
Tampa: SR-589 is expected to start construction soon. (Source: FDOT)	http://floridasturnpike.com/construction_current.cfm#Vets
I-495 ExpressLanes in Northern Virginia (Capital Beltway)	https://www.495expresslanes.com/
Austin, TX – Loop 1	
Bay Area, CA- I-580	**https://www.495expresslanes.com/**
Dallas, TX – I-30 and I-635	http://www.newlbj.com/default.asp?p=1
Fort Lauderdale, FL – I-595	http://www.i595express.com/
Minneapolis, MN-I-35	
Northern Virginia – I-95 and I-395	http://www.virginiadot.org/travel/hov-novasched.asp
Portland, OR – Highway 217	
Raleigh, NC – I-40	
Santa Cruz, CA – Highway 1	
Washington, DC – I-95, I-395, and I-495	
Keywords: ExpressLanes projects Hot Lanes in the US	

The Florida Department of Transportation (FDOT, 2014) is advancing sections of the I-95 and SR-589 by adopting the HOT-Lanes system to help travelers get home or to work faster with less stress at those areas. In 2007, the FDOT completed the Managed Lanes Comprehensive Traffic and Revenue Study. This study evaluated the potential operations of the corridor with the implementation of two tolled express lanes in each direction. They determined that this implementation could improve travel time by saving up to 38 minutes during peak periods (SCS, 2013).

This study was based on the continuous express lanes throughout Miami-Dade, Broward, and Palm Beach Counties. The system known as 95-Express occurred on the I-95 corridor in Miami-Dade County (Phase 1 the northbound lanes opened December, 2008 and southbound lanes opened January, 2010); Figure 9-2 shows Phase I & II project plan on I-95.

The HOV lane on I-95 was converted into two managed HOT-Lanes in each direction. In this scheme, users are charged a variable fee to drive in these lanes between the I-395 and the Golden Glades interchange. The goal of this system is to maintain a speed of 45 mph in the HOT-Lanes. Buses and high-occupancy vehicles with three or more passengers are allowed to use the HOT-Lanes for free (FT, 2014) using toll collection system called (E-ZPass Flex). Drivers can change the transponder mode manually by switching between Toll free HOV mode and Toll Pay HOT mode, Buses and high-occupancy vehicles with three or more passengers

are allowed to use the HOT-Lanes for free (FT, 2014).. Figures 9-3and 9-4 show the E-ZPass Flex transponder.

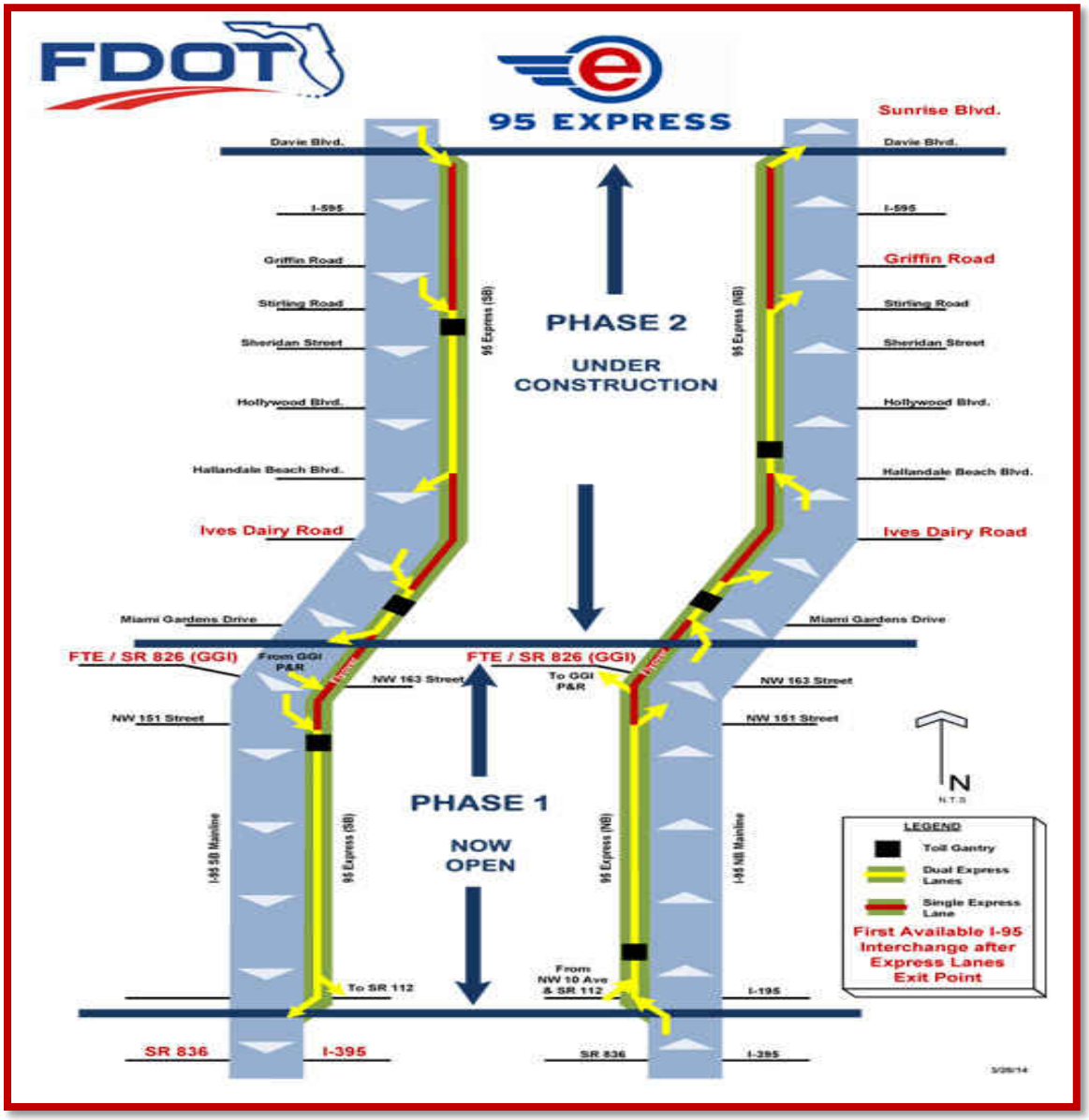


Figure 9-2: Shows Phase I & II project plan on I-95 (Source: 95-Express, 2014)

Figure 9-3: E-ZPass Flex (*Source:* Xerox Corporation, 2014)

Figure 9-4: Switching between HOV and HOT modes (*Source:* Xerox Corporation, 2014)

Since the opening of the I-95 Express Lanes commuters have experienced a number of benefits (SCS, Inc. 2013). The study found that the system improved throughput, it showed that from December 2008 to January 2009, there was a 9.5 percent increase in average weekday traffic volume throughput and a 15.7 percent increase during the PM peak period (4pm to 7pm).

Moreover, they found that a shift in travel modes has also occurred as a result of this system, and the ridership on the 95 Express bus route increased by an average of 33.5 percent between June 2007 and June 2009; also there were a significant improvement of the travel speeds after the implementation of the HOT-Lanes. The travel speed in the HOT-Lanes increased during peak periods from 20 MPH to a monthly average of 63 MPH. Drivers in the General Purpose Lanes (GPL) or (free lanes) also experienced an increase in the travel speed during the peak period (SCS, Inc. 2013). That may be attributed to the fact that the bus and carpool users increased while the total trips decreased. However, in the 95-Express the literature (FDOT, 2014) showed that the level of service significantly improved in the HOT-Lanes, while the speed in the GPL remained almost the same.

As of today, the HOT-Lanes system are in full operation in the following States: Florida (I-95), California (I-15), Colorado (I-25), Houston (I-10) and (US 290), Utah (I-15), Minnesota (I-394) and Washington (SR-167). In addition, many other countries adopted a peak-hour toll to reduce traffic congestion. The drivers can pay tolls electronically by enrolling in the prepaid transponders, which is read by an electronic reader and deducts the toll from their balance.

Some of these countries adopted another program called variable pricing which was applied to some highways to charge tolls based on demand and peak-hour. For example, in 2006 this program was applied in Stockholm, Sweden (Graham, 2013). This implementation resulted in a significant drop (more than 20 percent) of traffic on those highways (Franklin, 2012). Moreover, preliminary data indicates that the average number of crashes is down 2 percent when compared to the five year average prior to HOT-lanes opening in 2008 (WSDOT - FAPS, 2012). This program contributed to a shift in transport mode from single-occupant driver vehicles to mass transit system (FDOT, 2014)

After successfully adopting the 95-Express_in Phase 1 at Miami-Dade County (2008-2010), the application was scheduled to extend to Phase 2 on I-95 to the interchange of Davie Blvd. in Broward County. Also, the Florida Department of Transportation (FDOT) is implementing Phase 3 of the 95-Express Lanes continuing 29 miles north from Stirling Rd. in Broward County to Linton Blvd. in Palm Beach County; also this application was scheduled to be implemented to SR-589 in the Tampa area and on Interstate-4 in Central Florida known as (4-EXPRESS or I-4 ULTIMATE) starting 2015, (FDOT, 2014). Moreover, many other studies have been conducted to extend this application to many other roads in Florida. Figures 9-5 to 9-7 show the future plans of the HOT-Lanes in Florida. And Figure 9-8 shows reversible HOT-Plans South Florida on I-595

Figure 9-5: Improvement and HOT-Lanes in Orlando on I-4 (Source: I-4 Ultimate)

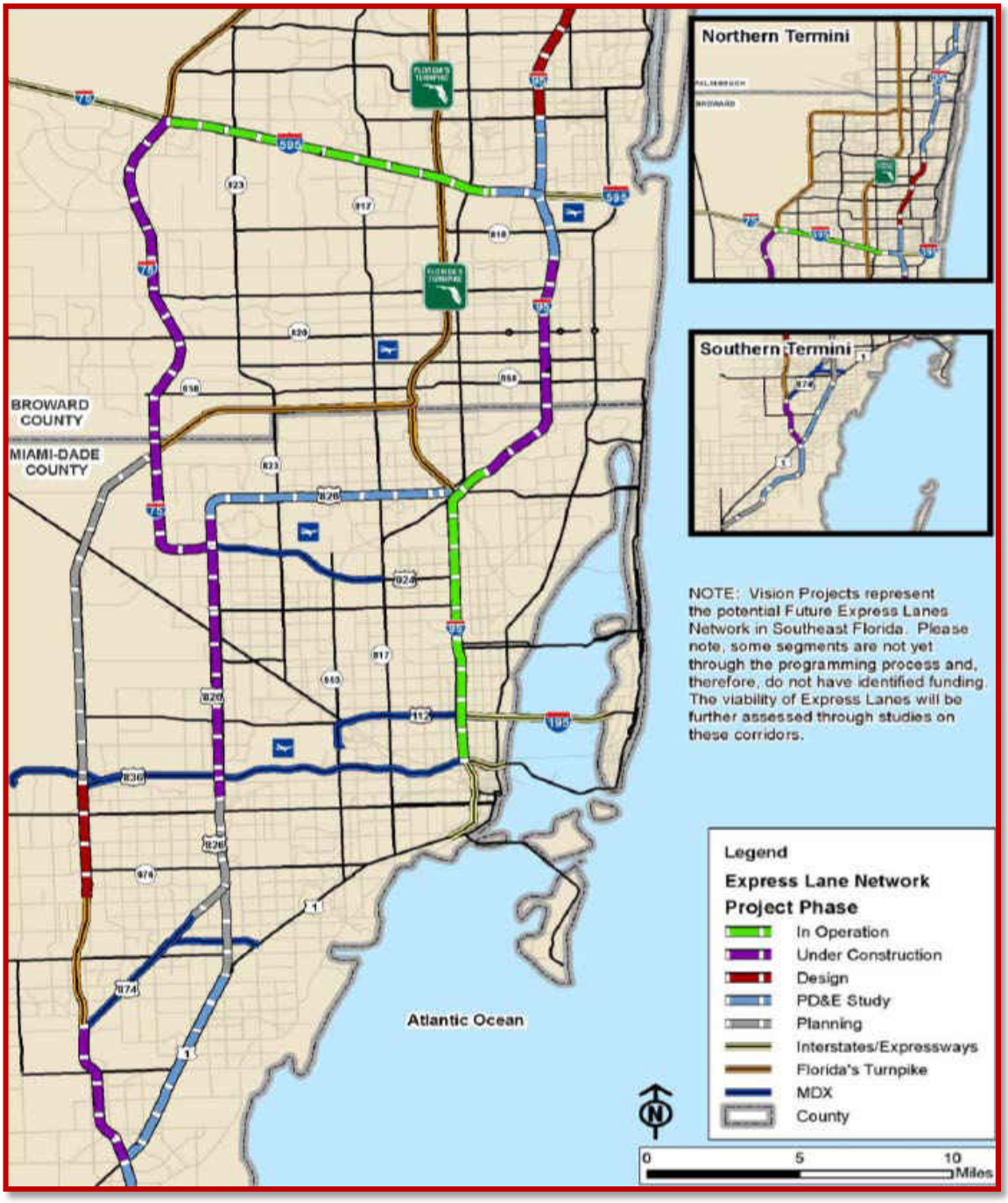


Figure 9-6: Future HOT-Lane (Phase 3) in South Florida on I-95 (*Source: 95-Express*)

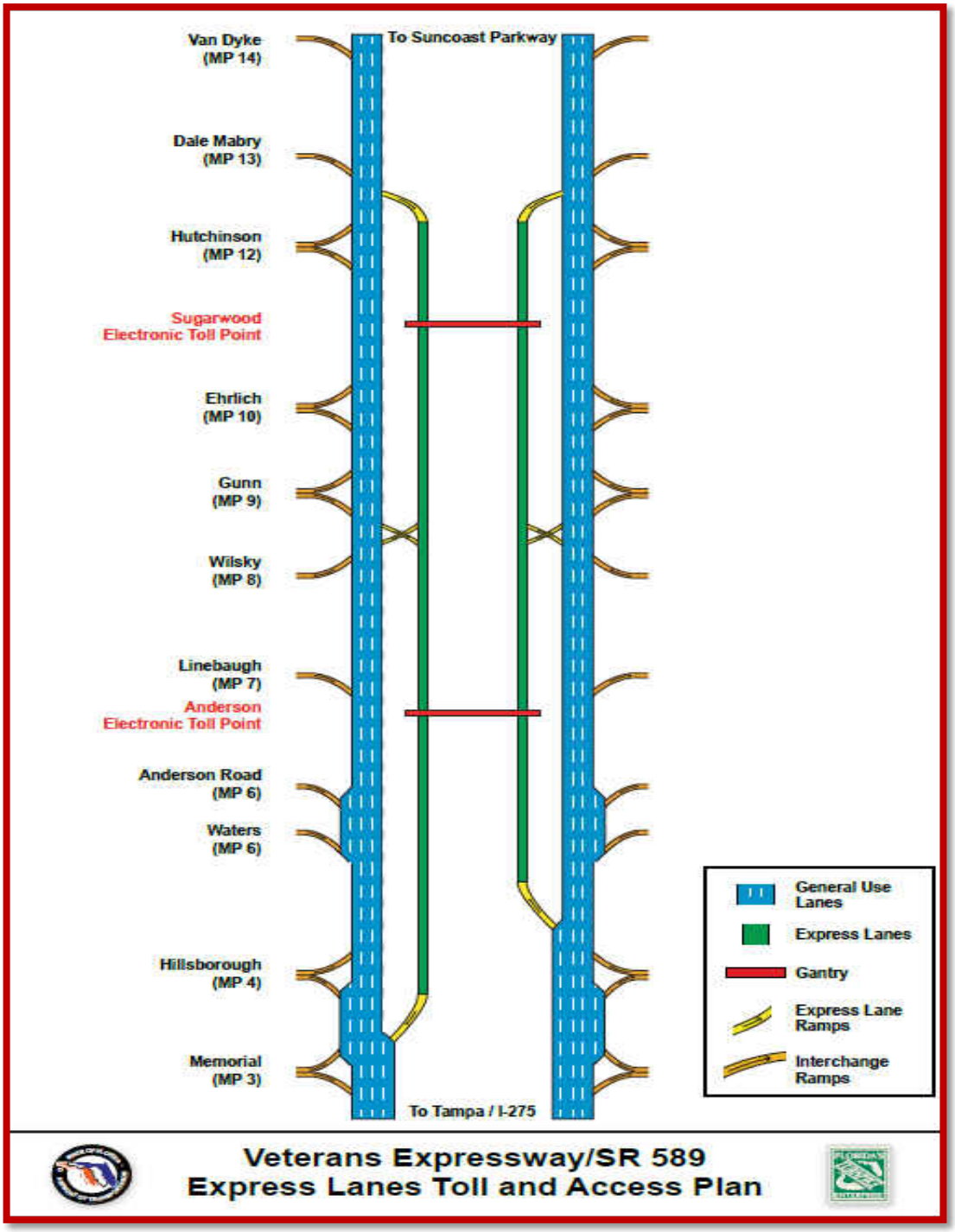


Figure 9-7: Future HOT-Plan Tampa-Florida on SR 589 (Source: FDOT, 2014)

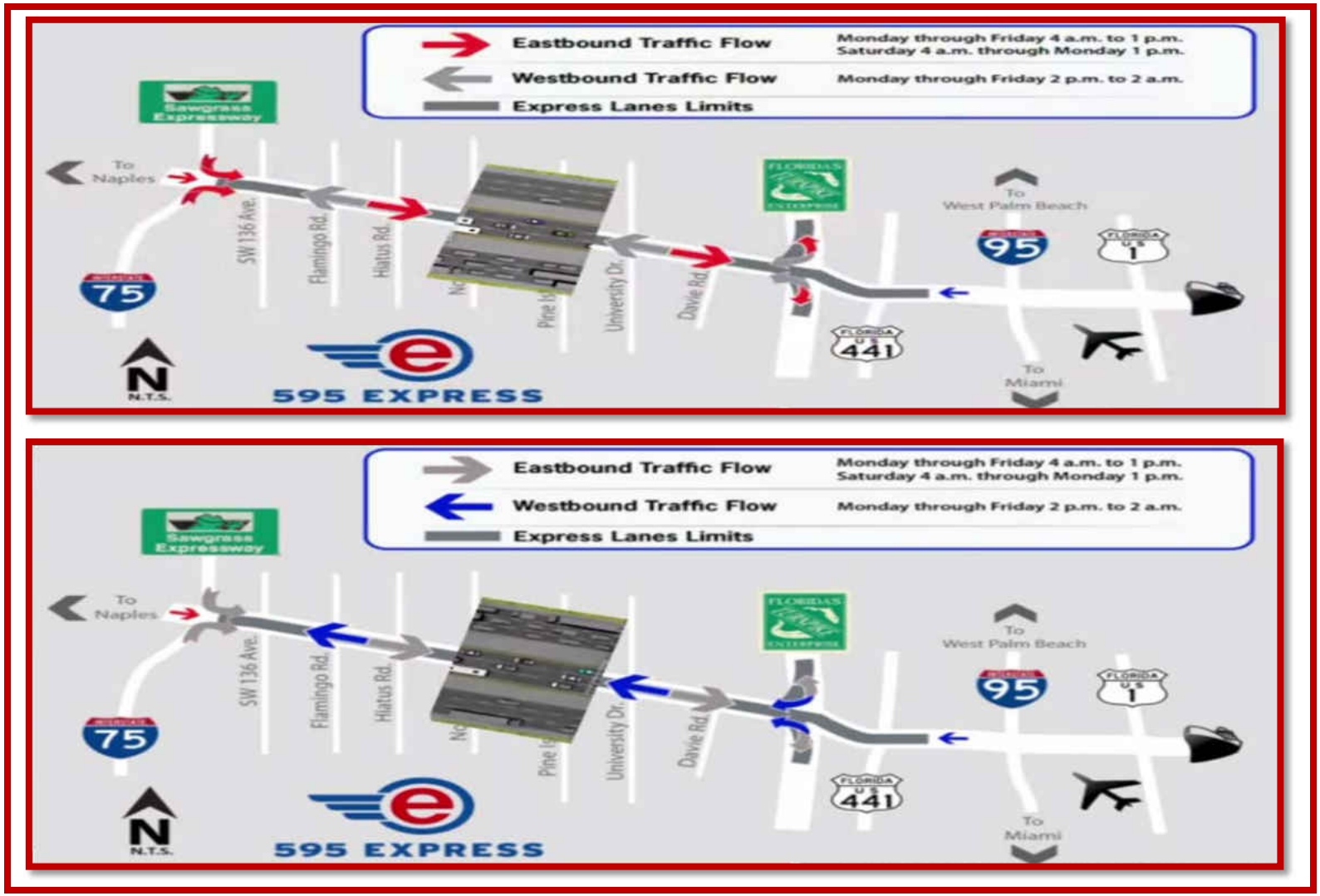


Figure 9-8: Reversible HOT-Plan South Florida on I-595 (*Source: 95-Express*)

This concept has been very successful in other metropolitan areas throughout the U.S by solving several traffic operations and environmental problems, as well as providing drivers with more choices to reach their final destinations quickly with less stress. However, the safety study of this system is very limited and only one previous study (Cao et al. 2012*)* evaluated the effect of HOV-to-HOT lane conversion on traffic safety using before-and-after method; they found that after the conversion of HOV-Lanes on I-394 in Minnesota to HOT-Lanes back in 2005, total crashes were reduced by 5.3 percent after the conversion, and they concluded that the benefits were practically important when compared to the tolls collected. In other words, the system considered as one of the most important sources of fund by providing more revenue to the transportation authority.

However, there is a limitation of the safety studies; therefore there is an urgent need to evaluate the safety impacts of the HOT lane system to draw consistent conclusions to provide quantitative information on crash analysis and evaluation for decision making in planning, design, operation, and maintenance.

9.2 Methodology

An observational– Before-After (B-A) study – was adopted to evaluate the safety effectiveness of the conversion from HOV lanes to HOT-Lanes on I-95 in Miami-Dade county in Florida. The Before-After method includes Before-After with Comparison Group (CG), and Before-After with Empirical Bayesian (EB). A set of Safety Performance Functions (SPFs) which

predict crash frequency as a function of explanatory variables were also developed. These HOT-Lanes specific SPFs were used to predict crash frequency for untreated sites in the after period or derive the Crash Modification Factors (CMFs) for the treatment sites for the EB method.

Both simple SPF (with traffic volume only as an explanatory variable) and full SPF (with traffic volume and additional explanatory variable(s)) were used to estimate the safety effectiveness of the treatment. Only the SPFs which produced the CMFs with lower standard errors, were presented. Similarly, comparing the CMFs calculated using the Before-After with CG and EB methods, only the CMF with lower standard error was selected.

9.2.1 Before-After with Comparison Group

The Comparison Group (CG) method is a well-known approach to evaluate the safety effectiveness of the treatments; this method uses the untreated sites as the comparison group, which has similar characteristics as the treated group. To account for changes in crashes, the ratio of the observed crash frequency in the before period to the observed frequency in the after period for the comparison group is calculated. The observed crash frequency for the treated group in the before period is multiplied by this ratio to calculate the expected crash frequency for the treated group in the after period. This expected crash frequency is compared to the observed crash frequency in the after period for the treated group to estimate the safety effect.

This method can provide more accurate estimates of the safety effect than a naïve Before-After study, particularly, if the similarity between treated and comparison sites is high.

9.2.2 Before-After with Empirical Bayes

The Before-After with Empirical Bayes method has been widely used in the literature. In this method, the expected crash frequencies at the treatment sites in the 'after' period had the countermeasures not been implemented is estimated more precisely using data from the crash history of the treated sites, as well as the information of what is known about the safety of reference sites with similar yearly traffic trend, physical characteristics, and land use.

The method is based on three fundamental assumptions*;* 1) the number of crashes at any site follows a Poisson distribution, 2) the means for a population of systems can be approximated by a Gamma distribution, and 3) changes from year to year from sundry factors are similar for all reference sites. One of the main advantages of the Before-After study with Empirical Bayes is that it accurately accounts for changes in crash frequencies in the 'before' and in the 'after' periods at the treatment sites that may be due to regression-to-the-mean bias. It is also a better approach than the comparison group for accounting for influences of traffic volumes and time trends on safety. The estimate of the expected crashes at treatment sites is based on a weighted average of information from treatment and reference sites.

9.2.3 Cross-Sectional Method

Cross-Sectional method was used in this approach to evaluate the effect of HOT-Lanes on the safety performance of Interstate 95 for (All crash types- All severities and Property Damage Only) crashes. The Before-After method cannot be used for these crash categories because of the changing of the crash reporting criteria since July 2012.

The Cross-sectional method requires the development of crash prediction models (i.e. SPFs) for calculation of CMFs. The models are developed using the crash data for both treated and untreated sites for the same time period. In the Cross-sectional models, the treated segments were used with reference segments in the after treatment time, both treated and untreated sites are located on I-95.

A set of SPFs using NB distribution were developed to estimate CMFs for the treatment at a specific road type and setting. SPFs describe crash frequency as a function of explanatory variables including the presence of HOT-Lanes, AADT and length of roadway segments as follows:

$$F_i = \exp(\alpha + \beta_1 * HOT - Lanes_i + \beta_2 * Length_i) * AADT_i^{\beta_3} \quad (9\text{-}1)$$

where,

F_i = crash frequency on a road segment i;

HOT-Lanes $_i$ = presence of HOT-Lanes on a road segment *i* (= 1 if the HOT-Lanes of a segment *i* is implemented, = 0 if the HOT-Lanes of a segment *i* is not implemented);

$Length_i$ = length of a road segment *i* (mi);

$AADT_i$ = average annual daily traffic on a road segment *i* (veh/day);

α = constant;

β = coefficients for variables.

Then CMFs were calculated using the following equation:

$$CMF = \exp(\beta_1 * (1-0)) = \exp(\beta_1) \tag{9-2}$$

The above model can be applied to prediction of total crash frequency or frequency of specific crash type or crash severity. The standard error (SE) of the CMF is calculated as follows (Bahar, 2010):

$$SE = \frac{\exp(\beta_k * (x_{kt} - x_{kb}) + SE_{\beta_k}) - \exp(\beta_k * (x_{kt} - x_{kb}) - SE_{\beta_k})}{2} \tag{9-3}$$

where,

SE = standard error of the CMF;

$SE_{\beta k}$ = standard error of the coefficient of the variable (HOT-Lanes).

9.2.4 Crash Modification Factors

The EB before-after evaluation of HOT-Lanes system will be used to predict the expected crash frequency at the treated sites assuming the treatment had not been implemented. The expected crash frequency will compared with the number of observed crashes in the period after HOT-Lanes system had been implemented. To compute the safety impacts of the treatment, Crash Modification Factors (CMFs) were estimated using different methods for all crash categories. Crash Modification Factors expresses the safety consequences of some treatment or intervention that has been implemented on a roadway facility.

A CMF greater than 1.0 indicates an expected increase in crashes, while a value less than 1.0 indicates an expected reduction in crashes after the implementation of a given countermeasure.

9.3 Data description

High–Occupancy Toll (HOT) lanes have become an increasingly more popular system on the US highway system. The HOT-Lanes on the I-95 corridor in Miami-Dade County known as 95-Express also called Express Lanes since December 2008. The HOV lane on I-95 was converted into two managed HOT-Lanes in each direction. These lanes are separated from the highway by using plastic poles; so the HOT-Lanes became a highway within the highway.

The primary goal of this upgrading is to provide the service at free flow speed by adjusting the toll rate depending on the level of traffic (traffic demand). The tolls are collected automatically

by using prepaid transponders, so there are no tollbooths in these lanes. Also, these lanes are managed by a variable message sign; as the demand increases, the toll rates increases.

Multiple sets of data maintained by FDOT were used in this study including: Roadway Characteristics Inventory system (RCI), TranStat IView aerial mapping system, and Financial Project Search Database. Moreover, Google Earth and the publication reports of Florida Turnpike were used to verify the locations.

It is worth noting that the total crash number in Florida has increased substantially in 2013, due to the change of the policy of the crash reporting strategy. Traffic crashes in Florida are generally reported by the use of two forms commonly referred to as the "Long Form" and the "Short Form." A Long Form crash report is used when one or more of the following criteria are met (FDOT, 2014):

- Death or personal injury
- Leaving the scene involving damage to - vehicles or property
- Driving while under the influence.

The Short Form crash report is used to report all other types of traffic crashes. According to FDOT, effective July 1, 2012 new criteria have been applied to reduce the proportion of short form crashes by encouraging all of the law enforcement agencies that are using field data collection software to adopt a "long-form-only" reporting strategy. This strategy caused an increase of the long form crashes by approximately 25 percent in the 2013 crash data (FDOT,

2014). In other words, this change affects the total and Property Damage Only (PDO) crashes. The data of severe crash levels (2 to 5) remained the same because agencies used to report them in long-form from the beginning. Therefore, due to this change and the limitation of the after period data, the Before-and-After method will be applied to the severe crashes with all crash types. For the total and PDO crashes the best method will be the Cross-Sectional method in the after period data assuming the change of the criteria affects all treated and the reference groups.

Data from 16 miles of 95-Express (Phase 1) (two directions) on I-95 in the southeast of Florida was used. This section was divided to 20 segments based on the number of lanes and the values of the Annual Average Daily Traffic (AADT). To select reference segments with similar characteristic to the 95-Express section, a 156 reference segments located on approximately 256 miles on I-95 were used to evaluate this application.

Crash data for a nine-year period (2005-2013) was investigated to examine the safety impact by evaluating crashes for a period of three years before and three years after the upgrading. Crashes that occurred within these segments were extracted from the crash database maintained by FDOT known as a Crash Analysis Reporting (CAR) system. It should be noted that data in the period when 95-Express were being implemented (2008–2010) was excluded from the analysis. Figure 9-9 shows an example of HOT-Lanes located on I-95 southeast of Florida.

Figure 9-9: Shows HOT-Lanes located on I-95 (Source 95-Express)

9.4 Analysis and results

The section was divided into two parts:

Part I: Evaluating the safety impact for the whole roadway section that have the HOT-Lanes.

Part II: Evaluating the safety impact on the HOT-Lanes and the general purpose lanes separately.

9.4.1 Before-After with Comparison Group

Data including all of the available treated sites that were converted from HOV-Lanes to the HOT-Lanes (16 miles= 20 segments) at Miami-Dade County in Florida were used in this approach. These sites were compared with data from the same number of untreated sites (comparison sites that have similar characteristics as the treated sites). The crash modification

factors were estimated for both individual and all sites combined using crash experience data from a group of HOV-lanes on I-95. Crash data for the before-and-after treatment was used.

9.4.2 Before-After with the Empirical Bayes

Data from 156 reference sites (i.e. HOV lanes) that have no treatment were used in the analysis. Crash data of three years in the before period was used to develop the specific Safety Performance Functions (SPFs) of the HOV-lane. These prediction models can be used to predict crashes for the HOV-Lanes in the after period, or for HOT-Lanes system assuming the treatment had not been implemented.

9.4.2.1 Safety Performance Functions

A Safety Performance Function (SPF) is generally known as a crash prediction model, which relates the frequency of crashes to traffic and the roadway characteristics. The SPF can be developed using the Negative Binomial (NB) model formulation with the data from the reference sites. Both simple SPF (with traffic volume only as an explanatory variable) and full SPF (with traffic volume and additional explanatory variable(s)) were used to estimate the safety effectiveness of the system.

A set of SPFs were developed in this study, these prediction models were used to predict the crashes at the HOT-Lanes application assuming the treatment had not been implemented to

evaluate the safety effectiveness in the after period. The Negative Binomial (NB) regression models for safety evaluation were developed for different type of crashes and injury levels; and functional form of these models is shown in the following equation (9-1):

$$N_{predicted} = \exp(\beta_0 + \beta_1 * \ln(AADT) + \beta_2 S) \quad (9\text{-}4)$$

Where,

$N_{predicted}$= Expected crash frequency without treatment,

β_i = coefficients of the significant variables,

AADT=Annual Average Daily Traffic,

S= Speed limit.

9.4.3 Part I: Evaluate the safety impact of HOT-lanes on the whole roadway section

An Observational Before-After with the Empirical Bayes was used. A 'Simple' and 'Full' SPFs were developed for the segments that have High-Occupancy Vehicle (HOV) lanes located on Interstate 95 (I-95). Table 9-3 summarizes the estimated parameters for the 'Full' and 'Simple' SPFs. It should be noted that only models with smaller AIC values were selected, because the less value of AIC means that the model fit better for the same dataset.

Table 9-3: Estimates of Coefficients for HOV Safety Performance Functions

HOV-Specific Full SPFs (All Lanes)									
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Speed Limit**		**Dispersion**	AIC
		Esti*	**P-Value**	**Esti***	**P-Value**	**Esti***	**P-Value**	**Esti***	
All	F+I	-1.2865	0.0932	0.9562	0.0325	-0.0411	<.0001	0.8860	1403
LCRC*	All	-6.3652	0.0056	0.8730	0.0001	-0.0403	<.0001	0.1786	1021
HOV-Specific Simple SPFs									
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Dispersion**			AIC
		Esti*	**P-Value**	**Esti***	**P-Value**	**Esti***			
Rear End	All	-5.4648	0.1365	0.6297	0.0360	0.5744			1229
All Others	All	-4.7418	0.0541	0.4810	0.0169	0.1784			822

LCRC*: Lane change related Crashes* = (i.e. sideswipe, angle crashes, etc.)
Esti* =Estimate

Several SPFs models included multiple crash related factors were developed and only significant SPFs with significant variables were presented in this section. Table 9-3 shows that log (AADT) and the speed limit came out to be significant in the final models of (F+I) and lane change related crashes. And only log (AADT) was significant in the final models of the Rear-End, and All-Other types of crashes.

The signs for the parameter estimates were as expected for all crash categories. For example, the coefficients of the traffic volumes were positive indicating that an increase in traffic volume

leads to increase in all injury levels and all type of crashes at the HOV-Lanes. And the coefficients of the speed limit were negative for both F+I and LCRC models indicating that increase in speed limit (up to 70 MPH) is associated with less severe crashes. This may be attributable to the fact that the variance of speeds is low. In other words, as the speed variances increase, the probability of the crashes will increase.

9.4.3.1 Crash Modification Factors

The EB before-after evaluation of HOT-Lanes system was used to predict the expected crash frequency at the treated sites assuming the treatment had not been implemented. The expected crash frequency was compared with the number of observed crashes in the period after HOT-Lanes system had been implemented. To compute the safety impacts of the treatment, Crash Modification Factors (CMFs) were estimated using different methods for all crash categories. Table 9-4 shows the crash modification factors that resulted from the treatment on the whole segments.

In this part, the CMFs were estimated using CG and EB methods. Both methods consistently show that the safety effects of the treatment do not significantly affect the safety performance of the roadway segments as a whole.

Table 9-4: CMFs for the whole segment that has HOT-Lanes

		Before-After with CG		Before-After with EB	
Crash Type	**Severity Levels**	**CMF**	**SE***	**CMF**	**SE***
All	**F+I**	0.88	0.15	**0.96**	**0.10**
Rear-end	**All**	1.08	0.11	**0.99**	**0.09**
LCRC*	**All**	0.84	0.19	0.88	0.13
All other	**All**	0.88	0.13	**0.89**	**0.10**

SE* = Standard Error of the CMF

9.4.3.2 Cross-Sectional Method for whole segment

Data including 156 reference segments (i.e. HOV lanes) and 20 treated segments were used in C-S analysis. Crash data of three years in the after period (2011-2013) was used to develop the specific Safety Performance Functions (SPFs). Table 9-5 shows the estimates of Coefficients for C-S specific SPF in the after period

Table 9-5: Estimates of Coefficients for C-S specific SPF in the after period

All-Types-All Severities and PDO crashes									
Crash Type	**Severity levels**	**Intercept**		**Log(AADT)**		**HOT-Lanes**		**(K*)**	**AIC**
		Esti*	**P-Value**	**Esti***	**P-Value**	**Esti***	**P-Value**		
All types	All	-14.3891	<.0001	1.4644	<.0001	0.2105	<.0001	0.4128	1626
	PDO	-13.1672	<0.0001	1.3201	<.0001	0.3051	<.0001	0.3799	1460

Esti*=Estimate
K*= Over Dispersion Parameter

Table 9-6: Recommended C-S's CMFs for segment that has HOT-Lanes system.

All-Types-All Severities and PDO crashes			
Cross-Sectional method			
Crash Type	**Severity Levels**	**CMF**	Standard Error
All types	All	**1.23**	**0.08**
	PDO	**1.35**	**0.07**

9.4.4 Part II: Evaluate the safety impact on HOT-Lanes and Free-Lanes separately.

9.4.4.1 Evaluating the safety on the HOT-Lanes only using EB Method.

An Observational Before -After with the Empirical Bayes was used. A 'Simple' and 'Full' SPFs were developed for the High-Occupancy Vehicle (HOV) lanes only located on Interstate 95 (I-95), these models will be applied on the treatment segments (HOT-Lanes) assuming that the treatment does not exist to evaluate the effect of the treatment . Table 9-7 summarizes the estimated parameters for only 'Simple' SPFs, as all other variables in "Full" SPFs were not significant.

Table 9-7: Estimates of Coefficients of Safety Performance Functions for HOV only

HOV-Specific Simple SPFs (HOT-Lanes only)							
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Dispersion**	**AIC**
		Estimate	**P-Value**	**Estimate**	**P-Value**	**Estimate**	
All	F+I	-2.0639	0.0325	0.6532	0.0526	0.4495	1121
LCRC*	All	-1.3652	0.0002	0.6325	<.0001	0.5656	675
Rear End	All	-5.4648	0.0623	0.8312	0.0060	0.9596	1012
All Others	All	-1.7418	0.0231	0.7360	0.0037	0.4784	482

LCRC*: Lane change related Crashes***** = (i.e. sideswipe, angle crashes, etc.)

In this part, the CMFs were also estimated using CG and EB methods. Both methods consistently show that the safety effects of the treatment would significantly affect the safety performance of HOT-Lanes only. This may be attributable to the fact that the HOT lanes became a highway within a highway, and traffic in these lanes will involve less congestion and more smooth flow as well as less lane changes. Table 9-8 shows the CMFs for HOT-Lanes only.

Table 9-8: CMFs for HOT-Lanes only.

		Before-After with CG		Before-After with EB (Full SPF)	
Crash Type	**Severity Levels**	**CMF**	**SE***	**CMF**	**SE***
All	**F+I**	0.70	0.12	**0.72**	0.12
Rear-end	**All**	0.65	0.12	**0.61**	**0.10**
LCRC*	**All**	0.57	0.09	**0.62**	**0.07**
All other	**All**	0.71	0.16	**0.77**	0.13

SE* = Standard Error of the CMF

9.4.4.2 Evaluating the safety on the HOT-Lanes only using C-S Method.

Similar to the previous part, data including 156 reference segments (i.e. HOV lanes) and 20 treated segments were used and crashes that occurred on the HOT-Lanes only were investigated. Crash data of three years in the after period (2011-2013) was used to develop the specific Safety Performance Functions (SPFs). Table 9-9 shows the estimates coefficients for HOV-Only. And Table 9-10 shows the CMFs of the total and PDO crashes at HOT-Lanes only using C-S.

Table 9-9: The estimate coefficients for C-S (HOV-Only).

All-Types-All Severities and PDO crashes									
Crash Type	**Severity levels**	**Intercept**		**Log(AADT)**		**HOT-Lanes**		**(K)**	**AIC**
		Esti*	**P-Value**	Esti*	**P-Value**	Esti*	**P-Value**		
All types	Total Crashes	-14.3891	<.0001	1.4644	<.0001	- 0.2212	<.0001	0.4128	1455
	PDO	-13.3883	0.0011	1.2506	0.0002	-0.4695	0.0008	0.4825	1144

Esti*=Estimate
K*= Over Dispersion Parameter

Table 9-10: Recommended C-S - CMFs for HOT-Lanes only.

All-Types-All Severities and PDO crashes			
Cross-Sectional method			
Crash Type	**Severity Levels**	**CMF**	Standard Error
All types	(Total Crashes)	0.80	0.10
	PDO	0.63	0.11

9.4.4.3 Evaluating the safety on the GPL (Free-Lanes) only using EB method.

Similarly, an Observational Before -After with the Empirical Bayes was used. A 'Simple' and 'Full' SPFs were developed for the Free-Lanes only located on Interstate 95 (I-95). Table 9-11 summarizes the estimated parameters for only 'Simple' SPFs, all other variables in the "Full" SPFs were not significant. Figure 9-10 shows the HOT and General Purpose Lanes (GPL) or (Free lanes) on a roadway segment. And Figure 9-11 shows the typical Sections on I-95 Express (Phase 3).

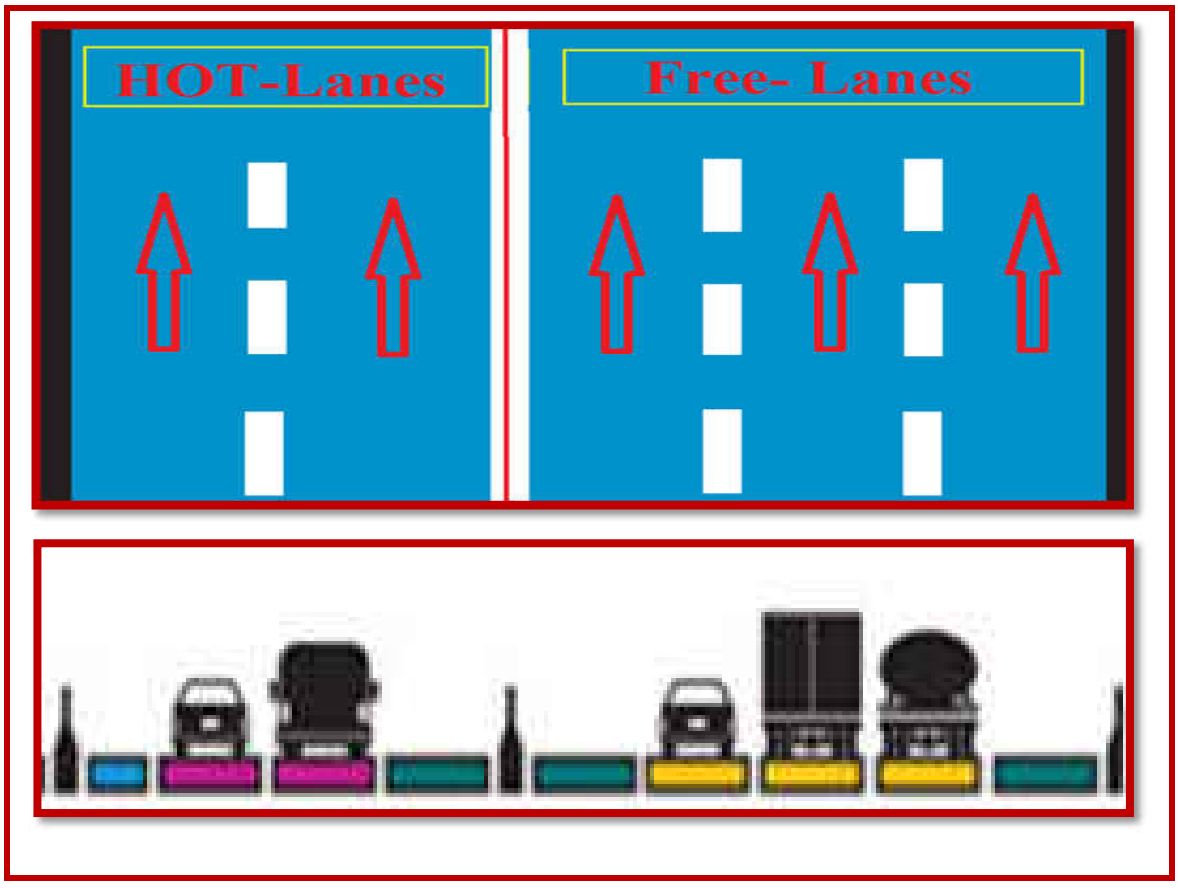


Figure 9-10: The HOT and GPL on a roadway segment (One direction).

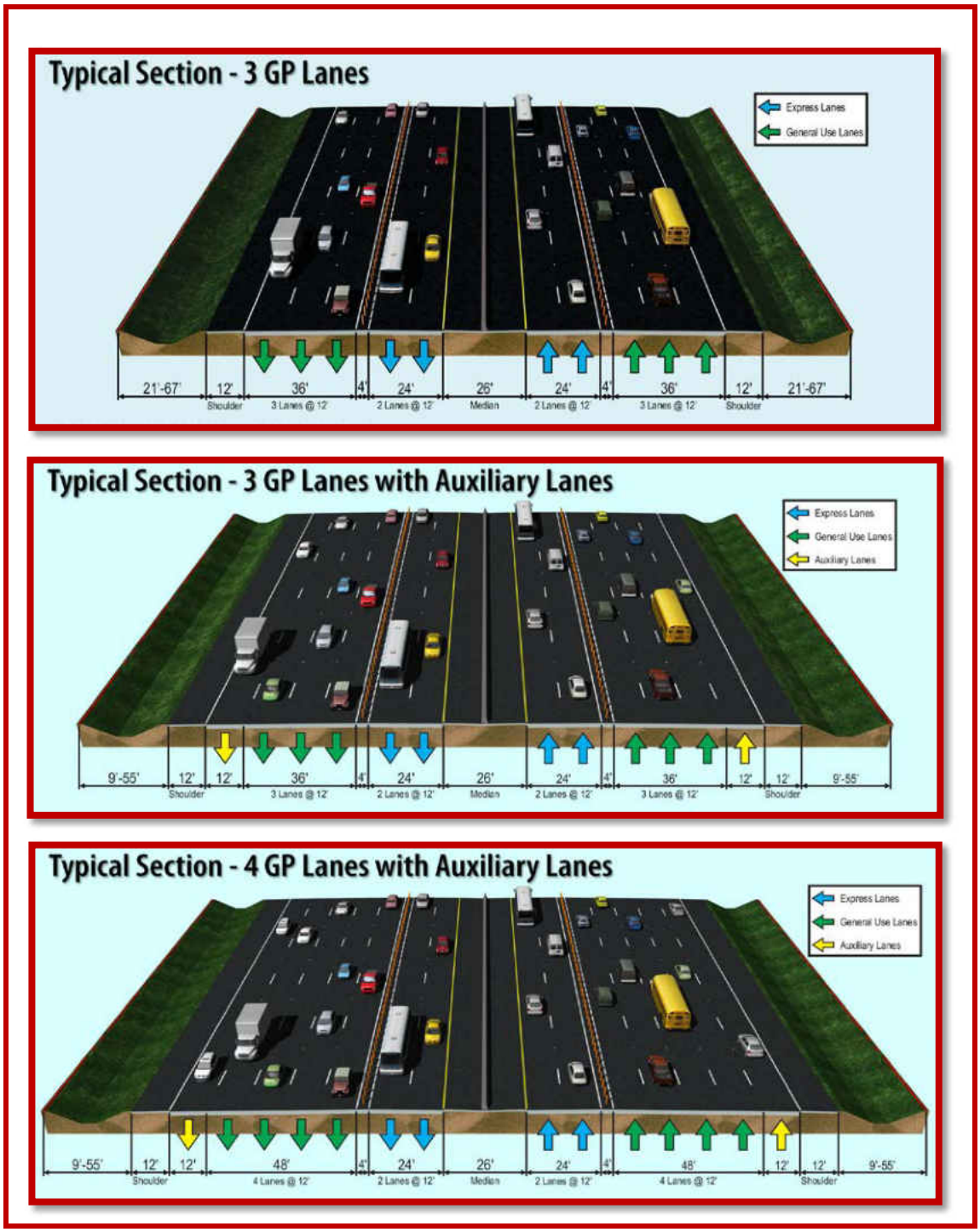


Figure 9-11: The Typical Sections on I-95 Express Phase 3 (Source: 95 Express)

Table 9-11: Estimates of Coefficients for HOV Safety Performance Functions

HOV-Specific Simple SPFs (General Purpose Lanes **only**)							
Crash Type	**Injury levels**	**Intercept**		**Log(AADT)**		**Dispersion**	**AIC**
		Estimate	**P-Value**	**Estimate**	**P-Value**	**Estimate**	
All	F+I	-9.9555	<.0001	1.0596	0.0022	0.9172	1025
LCRC*	All	-10.8371	<.0001	1.0649	<.0001	1.0401	568
Rear End	All	-17.1244	<.0001	1.7887	<.0001	3.5658	986
All Others	All	-18.7535	<.0001	2.0429	<.0001	4.4055	446

LCRC*: Lane change related Crashes*** =** (i.e. sideswipe, angle crashes, etc.)

Both methods CG and EB were used to estimate the CMFs and the results show that the treatment affected the safety performance of Free-Lanes. The treatment negatively affects safety by increasing all crash categories on Free-Lanes. This may be attributable to the fact that more traffic will use the Free-Lanes. Since the crash rates did not affect the segment as whole, and they were decreased on the HOT-Lanes, it is logic to infer that the crash rates will increase on the GPL or Free-Lanes. So, it can be concluded that the HOT-lanes are safer because they became a highway within a highway. Table 9-12 shows the CMFs for GPL or Free-Lanes only.

Table 9-12: CMFs for GPL (Free-Lanes) only

		Before-After with CG		Before-After with EB (Full SPF)	
Crash Type	**Severity Levels**	**CMF**	**SE***	**CMF**	**SE***
All	**F+I**	1.10	0.09	1.08	0.05
Rear-end	**All**	1.25	0.12	1.27	0.08
LCRC*	**All**	1.32	0.11	1.25	0.10
All other	**All**	1.18	0.14	1.22	0.11

SE* = Standard Error of the CMF

9.4.4.4 Evaluating the safety on the GPL (Free-Lanes) only using C-S method.

Similar to the previous parts, data including 156 reference segments (i.e. HOV lanes) and 20 treated segments were used and crashes that occurred on the Free-Lanes only were evaluated. Table 9-13 shows the estimates coefficients for Free-Lanes only, and Table 9-14 shows the recommended C-S - CMFs for Free-Lanes only.

Table 9-13: The coefficient estimates for C-S- GPL only.

All-Types-All Severities and PDO crashes								
Crash Type	Severity levels	Intercept		Log(AADT)		HOT-Lanes		Over Dispersion Parameter (K)
		Estimate	P-Value	Estimate	P-Value	Estimate	P-Value	
All types	All	-12.6621	<.0001	1.3254	<.0001	0.182	<.0001	0.5246
	PDO	-14.2253	0.0002	1.2235	<.0001	0.2532	0.0003	0.3254

Table 9-14: Recommended C-S - CMFs for Free-Lanes only.

All-Types-All Severities and PDO crashes			
Cross-Sectional method			
Crash Type	Severity Levels	CMF	Standard Error
All types	All	1.19	0.15
	PDO	1.28	0.10

9.5 Conclusion:

With the goal of relieving the congestion on the road network and generating revenues to meet the transportation needs, High-Occupancy-Toll (HOT) lanes has risen dramatically in the United States in recent years. In 2008, Florida converted its underused High-Occupancy-Vehicle (HOV) lanes on I-95 to HOT-lanes called 95-Express. Furthermore, dozens of future

HOT-lanes are under study. The HOT lanes offer users reliable travel times by managing traffic volume through dynamic tolls, especially during peak hours. Also, HOT-lanes give solo drivers an option to pay for the privilege of high travel speed, instead of traveling in congested general Free-Lanes.

This study investigated the safety impact of the conversion of I-95 HOV-Lanes to HOT-Lanes on the mainline of I-95 using multiple analytical techniques. It was found that the HOV-to-HOT conversion does not change crash rates for the whole segment. However there is an indication that the safety at the HOT-Lanes was significantly improved by reducing all crash rates. For example, the total and Fatal-and Injury (F+I) crashes were reduced by an average of 20 and 30 percent, respectively. On the other hand, the crash rates of all crash categories have increased on the Free-Lanes, the total and F+I crashes were increased by an average of 19 and 8 percent, respectively.

This is logical since the crash rates remain the same for the whole segment and decreased on the HOT-Lanes. Of course the rates are expected to increase on the Free-Lanes. So, it can be concluded that the HOT-lanes are safer because they became a highway within a highway. However, future research are recommended to reach a clear conclusions of the safety effectiveness of applying the HOT-lanes.

CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS

This dissertation provided an up-to-date safety effectiveness of applying multiple treatments on expressways to promote safety on the transportation network. The study utilized comprehensive databases from different sources to collect the most complete and accurate data. Multiple analytical techniques were used to achieve the objectives discussed in this dissertation.

This chapter discusses key findings, conclusions and future recommendations for expressways safety analysis.

10.1 General

An extensive data collection was conducted that included locations of multiple treatments that were applied on approximately 750 miles of expressways in Florida. Multiple sources of data available online maintained by Florida Department of Transportation were utilized to identify traffic, geometric and geographic characteristics of the locations, as well as investigation and determination of the most complete and accurate data. Different methods of observational before-after and Cross-Sectional techniques were used to evaluate the safety effectiveness of applying different treatments on expressways. The Before-After method includes Naïve Before-After, Before-After with Comparison Group, and Before-After with Empirical Bayesian.

A set of Safety Performance Functions (SPFs) which predict crash frequency as a function of explanatory variables were developed at the aggregate level using crash data and the corresponding exposure and risk factors. Results of the aggregate traffic safety analysis can be used to identify the hazardous locations (hot spots) such as traditional toll plazas, and also to predict crash frequency for untreated sites in the after period in the Before-After with EB method or derive Crash Modification Factors (CMF) for the treatment using the Cross-Sectional method.

This type of analysis is usually used to improve geometric characteristics and mainly focus on discovering the risk factors that are related to the total crash frequency, specific crash type, and/or different crash severity levels. Both simple SPFs (with traffic volume only as an explanatory variable) and full SPFs (with traffic volume and additional explanatory variable(s)) were used to estimate the CMFs and only CMFs with lower standard error were recommended.

10.2 Converting Traditional Mainline Toll Plaza to Hybrid Mainline Toll Plazas system

This section is aimed at evaluating the Safety Effectiveness of upgrading traditional mainline toll plazas to Hybrid Mainline Toll Plaza (HMTPs). Data from 98 sites located on approximately 750 miles of expressways in the State of Florida were used; thirty of them were upgraded to HMTPs. Crash data from a period of eleven years (2002-2012) were used by evaluating three years of crash data before and three years after the implementation of HMTPs.

The Safety Effectiveness of HMTPs was estimated using Observational Before-After studies including: Naïve before-after, before-after with comparison group and Empirical Bayes approaches. Negative binomial (NB) regression models were used to develop the mainline toll plazas' specific Safety Performance Functions (SPFs). The analysis focused on total crashes, property damage only crashes, fatal-and-injury crashes and crash types.

The analysis showed that the best crash modification factors for all crash categories were produced from multivariate EB method, and its results indicated that the conversion from traditional mainline toll plaza design to HMTP system resulted in an average crash reduction of 47 percent, 46 percent and 54 percent for total crashes, fatal–and-injury crashes and property damage only crashes, respectively. The use of HMTP design also significantly reduced rear end crashes and lane change related crashes (i.e. sideswipe, lost control, overturned and angle crashes) as well by an average of 65 percent and 55 percent, respectively.

Overall, the use of hybrid mainline toll plaza design was proven to be an excellent solution to several traffic operations, environmental and economic problems. The results of this study proved that the safety effectiveness across all locations that were upgraded to hybrid mainline toll plaza was significantly improved.

Choosing locations for the toll plazas that have safe distances from the interchanges and finding ways to increase the percentage of ETC users are potential means of reducing lane changes at these facilities. For practitioners it is recommended to use the multi-variable EB-CMFs results, and for future research, researchers may build on the crash modification functions that were developed in this study.

10.3 Converting TMTP or HMTP to All-Electronic Toll Collection system

All-Electronic Toll Collection (AETC) system is the future of toll collection, not just on Florida roads, but in many countries around the world. Even though the upgrade from the Traditional Mainline Toll Plaza (TMTP) to Hybrid Mainline Toll Plaza (HMTP) or to the AETC system has demonstrated measured improvements in traffic operations and environmental issues, there is a lack of research that quantifies the safety impacts of these new tolling systems.

Thus, the main objective of this study was to comprehensively evaluate the safety effects of upgrading from TMTP or HMTP to the AETC system. Data from a hundred sites located on approximately 750 miles of toll roads in Florida was used. Crash data from an eleven-year period (2003-2013) was used to evaluate the crash history of before and after the implementation of the AETC system.

The Safety Effectiveness of the AETC system was estimated using Observational Before-After studies including: before-after with comparison group and before-after with Empirical Bayes.

Negative binomial (NB) regression models were used to develop the hybrid mainline toll plaza's specific safety performance functions. These models were used to investigate different crash types and injury levels.

In this study, the results from the comparison group and the Empirical Bayes methods were very close to each other. However, the Empirical Bayes method provided more reliable estimates of crash modification factors for all crash categories (i.e. lower standard error) than the comparison group method, and the main conclusions are as follows:

1. The conversion from TMTP to the AETC system resulted in an average crash reduction of 77 percent, 76 percent and 67 percent for total crashes, fatal-and-injury crashes and Property Damage Only (PDO) crashes, respectively. This conversion also significantly reduced rear end and Lane Change Related Crashes (LCRC) by an average of 81 percent and 75 percent, respectively.

2. The conversion from HMTP to the AETC system enhanced traffic safety by 23 percent, 29 percent and 19 percent for total crashes, fatal-and-injury crashes and PDO crashes, respectively. Also, this system significantly reduced rear end crashes and LCRC by an average of 15 percent and 21 percent, respectively.

To the best of our knowledge, there were no studies that evaluated the safety benefits of using the AETC system. Thus, this section provided an up-to-date safety impact of using different toll collection systems. The results proved that the conversion from TMTP or HMTP to the AETC system significantly improved traffic safety for all crash categories, and changed toll plaza from a high risk location on the highway to a regular segment on the toll road. However, more data may be needed for future research, especially after all construction is complete and upgrades are made.

10.4 Effects of using different toll collection systems on safety performance of expressways

Expressways (toll roads) and freeways are considered an important part of any successful transportation system, because they are carrying the majority of daily trips on the transportation network. Although toll roads offer a high level of service, traditional plazas still experience many crashes, many of which are severe. Therefore, this study examines for the first time the traffic safety impact of using different designs, and diverge-and-merge areas of the Hybrid Mainline Toll Plazas (HMTP). HMTP is a plaza that combines open road tolling for electronic toll collection and plaza structure for manual payment. Also, this study helps understand the relationship between the crash frequency and several important crash-related factors and circumstances such as toll plaza types, traffic volume, and driver-age.

For this section crash data from a seven-year period (2007-2013) was investigated, and a hundred mainline toll plazas were evaluated using multiple analytical techniques. The current

data has indicated that certain designs and locations at toll plazas are more likely to experience traffic crashes than regular segments of the expressways.

The Incident Rate Ratios (IRR) value shows that the risk of crashes at design 2 (D_2) of the hybrid mainline toll plaza was approximately 19 percent higher than at the design 1 (D_1), given that all other variables are constant. The increased crash risk at D_2 may be explained by the fact that more than 81 percent of the vehicles in Florida are equipped with prepaid toll transponders (FTurnpike, 2014). Thus, the use of D_2 will cause more than 81 percent of the traffic to diverge and merge before and after the toll plaza. While in D_1, only 19 percent or less of the traffic (vehicles without transponders) will need to diverge and merge before and after the toll plaza. However, D2 could be a good temporary design depends on the percentage of vehicles with prepaid transponders. In the other words, it is dependent upon the percentage of the automatic tolling users. So, as this percentage increases, more traffic will need to diverge and merge; thus, this design becomes riskier. It should be noted that unfamiliar drivers could be confused and they may think that the Open Road Tolling lanes are in the mainline of the expressway as of design 1. So, in case of using design 2, an advanced warning system should be implemented before toll plaza.

Another finding is there is an indication that the majority of crashes occurred at diverge and merge areas before and after the HMTP. The IRR value shows that the risk of crashes at diverge areas were approximately 23 percent higher than at the merge areas, given that all other

variables are constant. The increased crash risk at diverge areas may be explained by the fact that diverge sections before the hybrid mainline toll plazas are associated with potential sudden lane change. Moreover, drivers may be distracted when they prepare to pay, search for cash or cards, and selecting either the cash or coin lane, while in the merge area they just accelerate and focus on merging with traffic, especially if the acceleration lane has a good design and signage.

The results indicated significant relationships between the crash frequency and toll plaza types, annual average daily traffic, and driver-age. This means all of these three variables significantly affect the frequency of toll plazas-related crashes. Moreover, it was found that the HMTP and the All-Electronic Toll Collection (AETC) were associated with less number of crashes than at the traditional mainline toll plaza by 44.7 and 72.6 percent, respectively. Therefore, HMTPs and AETCs are much safer than the traditional mainline toll plazas. For those agencies that cannot adopt the HMTP and the AETC systems, improving traffic safety at traditional toll plazas should take a priority.

10.5 Safety Effectiveness of Adding Highway Lighting

The literature showed that highway lighting could result in both crash and crime reduction and indicated that lighting can improve safety and security by an average of 20 to 30 percent, respectively (FHWA, 2014). However, there is a lack of research that evaluates the safety impacts of adding highway lighting to different road types. So, there is a need to assess the

traffic safety effects of this treatment. Therefore, the main goal of this section is to evaluate the safety effectiveness of the implementation of highway lighting on the Night-Time crashes on expressways. This section was divided into three approaches, 1) Evaluating the safety effectiveness of adding lighting to expressways, 2) Evaluating the safety effectiveness of adding lighting to all road types with all number of lanes, and 3) Comparing the results and providing the recommendations.

The results showed that for urban 4-lane/6-lane principal and minor arterials, adding lighting has a positive effect on crash reduction for the night-time crashes (all crash types and severity levels). Similar to all road types with all number of lanes, the safety was improved and the Before-After with EB method (using full SPFs) provided lower standard errors than the Before-After with CG method. Moreover adding roadway lighting has significantly improved traffic safety on the 4-lanes expressways by reducing the night-time crashes by an approximately 35 percent.

Overall, the Crash Modification Factors developed in this section would help officials to benefit from the extensive research in adding highway lighting to the road network, especially on expressways by providing quantitative information on crash analysis and evaluation for decision making in planning, design, operation, and maintenance.

10.6 High-Occupancy Toll (HOT) Lanes Studies

With the goal of relieving the congestion on the road network and generating revenues to meet the transportation needs, High-Occupancy-Toll (HOT) lanes has risen dramatically in the United States in recent years. In 2008, Florida converted its underused High-Occupancy-Vehicle (HOV) lanes on I-95 to HOT-lanes called 95-Express. Furthermore, dozens of future HOT-lanes are under study. The HOT lanes offer users reliable travel times by managing traffic volume through dynamic tolls, especially during congestion time. Also, HOT-lanes give solo drivers an option to pay for the privilege of high travel speed, instead of traveling in congested general Free-Lanes.

This study investigated the safety impact of the conversion of I-95 HOV-Lanes to HOT-Lanes on the mainline of I-95 using multiple analytical techniques. It was found that the HOV-to-HOT conversion does not change crash rates for the whole segment. However there is an indication that the safety at the HOT-Lanes was significantly improved by reducing all crash rates. For example, the total and Fatal-and Injury (F+I) crashes were reduced by an average of 20 and 30 percent, respectively. On the other hand, the crash rates of all crash categories have increased on the Free-Lanes,

The total and F+I crashes were increased by an average of 19 and 8 percent, respectively. This is logical since the crash rates remain the same for the whole segment and decreased on the HOT-Lanes. Of course the rates are expected to increase on the Free-Lanes. So, it can be

concluded that the HOT-lanes are safer because they became a highway within a highway. However, future research are recommended to reach a clear conclusions of the safety effectiveness of applying the HOT-lanes.

10.7 Overall

The results of this dissertation would be useful in providing expressway authorities with detailed information on where countermeasures must be implemented. This dissertation provided for the first time an up-to-date safety impact of using different toll collection systems, adding highway lighting, and the use of high-occupancy toll lanes and also developed safety guidelines for these systems which would be useful for practitioners and roadway users.

It should be noted that the use of HOT-lanes system is scheduled to be implemented in many other places in the near future. However, the results of this study showed that the crash rates reduced on the HOT-Lanes and increased on the general-purpose lanes (Free-Lanes). Therefore, there is an urgent need for more research to identify the problems, suggest solutions, and to reach a clear conclusions on the effect of the high-occupancy toll lanes on traffic safety.

LIST OF SOFTWARES

1. SAS.
2. Winbugs.
3. ArcMap
4. R.

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APPENDIX: A

Copyright Permission Letter

From: Internet <info@cfxway.com>
Sent: Thursday, July 10, 2014 4:28 PM
To: abuzwidah
Subject: RE: Expressway Maps and statistic information copyright permission

Hello,

You are welcome to use anything on our website that would be helpful to you.

Jeff Marshall
Communications Department
Central Florida Expressway Authority
(407) 690-5000
www.Facebook.com/EPASS

PLEASE NOTE: Florida has a very broad public records law (F. S. 119).
All e-mails to and from the Expressway Authority are kept as a public record.
Your e-mail communications, including your e-mail address may be
disclosed to the public and media at any time.

-----Original Message-----
From: abuzwidah [mailto:abuzwidah@knights.ucf.edu]
Sent: Thursday, July 10, 2014 6:03 AM
To: Internet
Subject: Expressway Maps and statistic information copyright permission

Dear Sir/ Madam

I am writing to request a copyright permission to use some of your useful maps and statistic information published on your website (www.oocea.com) in my PhD dissertation.

Thank you very much

Muamer Abuzwidah, M.Sc
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