Developing Safety Performance Function (SPF) and Crash Modification Factor (CMF) for Managed Lanes Separation Treatments

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DISCLAIMER

METRIC CONVERSION TABLE

U.S. UNITS TO SI* (MODERN METRIC) UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.400	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.610	kilometers	km
mm	millimeters	0.039	inches	in
m	meters	3.280	feet	ft
m	meters	1.090	yards	yd
km	kilometers	0.621	miles	mi

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	square inches	645.200	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.470	acres	ac
km^2	square kilometers	0.386	square miles	mi^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.570	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: volumes greater than 1,000 L shall be shown in m^3.				

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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16. Abstract

The goal of this project was to quantify the effects of managed lanes separation type on the safety performance of freeway facilities with managed lanes. The primary objective of the project was to develop quantitative measures that will be useful in comparing separation treatment alternatives for managed lanes.

Following a comprehensive review of the state-of-practice, performance measures, and studies conducted on managed lanes by different agencies in the U.S., data were collected and processed for study sites in Florida, Texas, and Georgia. Data collected consisted of roadway characteristics, traffic volumes, roadway geometric cross-section of the managed lanes facilities, separation types (i.e., pylons and concrete barriers), operation strategies (i.e., non-reversible managed lanes, reversible managed lanes, etc.), and crashes for the years 2015–2019. Two facilities in Florida, 95 Express and 595 Express, were analyzed, based on available crash data. The study also included seven facilities in Texas and one facility in Georgia. Overall, 137.6 total miles of managed lanes facilities were included in the analysis. All facilities have at least one managed lane operating along the general-purpose lanes. The analysis included a combined total of 44,472 crashes that occurred on the general-purpose lanes and managed lanes during the study period.

Safety performance functions (SPFs), crash modification factors (CMFs), and severity distribution functions (SDFs) were estimated. Separate crash models were developed by crash severity (i.e., fatal and injury (FI) and property damage only (PDO)) and collision type (i.e., single-vehicle (SV) and multi-vehicle (MV) crash), thus SV–FI, MV–FI, and SV–PDO, MV–PDO, to determine the predicted crash frequency for both non-reversible and reversible managed lanes facilities. Two managed lanes separation types were analyzed: tubular delineators (or tubular markers or pylons) and concrete barriers.

For non-reversible managed lanes, results indicate that FI and PDO crashes decrease with greater separation widths between the managed lanes and the general-purpose lanes in the presence of pylons. On average, MV crashes (FI and PDO) increase by 21.2% for each additional managed lane. For reversible managed lanes, results indicate that SV–FI crashes decrease in the presence of concrete barriers as separation width increases between the managed lanes and the general-purpose lanes. MV–FI and MV–PDO crashes decrease by 29.4% and 34.7%, respectively, for each additional managed lane.

The safety performance measures developed in this research could assist the Florida Department of Transportation (FDOT) as well as other transportation agencies when considering future managed lanes initiatives. In addition, the agencies could benefit from sample problems, spreadsheet application, managed lanes GIS inventory, and one-page summaries that were developed as part of this project.

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EXECUTIVE SUMMARY

Florida Department of Transportation (FDOT) has been at the forefront in adopting Transportation Systems Management and Operations (TSM&O) strategies to improve the safety and mobility of Florida's roadways. One of the strategies is the implementation of managed lanes on freeways. The Federal Highway Administration (FHWA) defines managed lanes as "highway lanes where operational strategies are proactively implemented and managed in response to changing conditions" (FHWA, 2008). Since their introduction in the late 1960s, managed lanes have been increasingly implemented across the United States (U.S.). Most managed lanes were operated as high occupancy vehicle (HOV) lanes. However, recently, states have been constructing new lanes and converting the existing HOV lanes to priced managed lanes. Currently, there are over 500 miles of priced managed lanes operating in the U.S. (Scott & McDowell, 2018). The state of Florida alone has over 80 miles of priced managed lanes, also referred to as the express lanes (ELs).

The types of separation between the managed lanes and the general-purpose lanes vary for different freeway facilities. Common separation treatments for the managed lanes include barrier separation, buffer separation with tubular delineators (or tubular markers or pylons), buffer separation with pavement marking, wide buffer separation, and grade separation. These separation treatments have varying impacts on the overall safety and operational performance of the managed lanes facilities. As such, developing safety performance measures that quantify the effects of different managed lanes separation treatments would assist FDOT when considering future managed lanes initiatives.

The goal of this project was to quantify the effects of separation type selection on the safety performance of freeway facilities with managed lanes. The primary objective of the project was to develop quantitative measures that will be useful in comparing separation treatment alternatives for managed lanes. The specific objectives included:

- Develop safety performance functions (SPFs).
- Develop crash modification factors (CMFs) for different separation treatments and other geometric attributes.
- Develop severity distribution functions (SDFs) to estimate the expected crash frequency for different crash severity levels: fatal injury, incapacitating injury, non-incapacitating injury, possible injury, and property damage only.

In addition to the SPFs, CMFs, and SDFs, the project also developed the following products:

- A geographic information systems (GIS) inventory of managed lanes in Florida which could be incorporated into the FDOT's *eTraffic* system.
- A spreadsheet application that allows the safety analysts to evaluate the safety performance of managed lanes facilities.
- A set of sample problems illustrating the applications of SPFs and CMFs developed in this research.

A comprehensive review of the state-of-the-practice, safety performance measures, and studies conducted on managed lanes by different agencies in the U.S. was performed to establish the foundation through which SPFs and CMFs for managed lanes separation types were developed. Key findings from the review of existing literature include:

- There are a variety of managed lanes facility types, including HOV lanes, high-occupancy toll (HOT) lanes, express lanes, dynamic shoulder lanes, truck lanes, interchange bypass lanes, and dual roadways in which at least one of the roadways is managed.
- Managed lanes have been implemented in over 30 states in the U.S. Florida alone has over 80 miles of priced managed lanes. Most states that have implemented managed lanes have an inventory of the existing facilities and facilities under construction or in the planning stages.
- Operation strategies for managed lanes facilities include exclusive lanes, concurrent flow lanes, and reversible lanes.
- Managed lanes are commonly constructed adjacent to general-purpose lanes. The types of separation treatments between the managed lanes and the general-purpose lanes along freeways vary among different facilities. Common separation treatments include barrier separation, buffer separation with pylons, buffer separation with pavement marking, wide buffer separation, and grade separation.
- Findings from previous studies present inconsistent results on crash rates and frequencies after the construction of managed lanes, regardless of the separation type.
- SPFs and CMFs for managed lanes facilities are generally sparse. The safety performance of HOV lanes has been studied more than the safety performance of HOT lanes and express lanes.

Data were collected for analysis to quantify the safety effects of the separation types between the managed lanes and the general-purpose lanes. Two separation treatments were studied, tubular delineators (or tubular markers or pylons) and concrete barriers. Study sites were limited to facilities with HOT lanes and express lanes, collectively called *priced managed lanes*, in Florida, Texas, and Georgia. Data collected consisted of roadway characteristics, traffic volumes, roadway geometric cross-section of the managed lanes facilities, separation types (pylons and concrete barriers), operation strategies (i.e., HOT, reversible lanes, etc.), and crashes for the years 2015–2019.

One facility in Georgia and seven facilities in Texas were included in the analysis. Only two facilities in Florida, 95 Express and 595 Express, were analyzed, based on available crash data. Overall, 137.6 total miles of managed lanes facilities were included in the analysis. All facilities have at least one managed lanes operating along the general-purpose lanes. The analysis included a combined total of 44,472 crashes that occurred on these ten managed lanes facilities during the study period.

Data processing primarily constituted segmentation, assigning crashes to segments, and preparing variables for statistical modeling. Segmentation, which involved dividing the sites into individual homogeneous segments, was the most critical, resource-intensive step and necessary to ensure homogeneity of segments in the analysis variables. The processed data were then analyzed further to obtain inferences. The analysis provided the following:

- SPFs: negative binomial models for non-reversible and reversible managed lanes freeway facilities, fatal and injury and property damage only crashes, single-vehicle and multi-vehicle crashes.
- CMFs: estimated from SPFs.
- SDFs: multinomial logistic regression for non-reversible and reversible managed lanes facilities.

Separate crash models were developed for fatal and injury (FI) and property damage only (PDO) and single-vehicle (SV) and multi-vehicle (MV). FI crashes included fatal, incapacitating injury, non-incapacitating, and possible injury severity levels. Crashes with no injury were classified as PDO. Four models (SV–FI, MV–FI, SV–PDO, and MV–PDO) were developed to determine the predicted crash frequency for both non-reversible and reversible managed lanes facilities.

The following key observations are worth mentioning from the results that are statistically significant at a 95% confidence level regarding the non-reversible managed lanes facilities:

- On average, in the presence of pylons, SV–PDO crashes decrease by 3.5% for each additional foot of lateral separation width. On the other hand, in the presence of pylons, MV–PDO crashes decrease by an average of 1.8% for each additional foot of lateral separation width.
- Similarly, in the presence of pylons, MV–FI crashes decrease by an average of 2.6% for each additional foot of lateral separation width.
- The number of managed lanes presents similar effects on MV–FI and MV–PDO crashes. On average, MV–FI and MV–PDO crashes increase by 21.2% for each additional managed lane.
- While the proportion of fatal and incapacitating injury (K + A) crashes remains nearly the same throughout the 55–65 mph posted speed limit window, the proportion of non-incapacitating injury (B) crashes increases with the posted speed limit.
- The proportions of fatal (K), incapacitating injury (A), and non-incapacitating injury (B) crashes:
    - increase at segments with ramps.
    - decrease as the separation width between the general-purpose lanes and the managed lanes increases in the presence of pylons.
    - decrease as the separation width between the general-purpose lanes and the managed lanes increases in the presence of concrete barrier.

In addition, the following key observations are worth mentioning from the results that are statistically significant at a 95% confidence level regarding the reversible managed lanes facilities:

- On average, in the presence of the concrete barrier, SV–FI crashes decrease by 2.6% for each additional foot of lateral separation width.
- On average, MV–FI crashes decrease by 29.4% for each additional managed lane. On the other hand, MV–PDO crashes decrease by an average of 34.7% for each additional managed lane.
- The proportions of fatal (K), incapacitating injury (A), and non-incapacitating injury (B) crashes:

- increase with the number of managed lanes.
- slightly increase at segments with ramps.
- decrease with the outside shoulder width on the general-purpose lanes.
- decrease with the inside shoulder width on managed lanes.

Technology Transfer Activities

Additional products were also developed to help practitioners better understand and use the research outcomes. These supplementary tools focus on reversible and non-reversible managed lanes facilities and include the following:

- Sample problems
  - Provide a step-by-step procedure for determining the total crash frequency on managed lanes facilities.
- Spreadsheet application
  - Provides a Microsoft Excel spreadsheet application to estimate the safety performance of a managed lanes facility.
- Geographic information systems (GIS) inventory
  - Provides an attribute-based inventory of seven managed lanes facilities in Florida that are currently operational.
- One-page summary sheets
  - Provide a one-page information source on separation treatments for reversible and non-reversible managed lanes facilities.

Additional Insights into the Safety Performance of Florida Express Lanes

Additional insights were provided into two managed lanes facilities in Florida, 95 Express (15.3 miles) and 595 Express (8.0 miles). The 95 Express is a non-reversible managed lanes facility separated from the general-purpose lanes by pylons, while the 595 Express is a reversible managed lanes facility separated from the general-purpose lanes by concrete barriers. Descriptive statistics on the number of crashes against crash occurrence lane, crash severity, first harmful event, and the number of vehicles involved were provided. Findings for each facility include:

95 Express Statistics

- Most crashes occurred on the general-purpose lanes only (71.7%).
- About 7.9% of crashes involved crossing over the pylons.
- Vehicle-vehicle collisions were the predominant first harmful events (88%).
- About 4.7% of crashes involved hitting the pylons as the first harmful event.
- Nearly half (53%) of crashes occurred during peak hours.
- Most crashes were PDO (78.9%).
- Most crashes involved two vehicles (72.6%).
- SV crashes account for only 9.5%, and MV crashes account for 90.5% of crashes.

595 Express Statistics

- Most crashes occurred on general-purpose lanes only (95.8%), while 3.4% of the crashes occurred on the express lanes.
- About 0.8% of crashes occurred at express lanes entry or exit points.
- More than half (59.5%) of crashes occurred during peak hours.
- Most crashes were PDO (72.8%).
- Most crashes involved two vehicles (63.7%).
- SV crashes account for only 26.0%, and MV crashes account for 74% of crashes.

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LIST OF ACRONYMS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike's Information Criterion
Caltrans	California Department of Transportation
CDA	Comprehensive Development Agreement
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
CRIS	Crash Records Information System
DFW	Dallas Fort Worth
EB	Empirical Bayes
EL	Express Lane
ESRI	Environmental Systems Research Institute
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FTE	Florida's Turnpike Enterprise
GDOT	Georgia Department of Transportation
GIS	Geographic Information Systems
GOF	Goodness-of-fit
GPL	General-purpose Lane
HCM	Highway Capacity Manual
HOT	High Occupancy Toll
HOV	High Occupancy Vehicle
HSM	Highway Safety Manual
ITS	Intelligent Transportation Systems
MLs	Managed Lanes
MNL	Multinomial Logit
MUTCD	Manual on Uniform Traffic Control Devices
NB	Negative Binomial
NCHRP	National Cooperative Highway Research Program
NLMIXED	Non-Linear Mixed
PCRRS	Police Crash Report Review System
PDO	Property Damage Only
RACS	Reversible Access Control System
RCI	Roadway Characteristics Inventory
RHINO	TxDOT Roadways Inventory
RITIS	Regional Integrated Transportation Information System
RTM	Regression-to-the-mean
SDF	Severity Distribution Function
SOV	Single Occupancy Vehicle
SPF	Safety Performance Function
SR	State Route
SRTA	State Road & Tollway Authority
TMC	Transportation Management Center
TPPPH	Turnpike Plans Preparation and Practices Handbook

TSM&O	Transportation Systems Management and Operations
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
ZINB	Zero-Inflated Negative Binomial
ZIP	Zero-Inflated Poisson

CHAPTER 1
INTRODUCTION

Florida Department of Transportation (FDOT) has been at the forefront in adopting Transportation Systems Management and Operations (TSM&O) strategies to improve the safety and mobility of Florida's roadways. One of the strategies is the implementation of managed lanes on freeways. The Federal Highway Administration (FHWA) defines managed lanes as "highway lanes where operational strategies are proactively implemented and managed in response to changing conditions" (FHWA, 2008). Since their introduction in the late 1960s, managed lanes have been increasingly implemented across the United States (U.S.). Most managed lanes were operated as high occupancy vehicle (HOV) lanes. However, recently states have been constructing new lanes and converting the existing HOV lanes to priced managed lanes. After the opening of the first priced managed lanes facility in 1995, the State Route 91 (SR-91) express lanes in California, more of these facilities have been constructed, and several others are either being planned or under construction in multiple metropolitan areas across the country. Currently, there are over 500 miles of priced managed lanes operating in the U.S. (Scott & McDowell, 2018). The state of Florida alone has over 80 miles of priced managed lanes, also referred to as the express lanes (ELs).

The types of separation between the managed lanes and the general-purpose lanes along freeways vary for different facilities. Common separation treatments for the managed lanes include barrier separation, buffer separation with pylons, buffer separation with pavement marking, wide buffer separation, and grade separation. These separation treatments have varying impacts on the overall safety and operational performance of the managed lanes facilities. As such, developing safety performance measures that quantify the effects of different managed lanes separation treatments would assist FDOT with future managed lanes initiatives.

The goal of this project was to quantify the effects of separation type selection on the safety performance of freeway facilities with managed lanes. The primary objective of the project was to develop quantitative measures that will be useful in comparing separation treatment alternatives for managed lanes. The specific objectives included:

- Develop safety performance functions (SPFs).
- Develop crash modification factors (CMFs) for different separation treatments and other geometric attributes.
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In addition to the SPFs, CMFs, and SDFs, the research also developed the following products:

- A geographic information systems (GIS) inventory of managed lanes in Florida which could be incorporated into the FDOT's *eTraffic* system.
- A spreadsheet application that allows the safety analysts to evaluate the safety performance of managed lanes facilities.
- A set of sample problems illustrating the applications of the SPFs, CMFs, and SDFs developed in this research.

This report is organized as follows:

- Chapter 1: Introduction
- Chapter 2: Literature Review
- Chapter 3: Data
- Chapter 4: Modeling Framework
- Chapter 5: Results and Discussion
- Chapter 6: Technology Transfer Activities
- Chapter 7: Safety Performance of Florida Express Lanes – Additional Insights
- Chapter 8: Summary and Conclusions

CHAPTER 2
LITERATURE REVIEW

This chapter presents a detailed literature review of managed lanes nationwide. Findings are discussed in the following sections:

- Section 2.1: Background
- Section 2.2: Introduction to Managed Lanes
- Section 2.3: Deployment of Managed Lanes
- Section 2.4: Managed Lane Separation Types
- Section 2.5: Safety Performance Measures
- Section 2.6: Safety-related Studies on Managed Lane Facilities
- Section 2.7: Summary

2.1 Background

To improve the safety and mobility of Florida's roadways, FDOT has implemented a number of TSM&O strategies throughout the state. One of the strategies is the use of managed lanes on freeways in several high traffic areas. These freeway facilities are managed by the FDOT districts and the Florida Turnpike Enterprise (FTE).

The Federal Highway Administration (FHWA) defines managed lanes as "highway lanes where operational strategies are proactively implemented and managed in response to changing conditions" (FHWA, 2008). Since their introduction in the late 1960s, managed lanes have been increasingly implemented across the U.S., mostly as high occupancy vehicle (HOV) lanes. In recent years, states have been constructing new lanes and converting the existing HOV lanes to priced managed lanes. The FHWA *Priced Managed Lanes Guide* points out several benefits of priced managed lanes, as shown in Figure 2.1 (Perez et al., 2012). After the opening of the first priced managed lanes facility in 1995, the State Route 91 (SR-91) express lanes in California, more of these facilities have been constructed, and several others are either being planned or under construction in multiple metropolitan areas across the country. There are over 500 miles of priced managed lanes operating in the U.S. and thousands of miles are under construction or in planning stages (Fitzpatrick et al., 2017; Scott & McDowell, 2018). The state of Florida alone has over 80 miles of priced managed lanes.

Managed lanes are commonly constructed adjacent to the general-purpose lanes. The types of separation between the managed lanes and the general-purpose lanes along freeways vary among facilities. Common separation treatments include barrier separation, buffer separation with pylons, buffer separation with pavement marking, wide buffer separation, and grade separation. These separation treatments have varying impacts on the overall safety and operational performance of the managed lanes facilities. As such, this research focuses on developing safety performance measures that quantify the effects of different managed lanes separation treatments. The research primarily uses data on managed lanes facilities in Florida, with data from Texas and Georgia used as a supplement where needed.

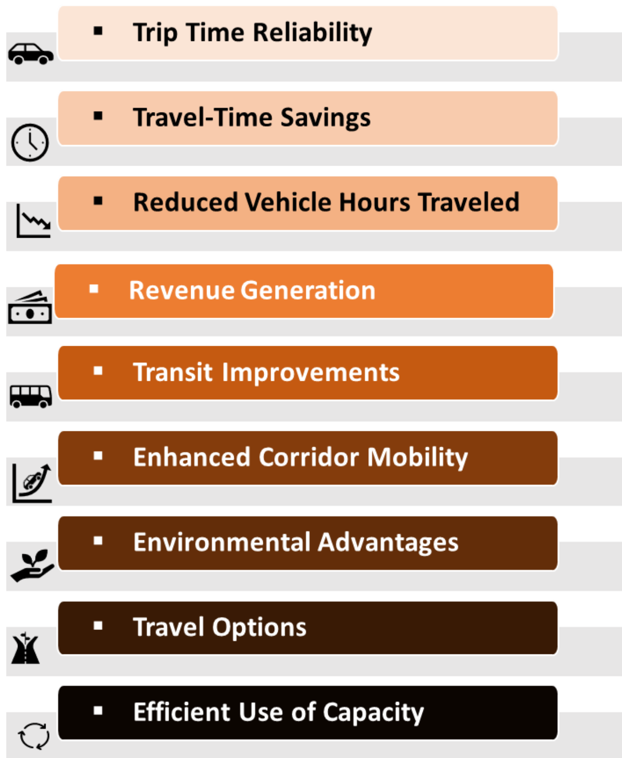


Figure 2.1: Benefits of Priced Managed Lanes (Source: Perez et al., 2012)

2.2 Introduction to Managed Lanes

Traffic congestion continues to challenge transportation agencies, resulting in investments in strategies that tackle the problem without expanding the existing right-of-way or building new roadway facilities. The advancement in transportation technologies has enabled the agencies to deploy different Intelligent Transportation Systems (ITS) infrastructure for managing the flow of traffic on access-controlled roadways. Along with the ITS solutions, several state agencies have extended the management of freeway traffic by assigning specific lanes that are proactively managed to ease freeway congestion. Although the traffic management strategies vary, based on need and local policies, these dedicated lanes are generally known as *managed lanes*.

This research reviewed the state-of-the-practice, performance measures, and studies on managed lanes conducted by different agencies in the U.S. The review establishes the foundation through which SPFs and CMFs for managed lanes separation types were developed.

2.2.1 Terminologies and Types

The FHWA defines managed lanes using three management strategies: pricing, vehicle eligibility, and access control, as shown in Figure 2.2. These lane management strategies may vary, depending on the project objective, whether the strategy is deployed on a new facility or an existing facility, the availability of right-of-way, current operational characteristics along the corridor, environmental and societal concerns, etc. Managed lanes strategies can be used independently or blended into two or more (multifaceted managed lanes facilities) to effectively manage the flow of traffic along a specific facility (FHWA, 2008). The list of facilities that can fall within the definition of managed lanes continues to increase as new combinations of management strategies are employed (Neudorff et al., 2011). The following are examples of facility types that can be considered managed lanes:

- High Occupancy Vehicle (HOV) lanes
- High Occupancy Toll (HOT) lanes
- Express lanes (ELs)
- Dynamic shoulder lanes
- Truck lanes
- Interchange bypass lanes (usually, transit, HOV, or truck only)
- Dual roadways in which at least one of the roadways is managed, etc.

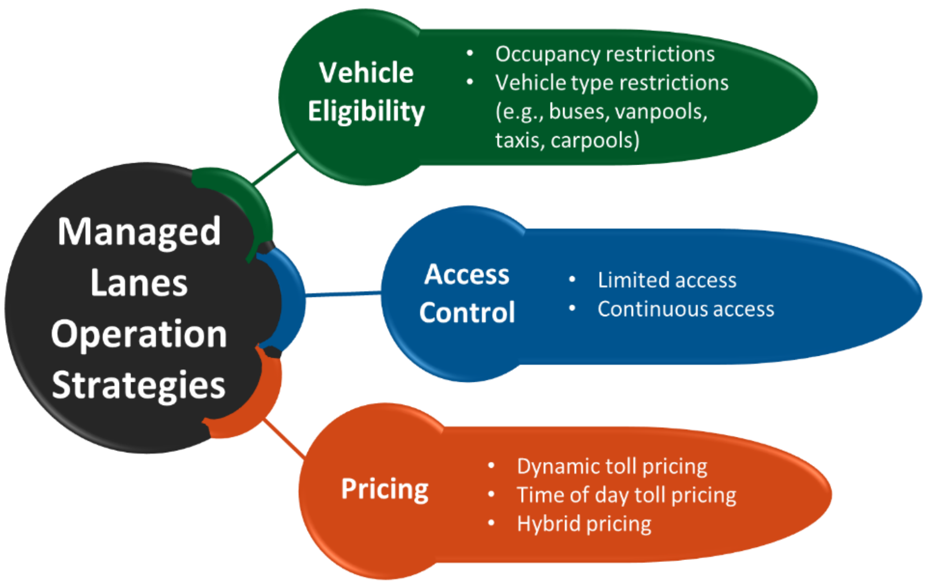


Figure 2.2: Managed Lanes Operation Control Strategies

The definitions of the first three management strategies listed above (i.e., HOV, HOT, and ELs) that form the core of this research project are given in the following subsections.

2.2.1.1 High Occupancy Vehicle (HOV) Lanes

HOV lanes are for vehicles that meet the minimum occupancy, usually 2+ or 3+ occupants (Kuhn et al., 2005; Wang et al., 2012). The increase in the number of occupants enables the facility to move more people and, consequently, reduce the overall congestion. Carpools, vanpools, and buses are some of the beneficiaries of the HOV lanes (Perez et al., 2012). HOV lanes are by far the most documented of the managed lanes strategies (Kuhn et al., 2002; Wang et al., 2012). There have been situations in which HOV lanes are underutilized because of limiting access to only HOVs. A study to evaluate the effectiveness of HOV lanes in California was conducted by Kwon and Varaiya (2008). The study documented the following findings regarding the utilization of HOV lanes.

- HOV lanes were under-utilized: 81% of HOV detectors measured flows below 1,400 vehicles per hour per lane (vphpl) during the PM peak hours.
- Many HOV lanes experienced degraded operations: 18% of all HOV miles during the AM peak hours and 32% during the PM peak hours have speeds below 45 mph for more than 10% of weekdays.
- HOV lanes suffered a 20% capacity penalty, achieving a maximum flow of 1,600 vphpl at 45 mph versus a maximum flow above 2,000 vphpl at 60 mph in the general-purpose lanes.

These findings have led some facilities to be converted from HOV lanes to HOT or express lanes.

2.2.1.2 High Occupancy Toll (HOT) Lanes

HOT lanes allow vehicles that do not meet the minimum occupancy requirement to pay a toll for access to the lane(s) (Perez et al., 2012; Wang et al., 2012; Kuhn et al., 2005). HOT lanes use both vehicle eligibility and pricing to regulate demand. Single occupancy vehicles (SOVs) can use the HOT lanes by paying a toll in exchange for travel time savings or improved trip reliability.

2.2.1.3 Express Lanes (ELs)

The term *express lanes* has several definitions, including being a highway with few access points. With respect to this project, *express lanes*, or *ELs*, reflect the condition where the lanes that are separated from the general-purpose lanes are managed with a pricing component. EL and HOT strategies are used interchangeably because they both factor in a pricing component. Although ELs focus more on pricing for both HOVs and SOVs, there may be situations where certain vehicles are exempted from paying tolls. For example, public transit buses, school buses, over-the-road buses, and vanpools, to mention a few, qualify for a toll exemption on Florida express lanes upon registration.[1] ELs also exercise access control using specific ingress and egress points. The focus of this research is on HOT and EL facilities, which were collectively placed under the term *priced managed lanes*.

2.2.2 Pricing

Priced managed lanes are operated by collecting tolls from vehicles that choose to use the lanes. Tolling policy may be customized for different facilities to achieve their specific objectives, such as to reduce emissions, collect revenue, increase the throughput, etc. Agencies may decide to use dynamic tolls, time-of-day tolls, flat toll, or flat rate, as defined by Neudorff et al. (2011) in the *Managed Lane Chapter for the Freeway Management and Operations Handbook*. For example, the 95 Express in South Florida uses congestion pricing. At this location, the toll price changes based on the level of congestion.

Drivers are informed of the toll rates in real-time in advance of each ingress, so they have enough time to decide on whether to use the managed lanes or continue driving on the general-purpose lanes (Neudorff et al., 2011). Figure 2.3 shows an example of the toll information displayed near the entrances of I-95 express lanes in South Florida. The use of electronic collection permits tolls

[1] Florida Department of Transportation (FDOT) (n.d.). Express Bus Registration. https://www.fdot.gov/traffic/its/managedlanes.shtm/express-bus-registration

to be collected from users with minimal disruption to travelers. In Florida, electronic toll collection is deployed using windshield-mounted transponders, a prepaid toll program called SunPass, or other acceptable transponders, as defined by FDOT.

Figure 2.3: Posted Dynamic Toll Price on I-95 Express Lanes in Florida
(Source: Link)

2.2.3 Operations

The operations of managed lanes facilities may vary, depending on the problem that the agency is targeting to solve. They are often deployed as a congestion management strategy. In some cases, traffic congestion is directional and occurs during specific periods, depending on the local traveling behavior. For example, MnPASS Lanes in Minnesota are typically restricted to peak hours only. Hours of operations are established to meet current traffic demand, as well as expected growth in demand on the corridor. The hours of operation are generally set for a longer period than when congestion typically occurs to help provide for a reliable trip in the MnPASS lanes, even in heavily congested conditions caused by increased demand, incidents, weather, or road work (MnDOT, 2016).

In other cases, a corridor may experience different levels of non-recurring traffic congestion throughout the day. Such inconsistent directional splits at all hours of the day are addressed by operating the managed lanes 24 hours a day, seven days a week, as is the case with 95 Express in Florida. Some agencies manage such inconsistent splits by operating the ELs only on weekdays (i.e., Monday – Friday), a practice common in Texas and California. All scenarios require managed lanes operational strategies tailored to tackle the problem at hand. Common ways of operating managed lanes facilities include (Kuhn et al., 2005):

- Exclusive managed lanes,
- Concurrent flow managed lanes, and
- Reversible managed lanes.

Exclusive Managed Lanes: Operations for exclusive managed lanes may consist of two-way facilities or reversible lanes physically separated from the general-purpose lanes. They often have limited access and may have their own direct ingress and egress treatments (Kuhn et al., 2002; Kuhn et al., 2005). There is no interaction between traffic traveling on the managed lanes and traffic in the general-purpose lanes. An example of exclusive managed lanes is the 75 Express in Florida, where the managed lanes are constructed in the median of the freeway facility, as shown in Figure 2.4.

Figure 2.4: Exclusive Express Lanes along I-75 in Florida
(Source: Link)

Concurrent Flow Managed Lanes: Concurrent flow managed lanes operate in the same direction of travel as the general-purpose lanes for both directions of traffic, as shown in Figure 2.5. A buffer or painted line may be used to separate the managed lanes from the general-purpose lanes. The facility may have limited or continuous access to the managed lanes. This operation presents some interaction between traffic in the managed and general-purpose lanes. When the general-purpose lanes are congested, drivers in the managed lanes can readily observe the slow traffic in the adjacent lanes and may feel uncomfortable passing the congested traffic at a high-speed differential. This impact on the interaction is referred to as the frictional effect (Neudorff et al., 2011; Wang et al., 2012).

Figure 2.5: Concurrent Flow Express Lanes along I-75 in Florida
(Source: Link)

Reversible Managed Lanes: Contraflow or reversible managed lane facilities consist of freeway facilities with lanes operated directionally based on the peak direction of traffic. This operation requires the use of barriers to separate the managed lanes from the general-purpose lanes. In contraflow, the lane(s) is separated from the peak direction of travel by a changeable barrier or posts, while reversible lanes may have a permanent separation from the general-purpose lanes.

I-595 Express (Figure 2.6) in Florida operates as a reversible variable toll managed lane (eastbound in the AM and westbound in the PM). The corridor serves express traffic to/from the I-75/Sawgrass Expressway from/to east of SR-7, with a direct connection to the median of Florida's Turnpike. The reversible lanes are opened on weekdays to eastbound traffic between 4:00 AM and 1:00 PM and to westbound drivers between 2:00 PM and 2:00 AM. They are closed between 1:00 PM and 2:00 PM and between 2:00 AM and 4:00 AM for routine maintenance. On weekends, the ELs are normally open in the eastbound direction only. Another example is the I-5 corridor in Seattle, Washington, which has a set of reversible express lanes separated from the general-purpose lanes by a concrete barrier.

One of the drawbacks of reversible flow managed lanes is that they require time to clear out the lanes prior to switching directions, compared to bi-directional systems, which flow continuously in both directions (GDOT, 2010a). Appendix A shows a matrix of advantages and disadvantages of reversible managed lanes compared to concurrent flow managed lanes on transferability and environmental and social aspects.

Figure 2.6: I-595's Reversible Lanes in Florida Separated by Concrete Barriers
(Source: Google Earth)

2.2.3.1 Continuous vs. Limited Access

According to the *Managed Lanes Handbook* (Kuhn et al., 2005), managed lanes often constitute three types of access points: direct access ramp, slip ramp, and at-grade access (i.e., continuous, or limited access). This research focused on at-grade access of managed lanes, the most common type of access implementation (Wang et al., 2012). Continuous access allows eligible vehicles to enter and leave the managed lanes facility at any point, and also allows for constant lane changing. No weave, acceleration, or deceleration lane is provided. Limited or restricted access regulates the locations where vehicles are allowed to enter and leave the managed lanes facility (MnDOT, 2016). The type of access and the number of access points can influence the type of separation to be used for managed lanes facilities and impact the interaction between vehicles in the managed lanes and the general-purpose lanes. The type of separation also affects the length of opening needed, since barriers require crash attenuators on their blunt ends, while delineators and pavement markings are more forgiving (Wang et al., 2012).

The *MnPASS Lanes Design and Implementation Guidelines* manual (MnDOT, 2016) suggests the use of continuous access design with access restriction on selected areas, such as high weaving volume, ramp volume, average daily volume, or directional traffic demand. The argument is supported by the experience gained from the I-394 MnPASS Lanes that were originally designed with restricted access to provide dedicated ingress/egress locations for better traffic flow. The goal at the time was to avoid unnecessary weaving maneuvers which can foster traffic shockwaves and crashes. A later study of the MnDOT MnPASS lane facilities found that continuous access (I-35W) and restricted access (I-394) designs were comparable in operational characteristics, with no difference in safety performance (Stanitsas et al., 2014). However, continuous access managed lanes may not be efficient for priced managed lanes (i.e., HOT lanes and ELs) due to management challenges.

2.2.4 Planning, Management, and Operation

The active management and operation of managed lanes facilities is not a single agency task. To achieve the goals of managing congestion, improving reliability, providing travel time savings, enhancing safety, etc., different stakeholders are involved. Stakeholders include road users, ITS specialists, roadway design engineers, and transit agencies, to mention a few. Neudorff et al. (2011) presented a list of agencies and other stakeholders involved in the development and operations of managed lanes, as shown in Table 2.1.

Table 2.1: Agencies and Groups Involved in Managed Lanes Development and Operations

Agency / Group	Potential Roles and Responsibilities
State Department of Transportation	• Overall project management • Developing operations and enforcement plans • Designing and operating the facility • Conducting or assisting with the collection of tolls • Conducting or assisting with customer relations • Staffing multi-agency team/committee • Monitoring the facility performance
Transit Agency	• Overall project management or supporting role • Developing or assisting with operations and enforcement plans • Bus and vanpool operations Enforcement or assisting with enforcement • Monitoring or assisting with monitoring facility performance
State / Local Police	• Assist with the development of operations, enforcement, and management plans • Responsible for enforcement of managed lanes facilities • Responsible for safety management during incidents • Coordination with judicial personnel
Local Municipalities	• Arterial connections to managed lanes facilities • Developing or assisting with the operations and enforcement plans • Conducting or assisting with the design and operations of the facility • Staffing a multi-agency team or participating on the team
Rideshare Agency	• Assist with the development of operations and enforcement plans • Participate in a multi-agency team
Toll Agency	• Developing or assisting with the operations and enforcement plans • Conducting or assisting with the design and operations of the facility • Developing the toll collection subsystems • Conducting customer relations • Monitoring the facility performance
Metropolitan Planning Organization	• Assist in multi-agency coordination • Ensure projects are included in necessary planning, programming, and environmental documentation • Prepare and approve policies concerning managed lanes governance
Federal Agencies	• Provide funding support • Approval of planning, programming, design, environmental, and operational documentation

Source: Neudorff et al., 2011.

2.3 Deployment of Managed Lanes

The successful implementation of the managed lanes in a few states sparked the need to construct more of these facilities throughout the country. Managed lanes were first implemented in California, in 1962, when an exclusive bus-only lane was established as a temporary traffic management strategy during the reconstruction of the San Francisco-Oakland Bay Bridge. A few years later, other strategies, such as HOV and HOT lanes were implemented. Managed lanes strategies have been implemented in several states in the U.S. Most of these states have an inventory of existing facilities and facilities under construction or in the planning stages. Several reports have provided the lists and inventoried managed lanes for states or a combination of states.

In Florida, express lanes are increasingly being constructed to relieve congestion. These facilities include congestion pricing, have vehicle restrictions, and may be operated as reversible flow or bi-directional facilities to best meet peak demands. These adjustments allow FDOT to offer drivers reliable mobility choices, deliver long-term solutions to managing traffic flow, decrease air pollution, and support transit usage (FDOT, 2015). FDOT has several express lane facilities either in operation, under construction, or in the planning phase. The express lanes in Florida have been deployed in four major regions, Northeast Florida, Central Florida, West Central Florida, and Southeast Florida, as shown in Figure 2.7, and further detailed in Appendix B.

Express lanes that are operational cover about 80 miles along the Interstates I-95, I-75, I-295, I-595, and the Palmetto Expressway. Note that I-595 is a reversible lanes facility. The I-95 HOV lanes in South Florida are being converted into express lanes in phases. Phase 1 and Phase 2 are currently operational, while Phase 3 of the conversion is under construction. Phase 1 extends approximately seven miles from SR-112 to the Golden Glades interchange. Phase 2 extends the express lanes to the north another 14 miles from the Golden Glades interchange to Broward Boulevard. Toll collection began in December 2008 for Phase 1 northbound and in January 2010 for Phase 1 southbound. Phase 2 began toll collection in October 2016. FDOT districts that maintain the express lanes periodically publish performance reports to keep track of the facilities and maintain the required operational and safety requirements. The reports are available to the public through the FDOT express lanes websites. Table 2.2 summarizes the express lanes in Florida, with most facilities located in districts 4 and 6 and a few in districts 2, 5, and 7. Most of the express lanes in Florida are operated for 24 hours a day all week, except for the I-595 reversible lanes.

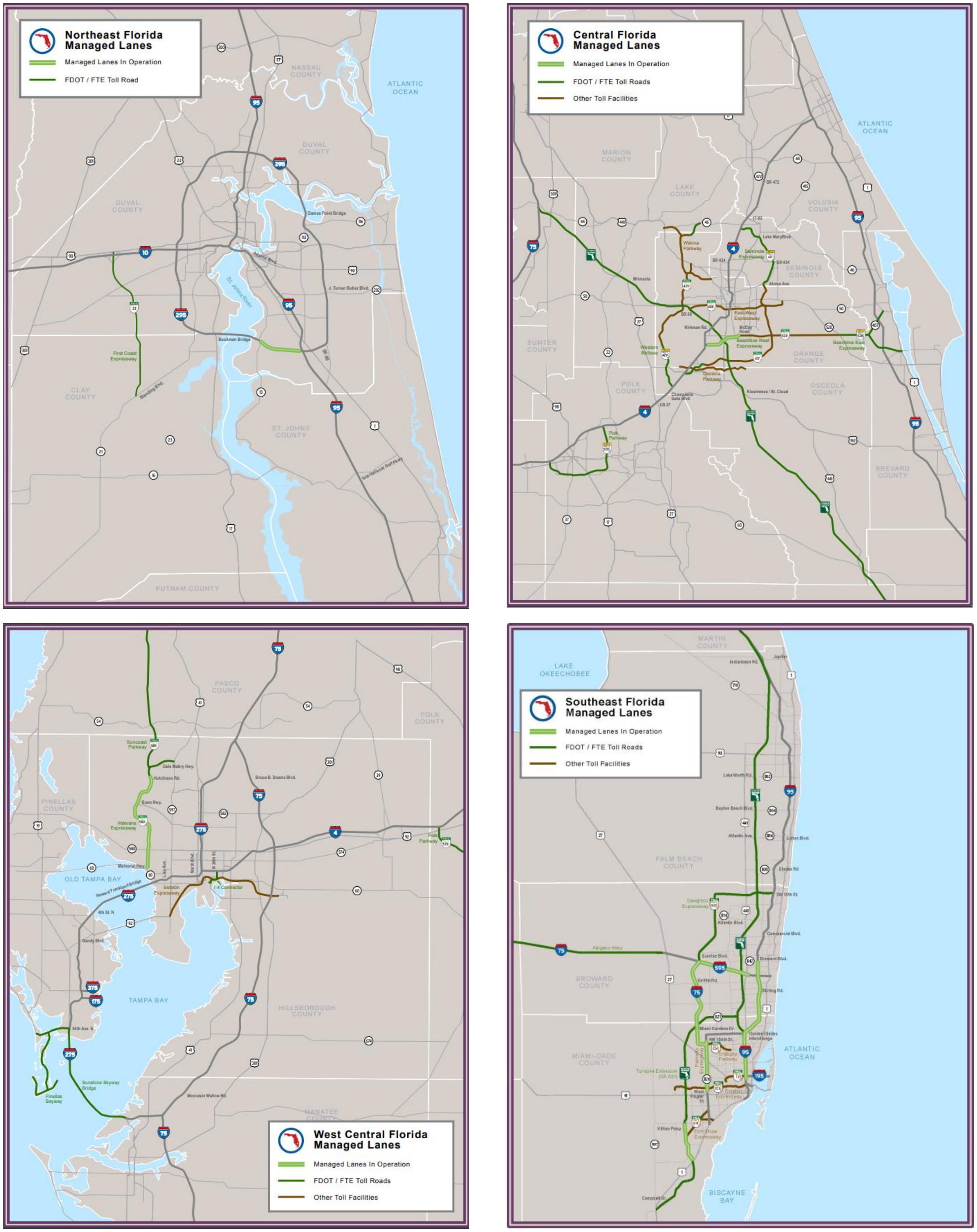


Figure 2.7: Express Lane Network in Florida [2]

[2] Florida Department of Transportation (FDOT). Managed Lanes. https://www.fdot.gov/traffic/its/managedlanes.shtm

Table 2.2: Existing Express Lane Facilities in Florida

Name	Length (miles)	FDOT District	From	To	Separation Type	Opened	No. of Lanes [b]
I-95 Phase I	7	6	Junction of I-95 and SR-836/I-395	Golden Glades interchange	Pylons	2008	2 (4)
I-595[a]	10	6	I-75/Sawgrass Expressway	Turnpike Mainline	Concrete Barrier	2014	3 (4)
I-95 Phase II	14	4&6	Golden Glades interchange	Broward Boulevard	Pylons	2016	1 to 2 (4)
Veterans Expressway	9	7	Hillsborough Ave	Dale Mabry Hwy	Pylons	2017	1 (3)
Beachline Expressway	4	5	I-4	Turnpike Mainline/SR-91	Double skip striping	2019	2 (2)
I-75	11	6	Miami Gardens Drive	I-595	Constructed in the median	2019	2 (4)
I-75	4	6	Palmetto Expressway	Miami Gardens Drive	Constructed in the median	2019	1 (4)
Palmetto Expressway	9	6	West Flagler Street	NW 154th Street	Lane markers	2019	2 (4)
I-295	5	2	I-95	Buckman Bridge	Pylons	2019	2 (3)

Note: [a] reversible lanes; [b] EL - express lanes (GPL - general-purpose lanes); the number in parentheses provides the number of general-purpose lanes. ELs (GPLs)[b]

Texas has been at the forefront of deploying and documenting several research findings on managed lanes facilities. Most of the research has been conducted by Texas A&M Transportation Institute (TTI), as evidenced by several published documents dating as far back as the 1960s. In Texas, most managed lanes contain no fee component. Where fee-based managed lanes exist, they offer drivers the option and convenience of bypassing congestion on adjacent the general-purpose lanes. Texas Department of Transportation (TxDOT), or in some cases project developers, manage the lanes, and entities, such as a toll road authority, may provide billing, either by mail or electronically, with reduced rates for vehicles equipped with any Texas transponder (such as TxTag, TollTag, or EZ Tag). The list of managed lanes in Texas and the associated details are provided in Appendix C.

2.4 Managed Lanes Separation Types

The geometry of managed lanes varies for different facilities. Since managed lanes are often built within existing freeway facilities, in many cases, right-of-way limitations and roadway constraints may make it difficult to meet all desirable design standards, and hence, compromise the safety of the facilities. For instance, research suggests that wider lanes on managed lanes facilities are associated with fewer crashes (Fitzpatrick & Avelar, 2016). Jang et al. (2013) documented an evaluation of the relationship between cross-section design (i.e., lane width, shoulder width, and buffer width) and safety performance for HOV lanes using 153 miles of HOV lanes in Southern California for the years 2005 to 2007. The authors stated that their findings could be used to determine optimal cross-sectional design elements that minimize the expected crash occurrences. A case study discussion was provided to demonstrate the applicability of the proposed method. For one example, based on the selective use of available geometric space, they recommended that a 12 ft lane and 10 ft left shoulder be converted to a 3.6 ft buffer, 12 ft lane, and 6.4 ft left shoulder.

The type of separation between the managed lanes and the general-purpose lanes is another geometric feature that influences the safety performance of managed lanes facilities. Several studies have evaluated the safety performance of managed lanes by relating crash occurrences to the geometric configurations of the facilities. Research has shown that the safety of managed lanes facilities has a strong correlation with the cross-section of the facility, type of separation (i.e., buffer or barrier), and the access design of the managed lanes (Eisele et al., 2006; Fitzpatrick & Avelar, 2016).

Several reports provide more details on separation treatments for managed lanes, including the National Cooperative Highway Research Program (NCHRP) 03-96–*Analysis of Managed Lanes on Freeway Facilities* (Wang et al., 2012) and the *Guidance for Effective Use of Pylons for Lane Separation on Preferential Lanes and Freeway Ramps* (Kuchangi et al., 2013). Several factors contribute to the selection of a managed lanes separation treatments, including issues of design specifications, costs, access, operations, enforcement, public perception, and safety (Michael, 2011; GDOT, 2010b). The goal of this research is to establish data-supported guidance on safety for different separation treatments by developing SPFs, CMFs, and SDFs.

2.4.1 Separation Treatments

The earliest priced managed lanes facilities implemented in the U.S. all featured continuous concrete barriers. However, the success of the I-394 MnPass lanes, which opened in 2005 and featured eight miles of painted buffers, has led to several new projects that do not have barrier separation. For example, the I-35W managed lanes, opened in Minneapolis in 2010, use a near-continuous access policy with skip striping to designate access, while the I-85 express lane facility in Atlanta incorporates a camera-based "virtual barrier system" to discourage weaving. The I-95 express lanes in South Florida had initially installed white flexible delineators, spaced at 20 ft center to center. Due to numerous crashes caused by driver confusion, FDOT enhanced visibility by changing the pylon color from white to orange. FDOT also reduced the delineator spacing to 10 ft centers since numerous vehicles were weaving in and out of the 20 ft spaced delineators. Reports indicate a significant reduction in crashes after implementing these changes (Kuchangi et al., 2013).

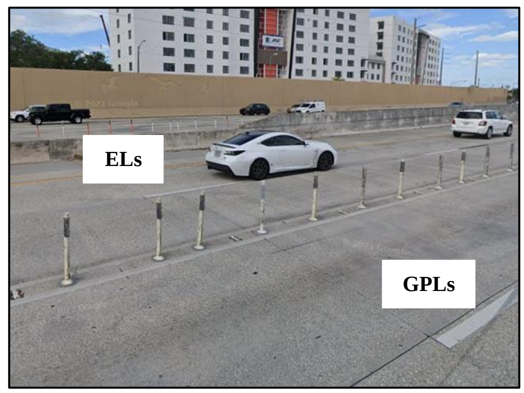
Since concrete barriers provide a physical barrier between the express lanes and the general-purpose lanes, they have been shown to reduce violations, especially regarding entering and exiting the express lanes at undesignated locations (Perez et al., 2002). Barrier separation is typically more expensive than buffer separation, but guarantees low toll violation rates and eliminates potential weaving movements between express and the general-purpose lanes. Unlike concrete barriers, pylons have been proven to be less expensive to install, require less right-of-way, and allow emergency and maintenance vehicles to traverse between the express lanes and the general-purpose lanes (Perez et al., 2002). Because of being traversable, pylons encourage risky behavior commonly referred to as *lane diving*, where traffic moves in and out of the express lanes at undesignated locations. This behavior increases the cost of maintaining the pylons and imposes a safety threat to both the express lane and the general-purpose lane traffic.

While concrete barriers and pylons provide some form of physical barrier between the express lanes and the general-purpose lanes, double solid white lines only provide a psychological barrier between the two types of lanes. The absence of the physical barrier on roadways with express lanes separated by double solid white lines may encourage lane diving, especially when express lanes are underutilized and when there is a significant variation in speed between the express lanes and the general-purpose lanes (Srinivasan et al., 2015).

Wide buffers, on the other hand, offer less opportunity for sideswipes and create a substantial sense of separation, but emergency vehicle access may be difficult, especially with soft grassed buffers. Additional right-of-way is also needed when wide buffers are used (Michael, 2011). Appendix D provides a summary comparison table of separation types for managed lanes extracted from the white papers by Michael (2011) and GDOT (2010b). Separation types used for managed lanes in Florida are shown in Figure 2.8, and include:

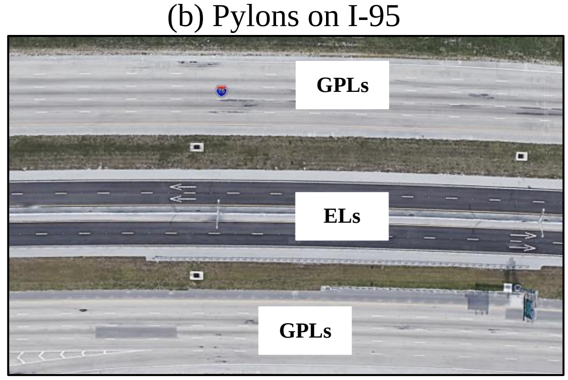
a) Barrier - a concrete barrier separates MLs from GPLs,
b) Pylons - pylons separate MLs from GPLs,
c) Buffer - only pavement markings (e.g., double dotted lines or double solid lines) separate MLs from GPLs, and
d) Wide Buffer – a wide buffer (e.g., median) separates MLs from GPLs.

(a) Concrete Barrier Separation on I-595



(b) Pylons on I-95

(c) Buffer Separation with Pavement Marking on Beachline Expressway



(d) Wide Buffer Separation on I-75

Figure 2.8: Managed Lanes Separation Types in Florida

2.4.2 Guidelines Specific to Separation Types

Neudorff et al. (2011) suggest that the main safety concern on managed lanes facilities is the speed differentials between the managed lanes and the general-purpose lanes. The authors argue that guidelines have been in favor of barrier separation between concurrent traffic streams as the safest treatment, although research results in terms of crash rates do not support this argument. The FHWA provides design standards and guidelines for most of the managed lanes elements. In addition to those standards and guidelines, different states have developed requirements for managed lanes design, e.g., *HOV Guidelines for Planning, Design, and Operations, Traffic Operations Policy Directive*, by Caltrans, the *MnPASS Lanes Design and Implementation Guidelines* by MnDOT, etc. Since the focus of this research is on separation types used for managed lanes, the different design guidelines for managed lanes separation types from selected literature are presented in the following subsections.

2.4.2.1 Pylons (also called Tubular Markers or Tubular Delineators)

Pylons can be used in buffer separated managed lanes as a series of highly visible, reflective, lightweight plastic tubes. Two primary types of pylons have been used in managed lanes facilities: pylons affixed to a mountable plastic raised curb, and individual plastic pylons attached to the roadway with adhesive, as shown in Figure 2.9(a) and Figure 2.9(b), respectively. Other than deciding whether to use a curb-mounted pylon or a pavement mounted assembly, key considerations in deploying pylons as a managed lanes separation treatment include:

- pylon spacing,
- buffer width,
- pylon height,
- pylon color and retro-reflectivity for nighttime visibility, and
- running length (mostly for freeway ramp to frontage road installations).

Considerations extracted from the *Guidance for effective use of pylons for lane separation on preferential lanes and freeway ramps* report by Kuchangi et al. (2013) are summarized in the following subsections.

(a) Mountable Raised Curb Pylon Separation on the I-95 Express

(b) Individual Pylon Separation on the SR-91 Express Lanes

Figure 2.9: Types of Pylons (Tubular Delineators)
(Source: Perez et al., 2012)

2.4.2.2 Longitudinal Pylon Spacing

On roadway segments with a history of a high number of crashes or a high rate of violations, a spacing of 10 ft is recommended. On roadway segments where strict enforcement is provided and violations are minimal, a larger pylon spacing of up to 20 ft may be considered. Near the entry and exit access locations on managed lanes, a minimum of 10 ft spacing is recommended. The first few pylons at access locations on managed lanes are the ones most hit by motorists. For freeway ramp-frontage road lane separation or access restriction applications, a pylon spacing of 6 ft is acceptable in most cases. The spacing of 3 ft may be used to provide a more restrictive barrier configuration to deter motorists from crossing the pylons. When curb-mounted pylons are used, drainage requirements at a specific site may influence the minimum spacing between the pylon units.

2.4.2.3 Buffer Width

Placement of pylons resulting in a 4 ft to 8 ft distance from pylon to the edge of travel lane should be avoided. Providing 4 ft to 8 ft of the shoulder is discouraged, as a vehicle taking refuge on a shoulder of that width partially encroaches on the adjacent travel lane, but not so much as to slow vehicle speeds in the travel lane. When buffer width is more than 10 ft on one side of the pylons, it may be confused as a travel lane. If geometry allows, larger buffer width on curves is recommended, with an unbalanced buffer provided as needed for more encroachment space on curves (e.g., buffer on the right side of a curve when the curve is to the left and pylons are on the right; or buffer on the left side of a curve when the curve is to the right and pylons are on the left).

2.4.2.4 Pylon Height and Color

The Manual on Uniform Traffic Control Devices (MUTCD) states that the tubular markers shall not be less than 28 inches in height when used on freeways or other high-speed facilities (FHWA, 2009). Agencies are found to commonly use 36-inch, 42-inch, and 48-inch pylons for lane separation applications. White, yellow, and orange pylon posts have been typically used for lane separation and channelization applications on roadways.

2.4.3 Concrete Barrier Separation

Barrier separation involves separating the managed lanes from the general-purpose lanes using a rigid barrier, such as a concrete barrier. Shoulders are provided on both sides of the barrier. Physical barriers are preferred for priced managed lanes, as they provide better access control and are more effective at reducing violations. They include continuous concrete barrier walls or movable barrier walls separating the managed lanes from the general-purpose lanes (FDOT, 2015). Skowronek et al., (2002) also proposed that barrier-separated HOT lanes may offer better safety compared to buffer-separated HOV lanes, primarily because of restricted access.

Concrete barrier separations, unlike buffers, require extra shoulder space to allow for the removal of incapacitated vehicles, the passage of emergency vehicles, and the clearance of accidents from the general flow (GDOT, 2010b). Hlavacek et al. (2007) suggest that, among delineation techniques, barriers have a unique property, in that they are unaffected by speed differentials. Because errant drivers cannot simply cross the barrier at any time, users of the managed lanes are likely to feel much more comfortable with a higher speed differential. Barriers are, therefore, the delineation technique of choice for congested freeways. Barrier-separated lanes need to have a sufficient cross-section to allow drivers to get out of the way of an incident. For barrier-separated facilities, 18 ft is suggested as an absolute minimum, amounting to a 12-ft lane, a 4-ft shoulder on one side, and a 2-ft shoulder on the other. A range of 22 ft to 26 ft is considered ideal: 12-ft main lane, one 8-ft shoulder, and one 2-ft shoulder (Hlavacek et al., 2007). If this amount of space is available, the barrier is probably the preferred delineation technique. The FHWA's *A Guide for HOT Lane Development* suggests that 18 ft, consisting of a 12-ft travel lane, 4-ft shoulder, and 2-ft barrier, is the minimum amount of room needed for a barrier-delineated facility. The guide adopts the NCHRP 414 and several managed lanes current practices nationwide. Figure 2.10 shows the typical cross-section for express lanes in Florida (FDOT, 2018).

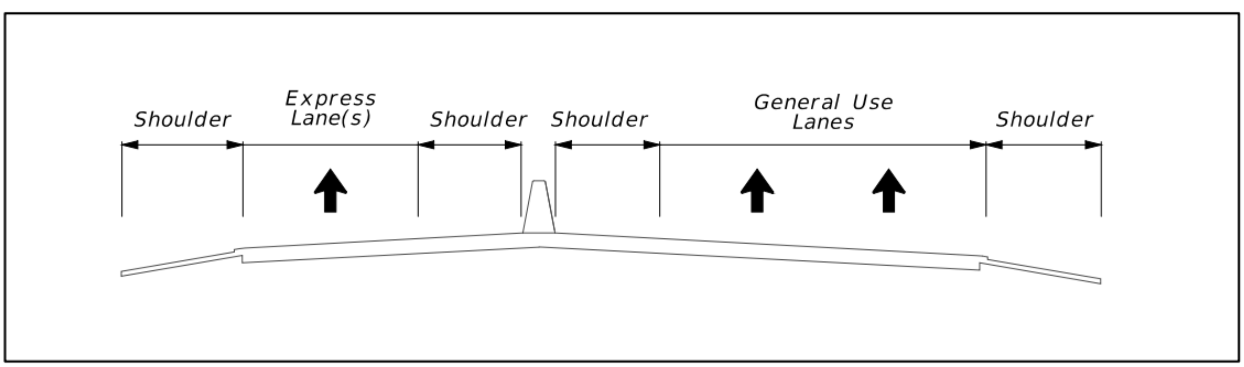


Figure 2.10: Express Lanes Barrier Separation Typical Section (FDOT, 2018)

2.4.4 Pavement Marking

Pavement markings are simple to install, inexpensive, and blend well aesthetically with the markings between other lanes (Hlavacek et al., 2007). FDOT's *Managed Lanes Handbook* (FDOT, 2015) mentions that the references available to assist in the design of express lane pavement markings are the MUTCD, the FDOT Traffic Engineering Manual, *Turnpike Plans Preparation and Practices Handbook* (TPPPH) guide drawings, and FDOT's Design Standards. Within the MUTCD, express lanes are referred to as priced managed lanes, and pavement marking guidelines are categorized under Chapter 3D – *Markings for Preferential Lanes*. When a general-use lane transitions directly into an express lane, it is recommended that pavement messages reading "EXPRESS" and "ONLY" be placed in advance of express lane access points. These messages should be placed with overhead advance guide signs.

2.5 Safety Performance Measures

A specific objective of this research involved developing performance measures that will be useful in comparing separation treatment alternatives for managed lanes. Discussed in the following subsections, these safety performance measures include:

- Safety performance functions (SPFs)
- Crash modification factors (CMFs)
- Severity distribution functions (SDFs)

2.5.1 Safety Performance Functions (SPFs)

An SPF is a regression equation that is developed to determine the predicted crash frequency at a location usually as a function of Annual Average Daily Traffic (AADT) with segment length, and in some cases, AADT with other roadway geometric or intersection characteristics, such as lane width, shoulder width, degree of curve, or any other specific condition (e.g., the presence of turn lanes or traffic control at intersections). The *Highway Safety Manual* (HSM) outlines at least three different ways in which SPFs can be used by jurisdictions to make better safety decisions (AASHTO, 2010). One application, discussed in Part B of the HSM, is to use SPFs as part of network screening to identify sections that may have the best potential for improvements. The second application, discussed in Part C of the HSM, is to use SPFs to determine the safety impacts of design changes at the project level. The third application is the use of SPFs in determining the safety effects of engineering treatments (Srinivasan et al., 2015).

The predictive models discussed in Part C of the HSM use the general form shown in Equation 2.1.

$$N_{predicted,\,x} = N_{spf,\,x} \times (CMF_{1,\,x} \times CMF_{2,\,x} \times \ldots \times CMF_{n,\,x}) \times C_x \qquad (2.1)$$

where,

$N_{predicted,\,x}$ = predicted average crash frequency for a specific year for site type *x*,

$N_{spf,\,x}$ = predicted average crash frequency for a specific year for site type *x* for base conditions,

$CMF_{n,x}$	=	crash modification factors for *n* geometric conditions for site type *x*, and
C_x	=	calibration factor to adjust for local conditions for site type *x*.

As can be observed from Equation 2.1, the three key components required to estimate predicted average crash frequency are the base SPFs, CMFs, and a calibration factor. The base SPF is a statistical regression model that establishes a relationship between crash occurrence and the associated factors under specific base conditions. Base conditions usually correspond to given geometric characteristics, roadway environment, and traffic control features of sites. The base SPFs in the HSM estimate the predicted average crash frequency as a function of AADT and segment length for roadway segments. Mathematically, the base SPF for segments can be expressed as shown in Equation 2.2.

$$N_{spf\text{-}rs} = e^{\alpha 0} \times AADT^{\alpha 1} \times L \tag{2.2}$$

where,

$N_{spf\text{-}rs}$	=	predicted average crash frequency per year for a roadway segment with base conditions,
AADT	=	average annual daily traffic (vehicles per day) on a roadway segment,
L	=	segment length (miles),
$\alpha 0$	=	intercept of the model, and
$\alpha 1$	=	coefficient of AADT.

In cases where sites deviate from the pre-defined base conditions, CMFs are multiplied, with the predicted crash frequency calculated using the base SPFs to account for the effects of non-base conditions on predicted crashes. The CMFs are calculated as the ratio of the effectiveness of one condition to that of another condition. Finally, a calibration factor is used “to account for differences between the jurisdiction and time for which the predictive models were developed and the jurisdiction and period to which they are applied” (AASHTO, 2010).

2.5.2 Crash Modification Factors (CMFs)

A CMF is a multiplicative factor used to compute the expected number of crashes when a specific countermeasure or a change in a design or operational characteristic is implemented at a specific site. It represents the relative change in crash frequency due to a change in one specific condition when all other conditions and site characteristics remain constant. A CMF of less than one (i.e., < 1) indicates a reduction in the crash frequency, while a CMF of greater than one (i.e., > 1) indicates an increase in the frequency of crashes when a particular design or operational characteristic or roadway geometric characteristic deviates from the base conditions. The crash reduction that might be expected after implementing a given countermeasure at a specific site may also be expressed as a percentage commonly known as a crash reduction factor (CRF). Both CRFs and CMFs are commonly used in the field of traffic safety and are related by a simple mathematical formula: CMF = 1 - (CRF/100). For example, if a particular countermeasure is expected to reduce the number of crashes by 20% (i.e., the CRF is 20), the CMF will be 1 - (20/100) = 0.80. The preferred methods for developing CMFs can be classified into two broad categories: before-after study, and cross-sectional study. The following subsections discuss these two methods in detail, and Table 2.3 lists the pros and cons of the two methods.

2.5.2.1 Before-after Study

In the before-after approach, the CMF is estimated from the change in crash frequency between the periods before and after the implementation of a treatment (construction of managed lanes, in this case). There are various types of before-after studies, which vary in the use of the untreated group to account for the confounding factors. Four common types of before-after studies (Lord et al., 2021) are (1) naïve before-after study, (2) before-after study with comparison group, (3) before-after study with the empirical Bayes (EB) approach, and (4) before-after study with the Full Bayes (FB) approach.

The naïve before-after study includes a simple before-after comparison of crash frequency, without accounting for changes unrelated to a treatment (Gross et al., 2010). Meanwhile, a before-after with comparison group study uses an untreated comparison group of sites similar to the treated ones to account for changes in crashes unrelated to the treatment, such as changes in economic conditions and weather patterns (i.e., regional area). These changes can influence traffic volume trends over time, for example. The before-after study with the EB approach, on the other hand, uses SPFs to account for the regression-to-the-mean (RTM). Compared to the comparison group method, the EB approach also uses SPFs to better account for regional changes by minimizing the RTM effects. The FB approach allows for additional flexibility in the development of the crash prediction models. In the FB, prior information and observed data are combined to develop a single robust statistical model which is used to generate a posterior distribution from which inference on selected parameters can be based (Lord et al., 2021). The hyper-prior distributions defined while estimating the posterior distribution for the anticipated number of crashes is carried over throughout the modeling process and finally the safety effectiveness computations (Kitali and Sando, 2017).

2.5.2.2 Cross-sectional Study

Cross-sectional studies look at the crash experience of locations with and without some feature and then attribute the difference in safety to that feature. In its most basic application, the CMF is estimated as the ratio of the average crash frequency for sites with and without the feature. For this approach to be reliable, all locations must be similar to each other in all other factors affecting crash risk. In practice, this requirement is difficult to meet. While rigorous before-after methods are usually preferred to cross-sectional methods, some situations call for an alternative approach because before-after methods are not practical (i.e., when there are insufficient before-after observations to allow for credible results, insufficient data in the after-period, treatment dates are not available, etc.).

2.5.3 Severity Distribution Functions (SDFs)

An SDF is represented by a discrete choice model (Lord et al., 2021). It is used to predict the proportion of crashes in each of the following severity categories: fatal (K), incapacitated injury (A), non-incapacitated injury (B), possible injury (C), or property damage only (PDO). The SDF can be used with the SPF to estimate the expected crash frequency for each severity category. The SDF includes various geometric, operation, and traffic variables that will allow the estimated proportion to be specific to an individual freeway segment. The SDF is developed using a highway safety database that combines crash data with roadway inventory data. Several statistical models are available to develop SDFs. The most common models used by transportation safety analysts include: the ordered logit or probit, partially-ordered logit, ordered mixed logit, multinomial logit, nested logit, and random parameters (mixed) logit model (Bonneson et al., 2012).

Table 2.3: Pros and Cons of Before-after Study with EB Method and Cross-sectional Study

	Applicability	Pros	Cons	Potential Biases
Before-after with EB	• Treatment is adequately comparable among treatment sites	Use SPF to account for: • Regression-to-the-mean • Traffic volume changes over time • Non-treatment related time trends	• Fairly complex • Cannot include prior knowledge of treatment • Cannot consider the spatial correlation • Cannot determine complex model forms	• Regression-to-the-mean • Changes in traffic volumes • Historic trends • Other safety treatments • Changes in crash reporting • Accounting for state-to-state differences if using multiple states • Suitability of comparison or reference groups
Cross-sectional	• Useful when limited before-after data are available • Requires sufficient sites that are similar except for the treatment of interest	• Possible to develop crash modification functions (instead of factors) • Allows estimation of CMFs when conversions are rare • Useful for predicting crashes	CMFs might be incorrect for a few reasons such as: • Inappropriate functional form • Omitted variable bias • Correlation among variables	• Control of confounding variables • Unobserved heterogeneity and omitted variable bias • Accounting for state-to-state differences if using multiple states • Selection of appropriate functional form • Correlation or collinearity among the independent variables • Overfitting of prediction models • The low sample mean and small sample size • Bias due to aggregation, averaging, or incompleteness in data • Temporal and spatial correlation • Endogenous independent variables • Misspecification of the structure of systematic variation and residual terms • Correlation between crash types and injury severities

Source: Gross et al., 2010.

2.5.3.1 HSM Crash Severity Models

Chapters 18 and 19 of the HSM 1st Edition Supplement and Chapter 12 of the HSM 2nd edition include the SDFs for estimating the proportion of different crash severities. The multinomial logit (MNL) model was used to predict the probability of crash severities. An individual crash severity among the given severities was considered to be predicted if the crash severity likelihood function was maximum for that particular severity. Each crash severity likelihood function, which is a dimensionless measure of the likelihood of a crash, was considered to have a deterministic component and random or error component. While the deterministic part is assumed to contain variables that can be measured, the random part corresponds to the unaccounted factors that impact injury severity. The deterministic part of the crash severity likelihood was designated as a linear function of the driver, roadway, vehicle, and weather characteristics, as shown in Equation 2.3.

$$V_j = ASC_j + \sum_{k=1}^{K} b_{k,j} X_k \quad (2.3)$$

where,

V_j = systematic component of crash severity likelihood for severity *j*,

ASC_j = alternative specific constant for crash severity *j*,

$b_{k,j}$ = a regression coefficient for crash severity *j* and variable *k*, *k* =1…K,

X_{ki} = independent variable *k*, and

K = the total number of independent variables included in the model.

The logit model was derived assuming that the error components are extreme value (or Gumbel) distributed. The probability for each crash severity is given by Equation 2.4, as follows:

$$P_j = \frac{e^{V_j}}{\sum_{j=1}^{J} e^{V_j}} \quad (2.4)$$

where, P_j is the probability of the occurrence of crash severity *j*, and J is the total number of crash severities to be modeled.

To adjust for the local conditions, Equation 2.5 is modified by considering the local calibration factor. The adjusted probability for each severity category is determined using Equations 2.6 – 2.8, where *C* is the local calibration factor.

$$P_K = \frac{e^{V_K}}{\frac{1}{C} + e^{V_K} + e^{V_A} + e^{V_B}} \quad (2.5)$$

$$P_A = \frac{e^{V_A}}{\frac{1}{C} + e^{V_K} + e^{V_A} + e^{V_B}} \quad (2.6)$$

$$P_B = \frac{e^{V_B}}{\frac{1}{C} + e^{V_K} + e^{V_A} + e^{V_B}} \quad (2.7)$$

$$P_C = 1 - (P_K + P_A + P_B) \quad (2.8)$$

The Safety Prediction Methodology and Analysis Tool for Freeways and Interchanges (NCHRP project 17-45) provides a discussion on statistical models that are available for developing SDFs. The discussed models that are more commonly used by safety analysts include: the ordered logit or probit, partially-ordered logit, ordered mixed logit, multinomial logit, nested logit, and random parameters (mixed) logit model (Bonneson et al., 2012).

2.6 Safety-related Studies on Managed Lanes

Research has suggested that after implementing the managed lanes, appropriate measures should be taken to evaluate the safety impacts, especially if the facility has undergone geometric changes, such as narrowing or eliminating main travel lanes or shoulders (Kuhn et al., 2002). Safety performance measures are usually selected to quantitatively evaluate the effectiveness of a given strategy or multiple strategies. Also, agencies that are maintaining express lanes have been documenting annual performance reports which help them to understand and make necessary adjustments to the operational strategies. This information, coupled with real-time and archived data, has enabled researchers to develop SPFs and CMFs for different managed lanes features. This section presents a brief synthesis of the literature on the existing safety performance findings for managed lanes facilities. Section 2.6.1 focuses on previous studies on the safety of facilities with managed lanes, and Section 2.6.2 presents some of the existing SPFs and CMFs for managed lanes facilities.

2.6.1 Previous Studies on Safety of Managed Lanes

The benefits of managed lanes on the operations and safety of the corridors they serve have been studied by several researchers. Most of the previous studies on freeways with managed lanes focused on the safety impacts of either adding managed lanes on existing freeway facilities or converting a portion of the general-purpose lanes to managed lanes and HOV lanes to HOT lanes (Eisele et al., 2006). Researchers generally found inconsistent results on crash rates and frequencies after the installation of the managed lanes, regardless of the separation types. The mixed results indicated an increase, decrease, or no change in crash rates following the installation of the managed lanes. A few selected studies on the safety of managed lanes facilities are summarized in the following paragraphs.

Bauer et al. (2004) evaluated the safety of adding a travel lane on urban freeways in California by narrowing existing lanes and converting a part of the existing shoulder into a travel lane. In most of the study locations, the additional lane was a buffer-separated HOV lane. The authors found a statistically significant increase in crash frequencies when 4-lane facilities were converted to 5-lane facilities. This increase was partly attributed to the increased speed differentials between the HOV lane and the general-purpose lanes. The same study also reported a statistically insignificant change in crashes when 5-lane facilities were converted to 6-lane facilities.

In 2004, Cothron et al. (2004) conducted a before-and-after crash analysis to evaluate the safety performance of one barrier-separated HOV lane corridor and two buffer-separated HOV lane corridors in Texas. The two corridors with buffer-separated HOV facilities showed a 56% and 41% increase in corridor injury crash rates in the "after" period relative to the "before" period. Also, crash rates were higher during peak periods in the after-period. The speed differential between the HOV lane and the adjacent general-purpose lane was found to contribute to the increased crash occurrence. The same study also concluded that the construction of buffer-separated HOV lanes resulted in an increase in the crash occurrences on the inside the general-purpose lane (i.e., on the general-purpose lane closest to the buffer-separated HOV lanes). The reduction in lane and shoulder width to accommodate the HOV lane was cited as a possible cause for the crash rate increase in the after-period.

A study to determine the benefit-cost ratio of a variable pricing project along SR-91 express lanes in California was conducted by Sullivan and Burris (2006). The express lanes were 10 miles long, consisting of two lanes in each direction, and separated from the general-purpose lanes by a painted buffer with plastic pylons. The authors monitored the trends in crashes and found no significant difference between the express lanes and the general-purpose lanes.

In Texas, Cooner and Ranft (2006) conducted a safety study to examine Dallas's buffer-separated concurrent-flow HOV lanes, which were implemented by lane widths being reduced and by the inside shoulder being converted to an HOV lane on I-35 East and I-635. Injury crash data from each corridor were analyzed based on crash rates, frequency trends, and manually reviewing police reports. The analysis considered the impact of design elements, including buffer width, shoulder presence, and lane width. Operationally, the analysis considered the impact of the speed differential between the HOV and the general-purpose lanes. This evaluation resulted in the following key findings: (a) both corridors had an increase in crash rates after implementation of the HOV lane, and (b) the increase in crashes was primarily attributed to the speed differential between the HOV and the general-purpose lanes and the reduced HOV cross-section. Based on the findings, the study recommended providing greater width for the total HOV cross-section (inside shoulder + HOV lane + painted buffer) than the width provided in the two interim corridors.

Lee et al. (2007) evaluated the safety of a freeway operations strategy that restricted the inside left lanes to HOV vehicles and allocated right shoulders as general-purpose lanes during peak hours along Interstate 66 (I-66). The study segment of I-66 is an urban freeway, approximately 6.5 miles long, that carries very heavy commuting traffic between Washington, D.C., and Northern Virginia. During designated peak hours, the inner left lanes convert to HOV-only lanes with continuous access, and the other two general-purpose lanes and right shoulders serve as travel lanes, resulting in a total of four travel lanes. The authors developed negative binomial (NB) regression models for different lane groups (i.e., all lanes combined, inside left lanes that were used as HOV lanes, general-purpose lanes excluding inside left lanes, and right shoulders that were used as general-purpose lanes). The study concluded that the operational strategy did not significantly affect crash frequency in the study area.

Finally, Jang et al. (2009) examined the crash data from HOV facilities with two different types of access, continuous and limited, in California. The findings revealed that HOV facilities with limited access offered no safety advantages over those with continuous access. Compared with continuous access HOV lanes, a higher percentage of collisions were concentrated on limited-access HOV lanes. Limited-access HOV lanes also had higher collision rates. Findings from investigating the relationship between collision rates in HOV lanes for shoulder width, length of access, and proximity of access to neighboring ramps were also documented.

2.6.2 Existing SPFs and CMFs

Very few documented studies exist pertaining to the SPFs and CMFs of freeways with managed lanes facilities. A few selected studies with SPFs and CMFs on managed lanes facilities are summarized in the following paragraphs.

Jang et al. (2009) compared the crash rates of four freeway segments with continuous access (40.7 lane miles in total) and four segments with limited access (50.9 lane miles in total) with a 1-ft to 5-ft buffer in California. For all the analysis segments, the managed lanes consisted of HOV lanes. Facilities with continuous access were found to have 16% fewer fatal and injury crashes than the facilities with limited access. The study results were published in the CMF Clearinghouse, an online database provided by the FHWA and containing more than 2,500 CMFs for 700+ countermeasures.

Cao et al. (2011) explored the benefits and costs associated with converting I-394 HOV lanes to HOT lanes in Minnesota. The authors applied the before-after study with the empirical Bayes (EB) method to estimate the safety benefits of the conversion, and found a 5.3% reduction in the number of crashes after the conversion. Additionally, the study results were published in the CMF Clearinghouse. Table 2.4 lists the CMFs and CRFs for converting HOV lanes to HOT lanes from Cao et al. (2011), as published on the clearinghouse website.

Table 2.4: CMFs and CRFs to Convert HOV Lanes to HOT Lanes (Cao et al., 2011)

Crash Severity	CMF	CRF
All	0.95[1]	5%[1]
Fatal (K)	0.00[2]	100%[2]
Serious Injury (A)	0.39[2]	61%[2]
Minor Injury (B)	1.06[1]	-6%[1]
Possible Injury (C)	0.96[1]	4%[1]
Property Damage Only (PDO) or No Injury (O)	0.89[1]	11%[1]

[1] Based on the study design, sample size, standard error, potential bias, and data source, the CMF Clearinghouse has given a star quality rating of three.

[2] Based on the study design, sample size, standard error, potential bias, and data source, the CMF Clearinghouse has given a star quality rating of two.

A Florida study developed crash prediction equations for freeway facilities with HOV and HOT lanes (Srinivasan et al., 2015). This study developed SPFs for estimating the expected crash frequency of urban freeway facilities with HOV or HOT lanes. Variables included AADT, segment length, left-shoulder-width, and four levels of separation between the managed lanes and the general-purpose lanes: painted stripe, buffer width of 0-1 ft, buffer width of 1-2 ft, and buffer width of 2-3 ft. Separate equations were developed depending on the total number of lanes in the freeway facility leading to models for 6-, 8-, 10-, and 12-lane facilities. All of the facilities had one HOV lane in each direction (included in the total number of lanes). The effect of separation type on crash rates was found to be statistically significant only in the models for 10-lane facilities. A painted stripe separation was correlated with more total (all) crashes on 10-lane freeways, compared to buffer separation. Wider buffer separation (2-3 ft) was correlated with fewer fatal and injury crashes. The effect of separation type was not statistically significant (at 90% confidence level) in the case of 6-, 8-, and 12-lane facilities. Equations 2.9 and 2.10 show an excerpt from the study.

$$N_{FI} = 0.2 * \ exp\,[-8.861 + ln(L) + 1.12\,ln(AADT) - 0.055\,ln(LSW) + 0.522(FL) + 0.310(WA) - 0.141(BW23)] \tag{2.9}$$

$$N_{all} = 0.2 * \ exp\,[-9.555 + ln(L) + 1.227\, ln(AADT) - 0.084\, ln(LSW) + 0.126(PS)] \quad (2.10)$$

where,
L represents the segment length (in miles),
LSW is the left shoulder-width (in feet),
FL is a binary (0 or 1) variable that indicates whether the segment is from Florida or not, and
WA is a binary variable that indicates whether the segment is from Washington or not.

There were four levels of separation between the managed lanes and the general-purpose lanes: painted stripe, buffer width of 0-1 ft, buffer width of 1-2 ft, and buffer width of 2-3 ft represented by binary variables PS, BW01, BW12, and BW23, respectively.

Fitzpatrick and Avelar (2016) investigated the safety implications of cross-sectional elements on buffer-separated managed lanes in California and Texas. The focus was to establish the relationship between crashes and buffer widths with or without pylons (flush buffers). The dataset included crashes on 128 miles of freeway in California with flush buffers and a total of 60.4 miles of freeway in Texas (41.7 miles with pylon buffers and 18.7 miles with flush buffers). The California sites included freeways with three or four general-purpose lanes, while the Texas freeways had three to five general-purpose lanes. The study reported that wider managed lanes envelope widths (i.e., left shoulder, managed lane, and buffer width combined) were associated with fewer freeway crashes for all severity levels and fatal and injury severity levels. Wider envelopes reduced total freeway crashes by 2.8% in Texas and 2.0% in California for each additional foot of envelope width. In California, wider envelopes reduced fatal and injury crashes by 4.4% for each additional foot of envelope width. Tables 2.5 and 2.6 show SPF excerpts from the study.

Table 2.5: Safety Performance Function on California Managed Lanes with Flush Buffers (All Severity Levels) (Fitzpatrick & Avelar, 2016)

Variable	Estimate	Standard Error	z value	Pr(>|z|)	Significance [c]
(Intercept)	1.1378	1.89107	0.602	0.54739	
log (AADTHV)	0.50131	0.14646	3.423	0.00062	***
ML_L_Shld_W	-0.03723	0.01456	-2.557	0.01055	*
ML_Ln_W	-0.39154	0.1063	-3.684	0.00023	***
Buf_W	-0.07717	0.04559	-1.693	0.09049	~

[c] Significance values are as follows: blank cell = not significant; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001; AADT = Annual average daily traffic for the freeway (vehicle/day); AADTHV = Annual average daily traffic for the managed lane (vehicle/day); Buf_Type=Pylons = Buffer type between the managed lane and general-purpose lanes is pylons; Buf_W = Buffer width (ft); ML_Env = Managed lane envelope, the sum of left shoulder width, lane width, and buffer width (ft); ML_L_Shld_W = Managed lane, left shoulder width (ft); ML_Ln_W = Managed lane, lane width (ft).

Table 2.6: Safety Performance Function on Texas Managed Lanes (All Severity Levels) (Fitzpatrick & Avelar, 2016)

Variable	Estimate	Standard Error	z value	Pr(>|z|)	Significance [c]
(Intercept)	0.42185	1.45744	0.289	0.77224	
log (AADT/2)	0.23482	0.12755	1.841	0.06563	~
ML_Env	-0.02808	0.01603	-1.752	0.07979	~
Buf_Type=Pylons	0.66049	0.22595	2.923	0.00346	**

[c] Significance values are as follows: blank cell = not significant; ~ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; and *** = $p < 0.001$; AADT = Annual average daily traffic for the freeway (vehicle/day); AADTHV = Annual average daily traffic for the managed lane (vehicle/day); Buf_Type=Pylons = Buffer type between the managed lane and general-purpose lanes is pylons; Buf_W = Buffer width (ft); ML_Env = Managed lane envelope, the sum of left shoulder width, lane width, and buffer width (ft); ML_L_Shld_W = Managed lane, left shoulder width (ft); ML_Ln_W = Managed lane, lane width (ft).

2.7 Summary

This chapter focused on reviewing the state-of-practice, performance measures, and studies conducted on managed lanes by different agencies in the U.S. The review establishes the foundation through which SPFs and CMFs for managed lanes separation types were developed. The review of existing studies focused on the following topics:

- introduction to managed lanes,
- deployment of managed lanes,
- managed lane separation types,
- safety performance measures, and
- existing SPFs and CMFs for managed lane facilities.

Key findings from the review of existing literature include:

- There are a variety of managed lanes facility types, including HOV lanes, HOT lanes, express lanes, dynamic shoulder lanes, truck lanes, interchange bypass lanes, and dual roadways in which at least one of the roadways is managed.
- Managed lanes have been implemented in over 30 states in the U.S. Florida alone has over 80 miles of priced managed lanes. Most states that have implemented managed lanes have an inventory of the existing facilities and facilities under construction or in the planning stages.
- Operation strategies for managed lanes facilities include exclusive lanes, concurrent flow lanes, and reversible lanes.
- Managed lanes are commonly constructed adjacent to the general-purpose lanes. The types of separation treatments between the managed lanes and the general-purpose lanes along freeways vary among different facilities. Common separation treatments include barrier separation, buffer separation with pylons, buffer separation with pavement marking, wide buffer separation, and grade separation.
- Findings from previous studies present inconsistent results on crash rates and frequencies after the installation of managed lanes, regardless of the separation type. The mixed results

indicated an increase, decrease, or no change in crash rates following the installation of managed lanes.

- SPFs and CMFs for managed lanes facilities are generally sparse. The safety performance of HOV lanes has been studied more than the safety performance of HOT lanes and express lanes.

Table 2.7 gives a summary of the reviewed studies and reports. The table provides managed lanes separation types under each study.

Table 2.7: Existing Literature on the Safety Performance of Managed Lanes

Study	Study Type	Location (Roadway)	Managed Lanes Type (miles)	Separation Type (Operation)	Results	Suggested reason
Bauer et al. (2004)	Observational Before (1991-1992), after (1994-2000)	California (unknown roadway)	1 HOV lane (48.9 mi) in each direction added by: • Narrowing lanes within the existing traveled way, or • Converting a portion of an existing paved shoulder to a travel lane	Buffer separation (concurrent flow)	• Converting 4 lanes to 5 lanes had a 10% to 11% increase in crash frequency • Insignificant change on 5- and 6-lane sections	• Speed differentials • Relocation of bottleneck
Cothron et al. (2004)	Before-and-after crash analysis	Dallas, Texas (IH-30)	HOV lane retrofitted into the existing freeway facility	Moveable barrier separation (limited-access contraflow)	Insignificant change in crash frequency	Not Available
		Dallas, Texas (IH-35E & IH-635)	HOV lane retrofitted into the existing freeway facility	Painted buffer separation (limited-access concurrent flow)	Two HOV facilities showed 56% and 41% increase in crash rates, respectively	• Speed differentials
Sullivan & Burris (2006)	Benefit-cost analysis	California (SR-91)	2 Express Lanes (10 mi) in each direction	Painted buffer with plastic pylons (limited-access concurrent flow)	No significant crash rates difference between the express lanes and the general-purpose lanes	Not Available
Cooner & Ranft (2006)	Performance evaluation	Dallas, Texas (I-35E & I-635)	HOV lanes, which were implemented by lane widths being reduced and by the inside shoulder being converted	2.5-ft & 3-ft Painted buffer-separation, respectively (limited-access concurrent-flow)	Both corridors had an increase in crash rates after implementation of the lanes	• Speed differential • Reduced HOV cross-section
Lee et al. (2007)	Safety performance evaluation	Virginia (I-66)	1 HOV lane (6.5 mi) implemented by: • Dedicating left lane as HOV, and • Allocating right shoulders as general-purpose lanes during peak hours	Continuous access concurrent flow	Insignificant change in crash frequency	Not Available
Jang et al. (2009)	Crash analysis	California	• Continuous access HOV corridors (279 mi) • Limited access HOV corridors (545 mi)	Comparison between the two different types of access, continuous and limited	Compared to continuous access HOV lanes, a higher percentage of crashes were concentrated on limited-access HOV lanes	Excessive lane changes concentrated at one point
Cao et al. (2011)	Before-and-after crash analysis	Minnesota (I-394 MnPass)	Conversion of HOV to HOT (11 mi)	• Concrete barrier (reversible flow) • Double white lines (limited-access concurrent-flow)	Total crashes were reduced by 5.3% after the conversion	Not Available

Note: HOV = High Occupancy Vehicle; HOV = High Occupancy Toll.

Table 2.7 (continued): Existing Literature on the Safety Performance of Managed Lanes

Study	Study Type	Location (Roadway)	Managed Lanes Type (miles)	Separation Type (Operation)	Results	Suggested reason
Srinivasan et al. (2015)	Develop crash prediction equations for freeways facilities with HOV & HOT lanes	California, Florida, Texas & Washington	• 1 HOV lane in each direction • 2 HOV lanes in each direction	• Painted stripe, buffer width 0-1 ft, buffer width 1-2 ft, and buffer width 2-3 ft	• A painted stripe separation was correlated with more total (all) crashes on 10-lane freeways (compared to buffer separation) • Wider buffer separation (2-3 ft) was correlated with fewer fatal and injury crashes The effect of separation type was not statistically significant (at 90%) in 6-, 8-, & 12-lane facilities	Not Available
Fitzpatrick and Avelar (2016)	Establish the relationship between crashes and buffer widths	California (I-105, SR-134, I-210, & I-405)	HOV lanes (128 mi)	• Painted buffer without pylons (limited-access concurrent-flow)	For each additional foot of envelope width, wider envelopes reduced: • total crashes by 2.0% fatal and injury crashes by 4.4%	Not Available
		Texas (I-635, US 75, US 290, I-10, & US 59S)	HOV lanes (41.7 mi) & HOV lanes (18.7 mi)	Painted buffer with & without plastic pylons, respectively • (limited-access concurrent-flow)	Wider envelopes reduced total crashes by 2.8% per additional foot	Not Available
CTS Engineering, Inc. (2017)	Before-and-after crash analysis; before (2005-2007), after (2010-2015)	Florida (I-95)	2 Express lanes in each direction	Painted buffer without plastic pylons (limited-access concurrent-flow)	• Fatal crashes dropped from 6.3 per year to 5.3 per year • The crash rate increased from 1.81 to 2.23 Inconclusive in demonstrating either an increase or a decrease in safety	An increase may be associated with distracted driving

Note: HOV = High Occupancy Vehicle; HOV = High Occupancy Toll.

CHAPTER 3
DATA

This chapter focuses on the data collected to quantify the safety effects of the separation types between the general-purpose lanes and the managed lanes. Data collection procedures are also discussed. Two separation treatments were studied, tubular delineators (or tubular markers or pylons) and concrete barrier separation types. Study sites were limited to facilities with HOT lanes and express lanes, collectively called *priced managed lanes*, in Florida, Texas, and Georgia. The following criteria were considered while selecting the study sites:

- availability of crash data for three to five years between the years 2015 – 2019,
- diversity in the roadway geometric cross-section of the managed lanes facilities, particularly the separation types (i.e., pylons and concrete barrier), and
- inclusion of different managed lanes operation strategies (i.e., non-reversible managed lanes and reversible managed lanes).

3.1 Florida

3.1.1 Study Corridors

Most of the express lanes in Florida became operational only recently; therefore, sufficient data to evaluate the safety performance of these facilities may not be available. For example, the 295 Express lanes in Jacksonville were opened to traffic in 2019. Only the 95 Express and 595 Express lanes were analyzed in this study. Both facilities are located in South Florida.

95 Express

The 95 Express consists of two phases that are currently operational. Phase 1 includes the junction of I-95 and SR-836/I-395 in downtown Miami to the Golden Glades interchange (seven miles) with two express lanes in each direction, and Phase 2 includes the Golden Glades interchange to Broward Boulevard (14 miles) with one to two express lanes in each direction. There are three toll locations in each direction with a minimum toll price of $0.50 per toll location. The variable pricing change is based on traffic volume in the express lanes. Figure 3.1 presents the 95 Express, along with other toll facilities.

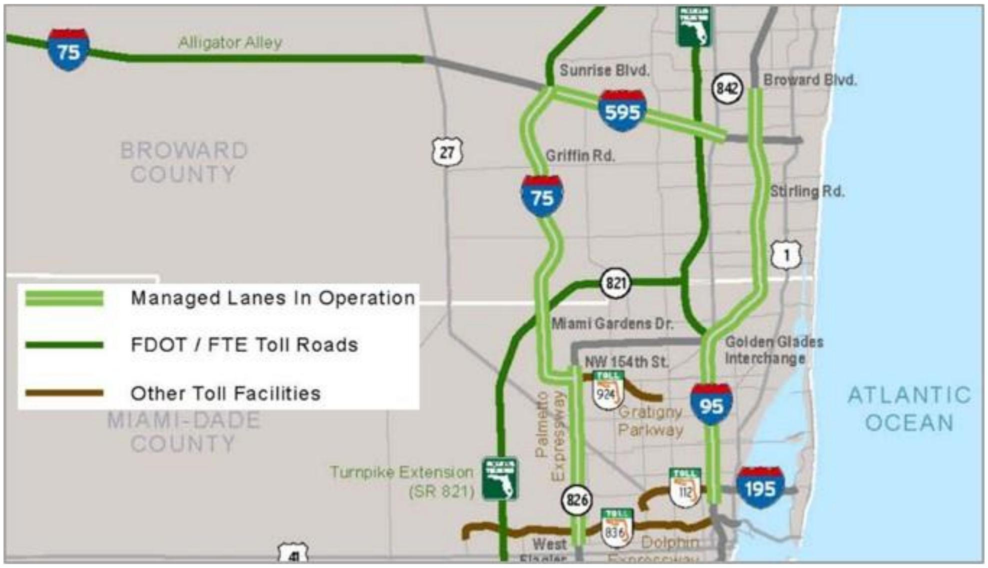


Figure 3.1: 95 Express Lanes in South Florida
(Source: Link)

The 95 Express has a concrete median barrier along the express-lane section, with about six feet on each side of the concrete barrier to the inside express lane (i.e., 6-ft inside shoulder width). The separation type between the general-purpose lanes and the express lanes is tubular delineators, also known as pylons. The pylons are mounted at an average interval of five feet between two solid white lines spaced two feet apart for all but a few section locations. Of the 21 miles, a 1.65-mile section at the Golden Glades interchange (milepost 11.95 to 13.60) was not included in the analysis as it is grade-separated. In addition, about four miles were also not included in the analysis as they had express lanes in one direction only. These sections were found at the end of express lanes. Figure 3.2 presents a typical express lane section along the 95 Express in South Florida.

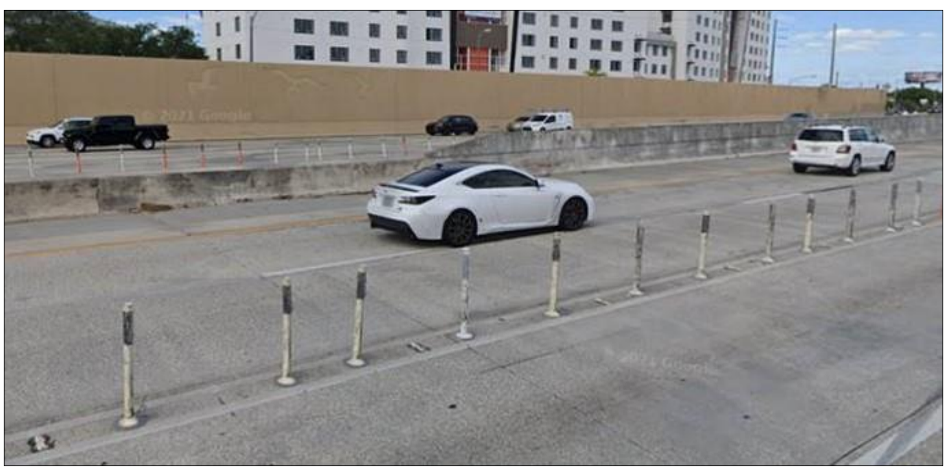


Figure 3.2: Express Lanes on I-95 in South Florida

595 Express

The 595 Express facility operates as a reversible variable toll managed lanes facility, with traffic traveling eastbound in the AM and westbound in the PM. The corridor serves express traffic to/from the I-75/Sawgrass Expressway from/to east of SR-7, directly connecting to the median of Florida's Turnpike. On weekdays, the reversible lanes are opened to eastbound traffic between 4:00 AM and 1:00 PM and westbound traffic between 2:00 PM and 2:00 AM. They are closed between 1:00 PM and 2:00 PM and between 2:00 AM and 4:00 AM for routine maintenance. The express lanes are usually open in the eastbound direction only on weekends. Figure 3.3 shows the 595 Express corridors in South Florida. Approximately eight miles were included in the analysis.

Figure 3.3: 595 Express Lanes in South Florida
(Source: Link)

3.1.2 Crash Data

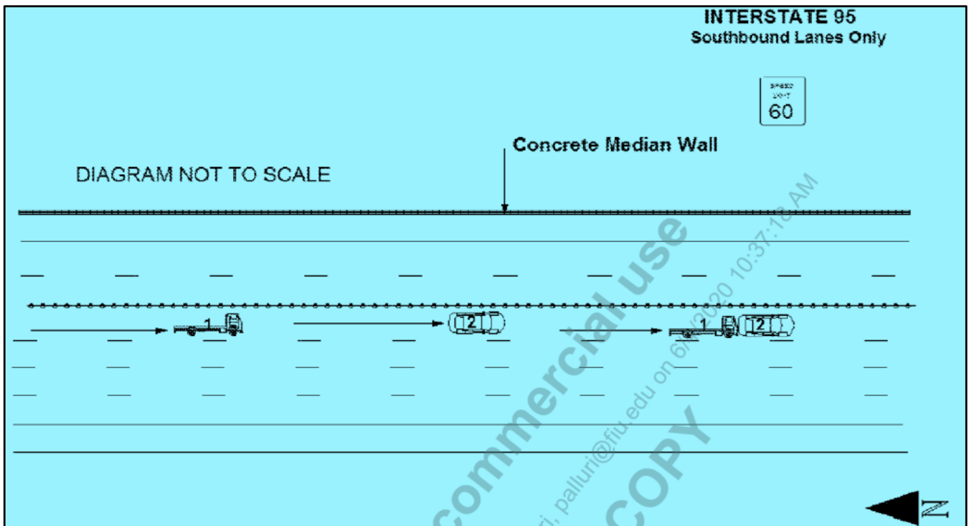
Study sites selected for Florida included the 95 Express and 595 Express facilities. Crash data from these two corridors were collected from SignalFour Analytics for the years 2015 to 2019. SignalFour Analytics is a statewide interactive, Web-based geospatial crash analytical tool hosted at the Geoplan Center, University of Florida. The data included the Excel crash summaries queried from the database using the roadway functional classifications 'interstate' and 'state roads'. ArcGIS was then used to filter out crashes that were not mapped on the study sites. The remaining data were further processed to retain crashes based on the variable 'Crash_Street'.

In addition to the above-listed variables, the lane where the crash occurred (i.e., managed lane or general-purpose lane) was critical for this study. However, this information cannot be accurately extracted (or inferred) from the crash summary records. Therefore, PDF police reports for the 28,393 crashes shown in Table 3.1 were downloaded to manually identify the crashes that occurred on the express lanes based on the provided illustrations and narratives in the police reports. Figure 3.4 gives an example of an illustrative sketch in a police report that clearly shows whether the crash occurred on express or general-purpose lanes.

Table 3.1: Summary of Crash Records on 95 Express and 595 Express

Roadway	Year	Crash Frequency	Total
95 Express	2017	8,035	23,784
	2018	7,886	
	2019	7,863	
595 Express	2015	756	4,609
	2016	873	
	2017	989	
	2018	989	
	2019	1,002	

Note: 95 Express Phase 2 opened to traffic in 2016, and 595 Express opened to traffic in 2014.



Observation: This crash occurred on the general-purpose lane in the southbound direction adjacent to the 95 Express lanes in Miami, Florida.

Figure 3.4: Illustrative Sketch of a Crash on a Managed Lanes Facility in Florida

Florida International University (FIU) uses an in-house Web-based system to facilitate the police report review process. The system, named *Police Crash Report Review System (PCRRS)*, allows to upload the crash police reports, and then save as a complete project with a set of target review questions for easy information recording. It then provides a user-friendly interface to review the police reports and record the review results quickly in a table format. The system also includes a feature to display the crash locations on Google Maps side-by-side with the police report to obtain site information. Figure 3.5 shows a screen capture of the application with Google Maps and the police sketch displayed side-by-side.

The questions designed to collect information from the police reports include:

1) Did the crash occur within an express lane facility? (Yes, No, Not sure)
2) If No/Not sure, what is the reason? (There is not enough information, no sketch, the crash occurred on a side street)

3) What was the crash occurrence lane? (express lanes only; general-purpose lane only; started on the general-purpose lanes and ended on the express lanes; started on the express lanes and ended on the general-purpose lanes; within the express lanes facility but on the ramp)
4) What was the roadway direction? (northbound/southbound, eastbound/westbound)
5) What was the lane where the crash started? (express lane 1, 2, 3, or not sure; express lanes entry or exit; general-purpose lane 1, 2, 3, 4, or not sure; ramp)
6) What was the first harmful event? (hitting the pylons, hitting the median concrete barrier, hitting other roadside objects, vehicle-to-vehicle crash, not sure)

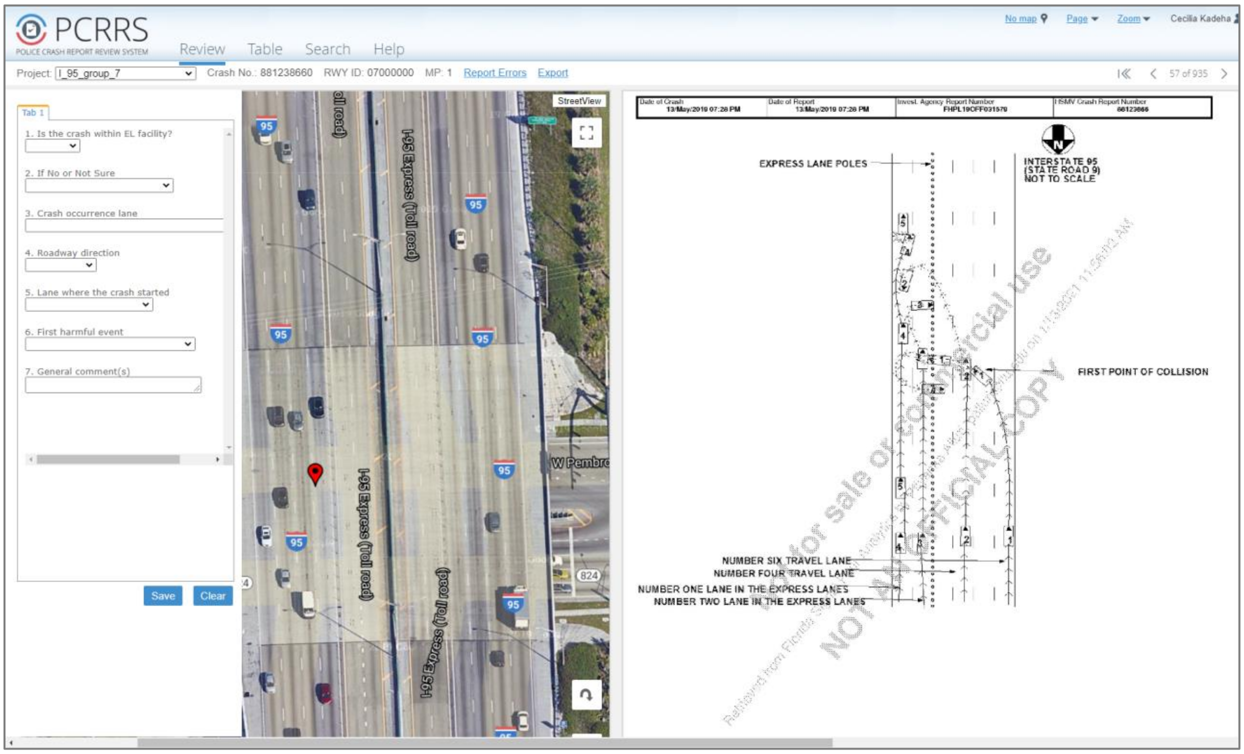


Figure 3.5: PCRRS Application with Google Maps and Police Sketch Displayed

In summary, the crash data collection in Florida was conducted using the steps illustrated in Figure 3.6.

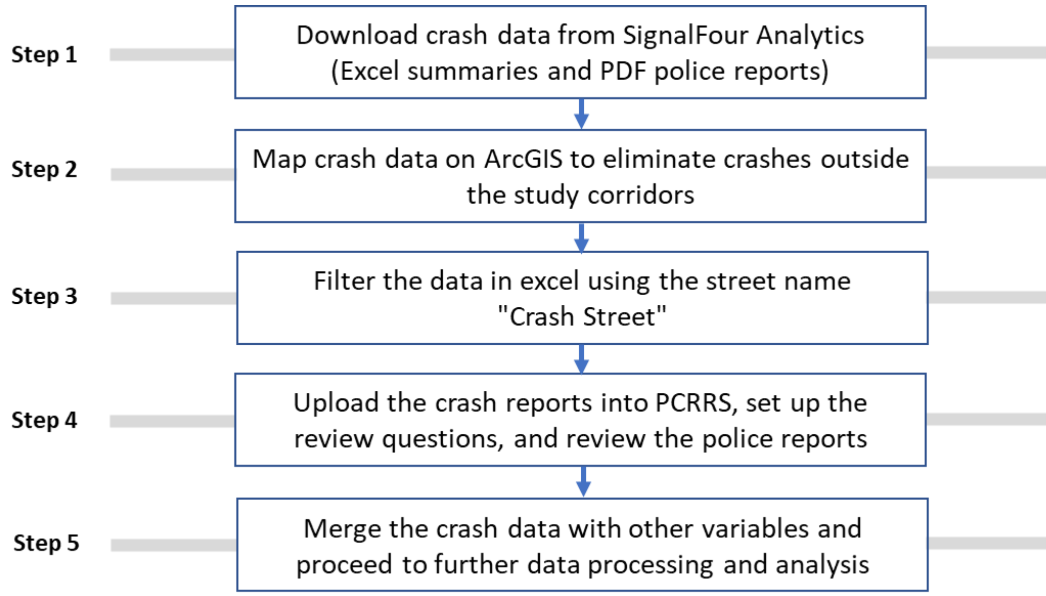


Figure 3.6: Crash Data Collection Flowchart

3.1.3 Roadway Characteristics and Traffic Volume Data

FDOT maintains and updates its Roadway Characteristics Inventory (RCI) database every year for the entire state roadway network. This database has information on more than 200 roadway characteristics. After reviewing all the variables within the RCI database, the list of potential variables for this research was identified. The roadway characteristics data collected for this study include:

- Roadway segment location,
- Presence and type of the managed lanes,
- Type of managed lanes separation,
- Number of the general-purpose lanes,
- Number of managed lanes,
- Presence of horizontal curve,
- Presence of vertical curve,
- Interchange and ramp information,
- Inside shoulder width and type,
- Outside shoulder width and type,
- Lane width,
- Median type and width, and
- Posted speed limit.

AADT data was also required to develop the SPFs, CMFs, and SDFs. FDOT has an online source for traffic data, the *Florida Traffic Online Web Application*, which has the historical AADT for the 5-year study period (2015 to 2019). Figure 3.7 shows a screenshot from the Web application. Note that the information can also be obtained in the form of GIS shapefiles.

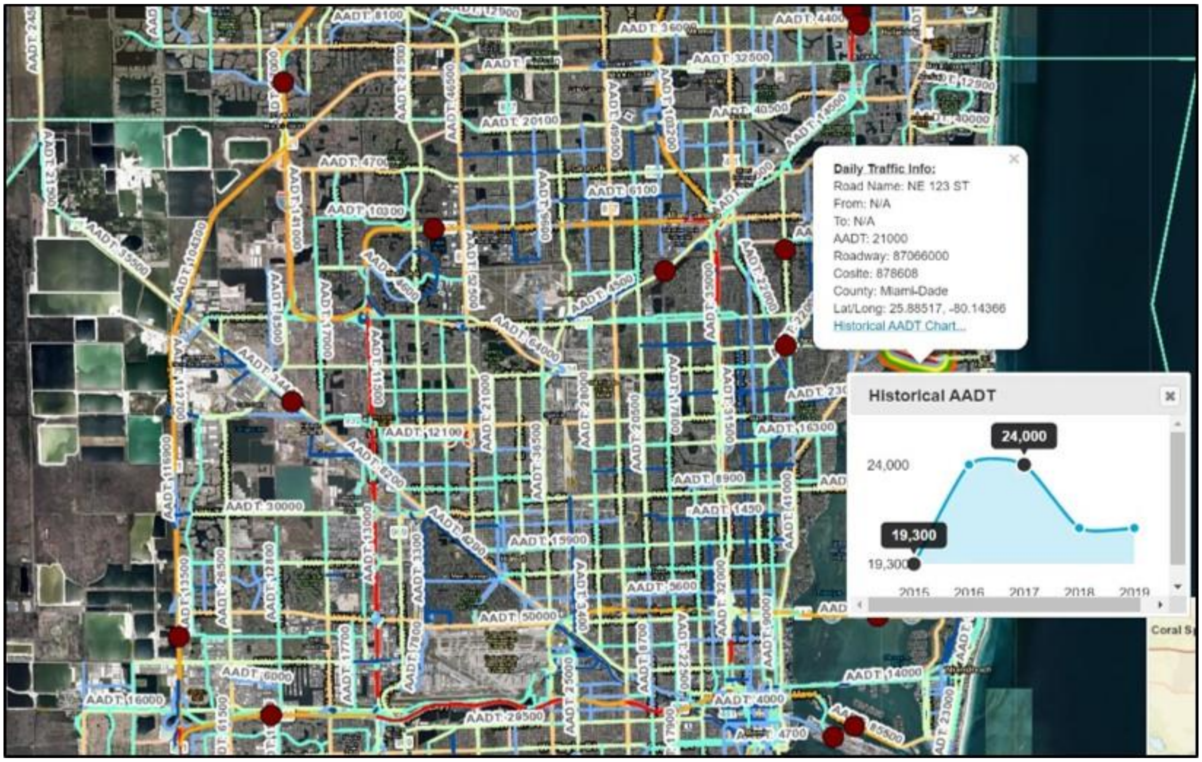


Figure 3.7: Screenshot of the Florida Traffic Online Web Application

3.2 Texas

3.2.1 Study Corridors

Texas has several managed lanes facilities that are currently operational. The HOT lanes are primarily concentrated in two major metro areas: Dallas-Fort Worth (DFW) and Houston (HOU). Several Comprehensive Development Agreements (CDAs) based and design-build corridors have been built since 2015 and are part of an extensive network of tolled managed lanes (TEXpress) in the DFW region (Figure 3.8). TEXpress uses variable pricing in which tolls fluctuate depending on real-time traffic conditions on the corridors. Table 3.2 summarizes the managed lanes study corridors in Texas.

Houston's managed lanes system is shown in Figure 3.9. The Houston transit authority, METRO, operates all of the corridors, except for the I-10 corridor (Katy Freeway), which the Harris County Toll Road Authority operates. Tolls are based on the time of day and congestion level for each of METRO's HOT (express) lane corridors.

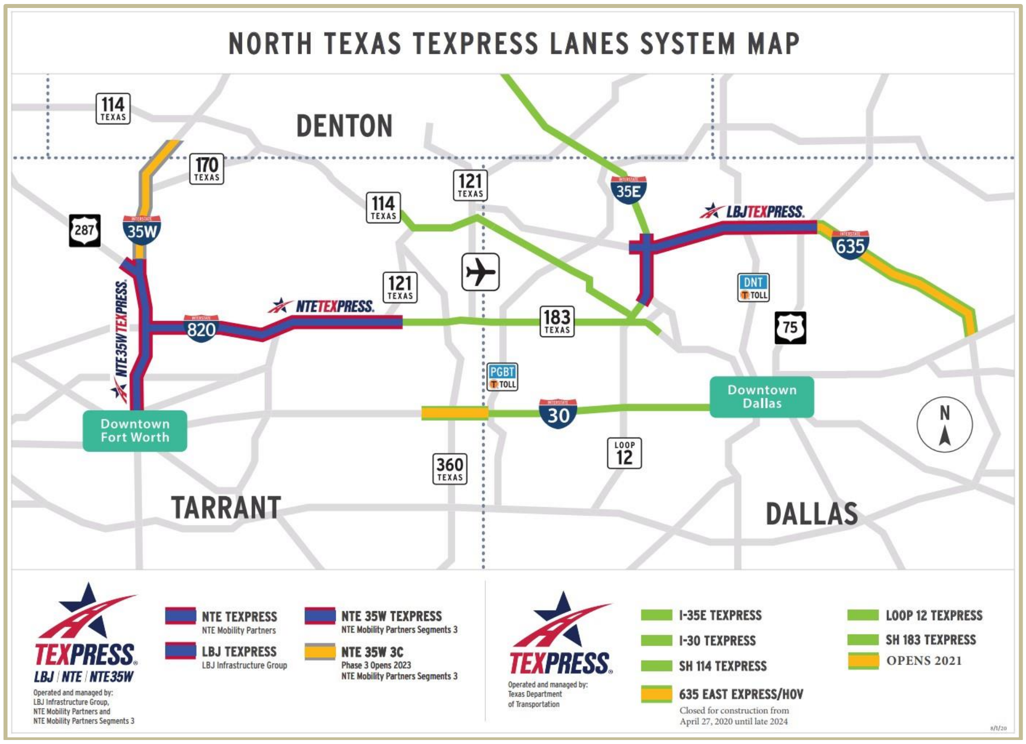


Figure 3.8: Dallas-Fort Worth TEXpress System
(Source: Link)

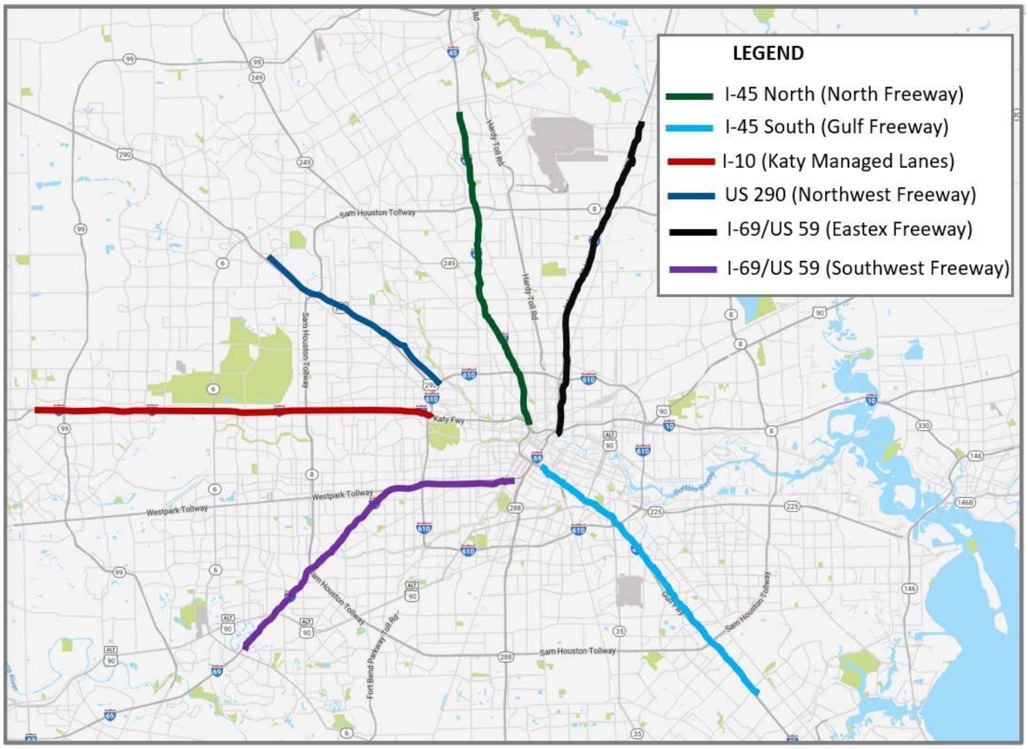


Figure 3.9: Houston HOT Lane System

Table 3.2: Texas Study Corridors

Roadway	Corridor Length (Miles)	Region	Separation Type	Managed Lanes	General-purpose Lanes	Operating Hours
SH-114	9.9	DFW	Concrete Barrier	1	2-3	24/7
I-30	12.4	DFW	Concrete Barrier	1-2*	4	EB: 9 PM–11 AM WB: 12 PM–8 PM
I-10	12.1	HOU	Pylons	2	5	5–11 AM; 2–8 PM
I-45	18.3	HOU	Concrete Barrier	1*	4 to 5	5–11 AM; 1–8 PM
I-69	14	HOU	Concrete Barrier	1*	2 to 6	24/7
SH-59	27.4	HOU	Concrete Barrier	1*	2 to 6	24/7
SH-77	17.4	HOU	Concrete Barrier	1*	3 to 5	24/7

*Reversible lanes facility; DFW = Dallas-Fort Worth; HOU = Houston.

3.2.2 Crash Data

Texas crash data were collected from the Crash Records Information System (CRIS) maintained by TxDOT. Three types of information are available in the CRIS database: crash, unit, and person-level information. The crash file contains detailed information on the highway area type, crash type, location, severity, lighting and weather condition, and time of the crash, among others. Unit data includes information about vehicle type, vehicle model, crash contributing factors, and other variables. The person file contains data on driver/passenger age, gender, crash causing factors, such as driving under the influence, fatigue, and driver vision defects.

Since it is widely recognized that property damage only (PDO) crash counts vary widely on a regional basis, due to significant variation in reporting thresholds, crashes that were associated with injury or fatality were considered separately from the PDO crashes in this analysis. The following crash severity levels were considered in the fatality and injury category:

- fatal (K),
- incapacitating injury (A),
- non-incapacitating injury (B), and
- possible injury (C).

3.2.3 Roadway Characteristics and AADT Data

TxDOT Roadways Inventory (RHINO) database was used to extract geometric and traffic-related variables. This database is updated every year for the entire state, city, toll, and county roadway networks in Texas and is available to download directly from the TxDOT website. The available roadway characteristics include:

- Functional classification,

- Number of general-purpose lanes and managed lanes,
- Surface width,
- Inside and outside shoulder type and width,
- Posted speed limit, and
- Median type and width.

Some specific roadway characteristics that are not included in the RHINO database were identified using Google Earth, including managed lanes separation and access control type, shoulder rumble strips, horizontal and vertical curve properties, and interchange and ramp information.

3.3 Georgia

3.3.1 Study Corridors

All Georgia express lanes rely on congestion-based pricing to maintain free-flow travel, even during peak hours. Currently, express lanes in Georgia are operational on I-85 and I-75. However, only the I-75 South Metro Express Lanes were considered due to data availability. Figure 3.10 presents the Georgia express lanes system, including the two facilities that are currently operational. The I-75 South Metro Express Lanes are reversible toll lanes that run 12 miles along the median of I-75 from SR-155 (McDonough Road) in Henry County to SR-138 (Stockbridge Highway) in Clayton County. The I-75 South Metro Express Lane is designed to carry traffic in the predominant commuting direction. The express lane's Reversible Access Control System (RACS) is operated and maintained by the Georgia Department of Transportation (GDOT), and the tolling system is operated and maintained by the State Road & Tollway Authority (SRTA). All express lane users must register their vehicles on an active Peach Pass account, even those that are exempt from paying tolls. The study analyzed 12 miles of the I-75 South Metro Express Lanes.

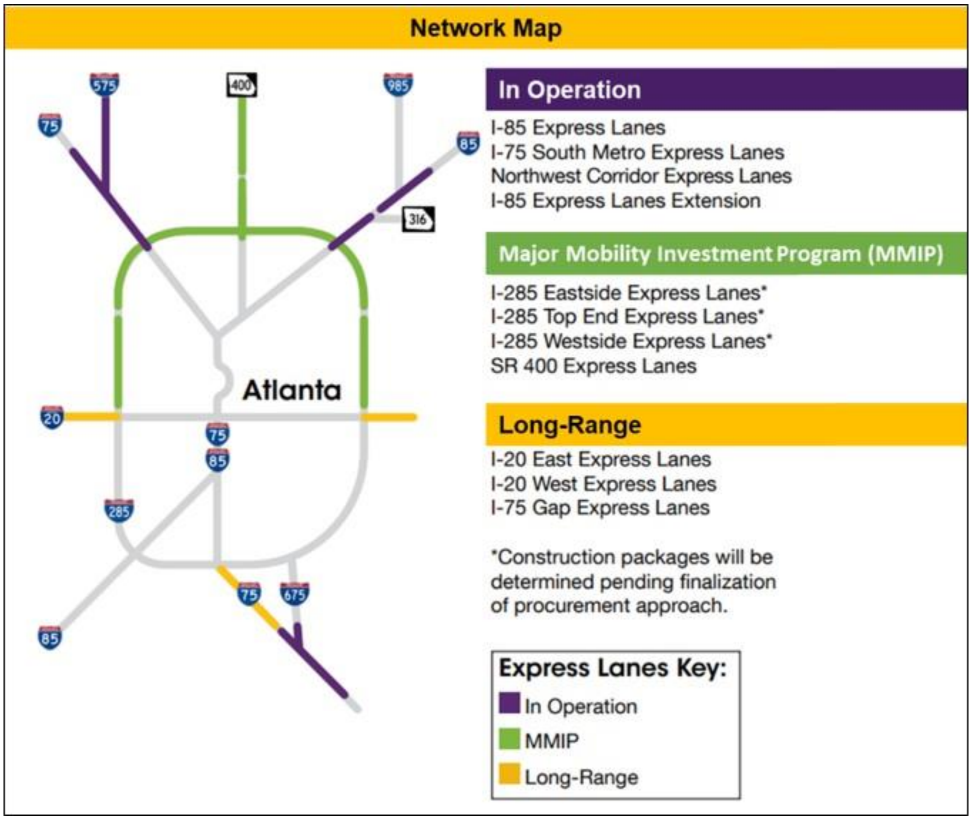


Figure 3.10: Georgia Express Lanes System
(Source: Link)

3.3.2 Crash Data

Crash data were obtained from GDOT for the years 2015 - 2019. The dataset included the variables listed below. The accident number served as a unique identification number for each crash. The agency name indicated whether the responding agency was from the Henry County Police Department, McDonough Police Department, or Not Specified. The crash location was essential to assign crashes to the respective segments.

- Accident number
- Agency name
- Incident time and date
- Incident location (coordinates)
- County
- Route
- Crash severity
- Manner of collision
- Lighting conditions
- First harmful event
- Number of vehicles involved
- Surface conditions

3.3.3 Roadway Characteristics and AADT Data

Similar to the crash data, roadway and AADT data were also requested from GDOT. The following roadway characteristics variables were requested for the study corridors:

- Roadway segment location
- Presence and type of the managed lanes
- Type of managed lanes separation
- Number of the general-purpose lanes
- Number of managed lanes
- Presence of horizontal curve
- Presence of vertical curve
- Interchange and ramp information
- Inside shoulder width and type
- Outside shoulder width and type
- Lane width
- Median type and width
- Posted speed limit

3.4 Summary

Table 3.3 presents a summary of study corridors. Overall, about 137.6 total miles of managed lanes facilities were included in the analysis. All facilities have at least one managed lane operating along the general-purpose lanes. The roadway characteristics and AADT variables were used in segmentation and in model estimations, as explained in the Chapter 4 of this report. Overall, about 45,889 crashes were assigned to segments. Note that these crashes occurred on both the general-purpose lanes and the managed lanes.

Table 3.3: Study Corridors

Facility Type	State	Facility	Crash Data Analysis Period	Length (miles)	Separation Type
Non-reversible	Florida	95 Express	2017 - 2019	15.3	Pylons
	Texas	IH-10	2015 - 2019	12.1	Pylons
		SH 114	2017 - 2019	9.9	Concrete barrier
Reversible	Florida	595 Express	2015 - 2019	8.0	Concrete barrier
	Georgia	I-75S Metro	2015 - 2019	11.5	Concrete barrier
	Texas	IH-30	2017 - 2019	12.4	Concrete barrier
		IH-45	2015 - 2019	18.3	Concrete barrier
		IH-69	2015 - 2019	4.9	Concrete barrier
		SH 59	2015 - 2019	27.8	Concrete barrier
		SH 77	2017 - 2019	17.4	Concrete barrier
Total				137.6	

CHAPTER 4
MODELING FRAMEWORK

This chapter focuses on the data preparation and the data analysis efforts. The chapter covers the segmentation process and also provides a detailed description of the variables. It also discusses how crashes were assigned to the segments. The chapter then discusses the specific approaches used to develop SPFs, CMFs and SDFs.

4.1 Process Data

Data processing primarily consisted of generating homogeneous segments, assigning crashes to segments, and preparing variables for analysis. Segmentation, which involved dividing the sites into individual homogeneous segments, was the most critical and resource-intensive step. Segmentation was necessary to ensure segment homogeneity in the analysis variables (AASHTO, 2010). Figure 4.1 presents the data processing workflow.

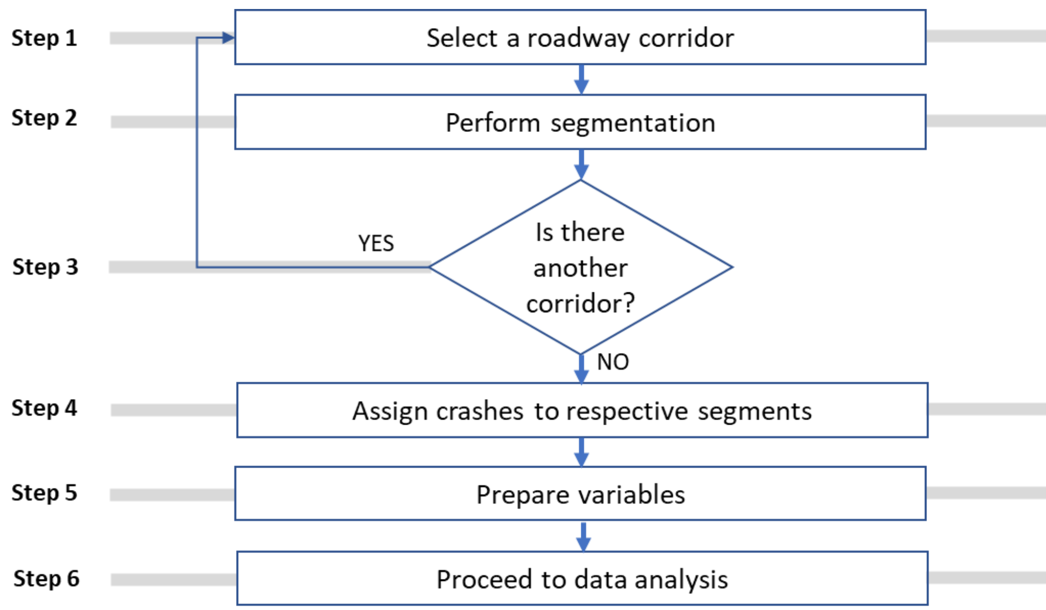


Figure 4.1: Data Processing Flowchart

4.2 Generate Homogeneous Segments

Having identified the study corridors, segmentation was performed according to the Highway Safety Manual (HSM) guidelines. A new segment started whenever there was a change in any of the variables. The following variables were used in segmentation, where applicable:

- Posted speed limit
- AADT
- Number of general-purpose lanes
- Median width

- Inside shoulder width
- Outside shoulder width
- Number of managed lanes

With respect to the following:

- Roadway identification (ID)
- Begin and end mileposts
- Roadside (Right (R), Left (L), or Center (C))
- Road section characteristics

A new segment was created whenever any given variable changed along a particular roadway facility. The results produced homogeneous segments with similar values of stated variables. Since each divided roadway has two roadsides, i.e., Left (L) and Right (R), a combination of the outlined variables produced two segments for the same milepost. To obtain a single segment per milepost, the two segments were combined as follows:

- Posted speed limit – taking the maximum of the two directions
- AADT – the value is for the entire section (L and R combined)
- Number of general-purpose lanes – taking the total number of general-purpose lanes for each direction (i.e., L+R)
- Median width – taking the average of L and R for each direction
- Inside shoulder width – taking the average of L and R for each direction
- Outside shoulder width – taking the average of L and R for each direction
- Number of managed lanes – taking the total number of managed lanes for L and R

Table 4.1 summarizes the segments from 10 facilities (three non-reversible managed lanes facilities and seven reversible flow facilities) from the three states included in the study. About 574 segments were produced, totaling 137.6 miles. The average segment length was 0.239 miles.

Table 4.1: Descriptive Statistics of Segments Included in the Analysis

Facility Type	State	Facility	Length (miles)	Separation Type	Number of Segments	Average Segment Length (miles)
Non-reversible	Florida	95 Express	15.3	Pylons	206	0.074
	Texas	IH-10	12.1	Pylons	27	0.448
		SH 114	9.9	Concrete barrier	45	0.221
Reversible	Florida	595 Express	8.0	Concrete barrier	10	0.799
	Georgia	I-75 South Metro	11.5	Concrete barrier	35	0.328
	Texas	IH-30	12.4	Concrete barrier	25	0.496
		IH-45	18.3	Concrete barrier	58	0.315
		IH-69	4.9	Concrete barrier	13	0.377
		SH 59	27.8	Concrete barrier	100	0.278
		SH 77	17.4	Concrete barrier	55	0.316
Total			137.6		574	

Note: Segments shorter than 0.01 miles were excluded from the analysis.

4.3 Assign Crashes to Segments

Once the study corridors were segmented, the next step was to assign crashes to their respective segments using mileposts. Since crash locations are regularly reported in geographic coordinates, i.e., longitudes and latitudes, the coordinates were converted into milepost locations using the *Linear Referencing Tools* in ArcGIS. Using mileposts, each crash was assigned to the respective segment. Table 4.2 presents the number of crashes assigned to each study corridor. Overall, about 45,889 crashes (that occurred on the managed lanes and the general-purpose lanes) were assigned to segments.

Table 4.2: Crash Frequencies by Study Corridor

Facility Type	State	Facility	Length (Miles)	Separation Type	Analysis Period (Years)	Number of Crashes	Crashes/ Mile/Year
Non-reversible	Florida	95 Express	15.3	Pylons	3	20,794	453.0
	Texas	IH-10	12.1	Pylons	5	5,348	88.4
		SH 114	9.9	Concrete barrier	2.16	418	19.5
Reversible	Florida	595 Express	8.0	Concrete barrier	4	1,057	33.0
	Georgia	I-75S Metro	11.5	Concrete barrier	3	4,295	124.5
	Texas	IH-30	12.4	Concrete barrier	2.69	1,516	45.4
		IH-45	18.3	Concrete barrier	5	9,738	106.4
		IH-69	4.9	Concrete barrier	5	1,572	64.2
		SH 59	27.8	Concrete barrier	5	4,697	33.8
		SH 77	17.4	Concrete barrier	2.62	1,668	36.6
Total			137.6		3.75	45,889	88.9

4.4 Prepare Variables

4.4.1 Response Variables

The response variables were the crash frequencies, as presented in Table 4.3. Single-vehicle crashes involve only one vehicle, and multi-vehicle crashes involve two or more vehicles (Kitali et al., 2018). Some researchers have recently noted that developing two distinct models for these two categories of crashes provides better prediction than developing models combining both the crash categories. This implies that modeling single- and multi-vehicle crashes separately predicts larger confidence intervals than modeling them together as a single model. The difference is much larger for fatal and injury crash models than for models for all severity levels (Geedipally & Lord, 2010). Thus, the present research developed single- and multi-vehicle crash models and fatal and injury (FI) and PDO crash models separately.

Table 4.3: List of Response Variables

Variable	Description	Consideration
SV–FI	Single-vehicle fatal and injury crash frequency	• Discrete (count) variable • Sum of single-vehicle fatal and injury crashes for each roadway segment over a known number of years
MV–FI	Multi-vehicle fatal and injury crash frequency	• Discrete (count) variable • Sum of multi-vehicle fatal and injury crashes for each roadway segment over a known number of years
SV–PDO	Single-vehicle property damage only (no injury) crash frequency	• Discrete (count) variable • Sum of single-vehicle property damage only crashes for each roadway segment over a known number of years
MV–PDO	Multi-vehicle property damage only (no injury) crash frequency	• Discrete (count) variable • Sum of multi-vehicle property damage only crashes for each roadway segment over a known number of years

4.4.2 Explanatory Variables

Table 4.4 lists the explanatory variables. These variables include discrete variables, such as AADT, number of lanes, and posted speed limit. There are also categorical variables, such as separation type and location. Shoulder widths are the only continuous variables.

Table 4.4: List of Explanatory Variables

Variable	Description	Consideration
AADT	Annual average daily traffic	• Discrete (count) variable • Average of AADT for each roadway segment over a known number of years
GPL	Number of general-purpose lanes	• Discrete (count) variable • Total number of general-purpose lanes for each roadway segment
ML	Number of managed lanes	• Discrete (count) variable • Total number of managed lanes for each roadway segment
SPEED	Posted speed limit	• Discrete (count) variable • The maximum posted speed limit for each roadway segment
IN_SHLD_ML	Inside shoulder width of managed lanes	• Continuous variable (in ft) • The average of shoulder widths from both directions for each roadway segment
OUT_SHLD_GPL	Outside shoulder width of general-purpose lanes	• Continuous variable (in ft) • The average of shoulder widths from both directions for each roadway segment
ENTRY_EXIT	Presence of managed lanes entry or exit	• Categorical (indicator) variable • 1 if present, 0 if absent for each roadway segment
RAMP	Presence of a ramp	• Categorical (indicator) variable • 1 if present, 0 if absent for each roadway segment
HCURVE	Presence of a horizontal curve	• Categorical (indicator) variable • 1 if present, 0 if absent for each roadway segment
LOCATION	Location (Florida, Georgia, or Texas)	• Categorical (indicator) variable • 0 if Florida, 1 if Texas, and 2 if Georgia for each roadway segment
SEPARATION TYPE	Separation type between general-purpose and managed lanes	• categorical (indicator) variable • 0 if Pylons and 1 if Concrete barrier for each roadway segment

4.4.2.1 Offset Variables

As stated in Chapter 3 of this report, the data collection periods differed depending on crash data availability. For this reason, the number of years was different among segments, especially for different roadway facilities. In addition, segment length, being a continuous variable, varied considerably. The two variables *"segment length"* and *"the number of years"* were used as *offset variables*. Ideally, offset is the variable that is used to denote the exposure period in the regression analysis (the exponent of the variable is fixed to 1).

4.4.2.2 Interaction Variable

Interaction effects occur when the effect of one variable depends on or influences the effect of another variable. For instance, changing the separation type can affect the crash frequency. In this manner, analysts use models to assess the relationship between independent and dependent variables, commonly known as main effects. In more complex scenarios, the independent variables might interact with each other. Interaction effects indicate that a third variable influences the relationship between an independent and dependent variable. For example, the relationship between crash frequency and separation type probably depends on the separation width. To put things in perspective, a 5-ft pylon separated facility would perform differently from a 10-ft pylon separated facility. With this regard, the current study sought to model by interacting the separation width with the separation type. Separation width is defined as follow:

- *Separation width* is the width measured from the left edge of the innermost general-purpose lane to the right edge of managed lanes. In other words, it is the summation of the inside shoulder width of the general-purpose lanes and the outside shoulder width of the managed lanes plus the width of either a concrete barrier or pylons. This variable was considered continuous, taking the average of separation widths from both directions for each roadway segment. Figure 4.2 provides additional details on separation width.

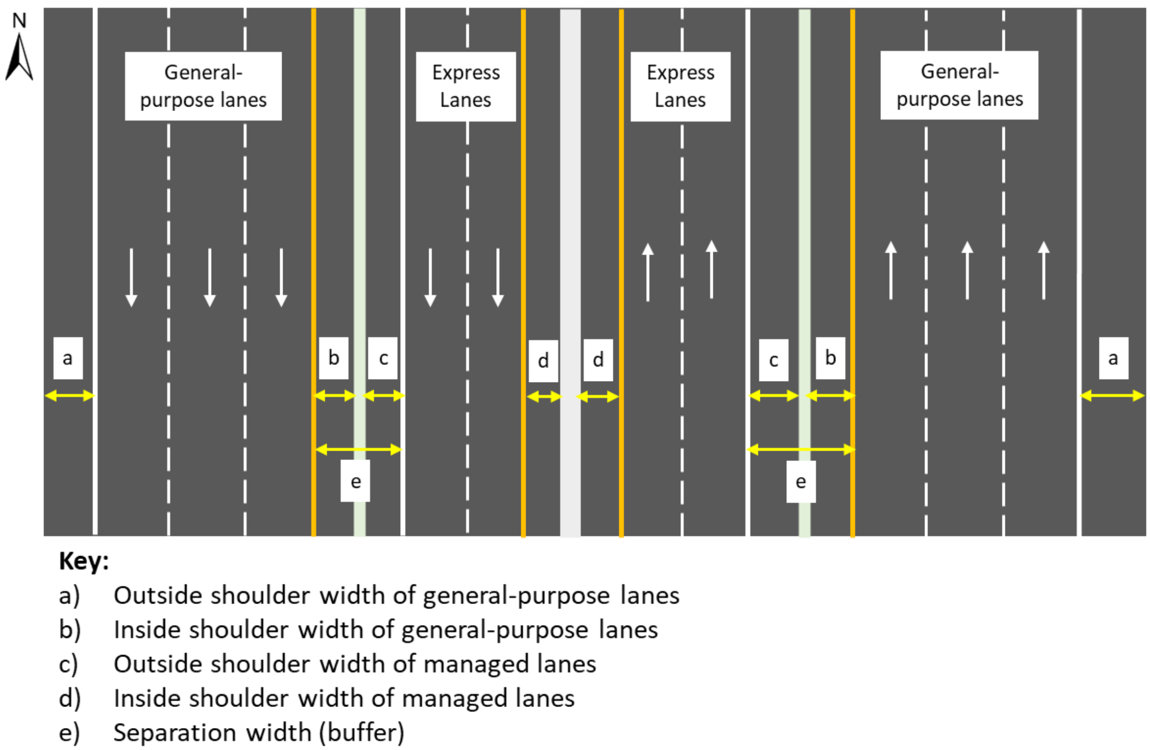


Figure 4.2: Cross-section of a Typical Managed Lanes Facility

4.4.3 Summary Statistics

Tables 4.5 through 4.8 present a summary of variables and descriptive statistics for non-reversible managed lanes facilities and reversible managed lanes facilities analyzed in this study.

Table 4.5: Discrete and Continuous Variables for Non-reversible Managed Lanes Facilities

Variable	Minimum	Mean	Median	Standard Deviation	Maximum
SV- FI (crash/mile/year)	0	10.0	0	40.6	404
MV- FI (crash/mile/year)	0	66.5	10.7	240.9	2,374
SV- PDO (crash/mile/year)	0	24.8	3.0	86.6	808
MV- PDO (crash/mile/year)	0	248.4	31.7	922.3	8,343
AADT (veh/day)	72,276	254,552	273,667	68,553	322,667
GPL	4	8	8	1	13
ML	1	3	4	1	6
SPEED (mph)	55	60.1	60	3.4	65
IN_SHLD_ML (ft)	0	5.3	6	2.3	15
OUT_SHLD_GPL (ft)	4	13.7	11	5.8	32
SEGMENT LENGTH (mi)	0.0004	0.134	0.054	0.248	2.158
NUMBER OF YEARS	2.16	3.1	3.0	0.7	5
SEPARATION WIDTH: Concrete barrier (ft)	0.0	13.0	12.5	4.8	25.0
SEPARATION WIDTH: Pylons (ft)	2.0	4.0	2.0	5.8	32.5

N = 278

Table 4.6: Categorical Variables for Non-reversible Managed Lanes Facilities

Variable	Factor	Count	Percent (%)
ENTRY_EXIT	Yes	24	8.6%
	No	254	91.4%
RAMP	Yes	92	33.1%
	No	186	66.9%
HCURVE	Yes	24	8.6%
	No	254	91.4%
LOCATION	Florida	206	74.1%
	Texas	72	25.9%
SEPARATION TYPE	Pylons	233	83.8%
	Concrete barrier	45	16.2%

N = 278

Table 4.7: Discrete and Continuous Variables for Reversible Managed Lanes Facilities

Variable	Minimum	Mean	Median	Standard deviation	Maximum
SV- FI (crash/mile/year)	0	5.0	1.9	12.0	133
MV- FI (crash/mile/year)	0	19.8	6.7	48.6	600
SV- PDO (crash/mile/year)	0	12.8	5.4	31.6	400
MV- PDO (crash/mile/year)	0	54.2	20.2	133.3	1900
AADT (veh/day)	98,401	185,681	179,700	51,420	328,599
GPL	6	8	8	2	13
ML	1	2	1	1	4
SPEED (mph)	50	63.2	60.0	5.3	70
IN_SHLD_ML (ft)	0	1.8	0.0	3.7	14
OUT_SHLD_GPL (ft)	0	18.2	20.0	4.8	24
SEGMENT LENGTH (mi)	0.001	0.338	0.151	0.490	3.621
NUMBER OF YEARS	2.6	4.1	5.0	1.1	5.0
SEPARATION WIDTH (ft)	0.5	10.9	10.8	7.1	28.5

N = 297

Table 4.8: Categorical Variables for Reversible Managed Lanes Facilities

Variable	Factor	Count	Percent (%)
ENTRY_EXIT	Yes	56	18.9%
	No	229	77.1%
	No value	12	4.0%
RAMP	Yes	155	52.2%
	No	130	43.8%
	No value	12	4.0%
HCURVE	Yes	64	21.5%
	No	233	78.5%
LOCATION	Florida	10	3.4%
	Texas	252	84.8%
	Georgia	35	11.8%
SEPARATION TYPE	Concrete barrier	297	100%

N = 297

4.5 Develop SPFs

An SPF is a regression equation that is developed to determine the predicted crash frequency at a location, usually as a function of AADT with segment length and other characteristics, such as lane width, shoulder width, degree of horizontal curves, or any other specific condition. Although the regression equations for SPFs may contain multiple variables, not all multiple regression models can be used to develop the SPFs. Multiple regression models have limitations in modeling crash frequency because traffic crashes are random and rare events. For example, the number of crashes can be predicted to be negative when a general linear regression model is used (Choi et al., 2018). Thus, several studies have used regression models that acknowledge the discrete nature of crashes. The most common models include Poisson and Negative Binomial (NB) regression models (Washington et al., 2003).

Negative Binomial models are widely used in developing SPFs to account for the crash events' overdispersion (Lord & Mannering, 2010; Lord et al., 2021). NB regression models are used by many researchers because crash data have a gamma-distributed mean for a population of systems. It allows for the crash variance to differ from the crash mean. A basic form of the NB regression model is the log-linear model shown in Equation 4.1 (Miaou & Lord, 2003), as follows:

$$ln(\lambda_i) = \boldsymbol{\beta X}_i + €_i \quad (4.1)$$

where,

- λ_i = expected value, presents the probability of the segment *i* to be perfectly safe, i.e., probability of true zero crash occurrence at segment *i*,
- $\boldsymbol{X}_i$ = vector of explanatory variables,
- $\boldsymbol{\beta}_i$ = vector of estimated parameters, and
- € = the gamma-distributed error term that accounts for the overdispersion.

4.6 Develop CMFs

A CMF is a multiplicative factor used to compute the expected number of crashes when a specific countermeasure is implemented at a particular site. As described above, it represents the relative change in crash frequency due to a change in a specific condition when all other conditions and location characteristics remain constant. A CMF of less than one (< 1) indicates a reduction in the crash frequency, while a CMF of greater than one (> 1) indicates an increase in the frequency of crashes when a particular design or operational characteristic or roadway geometric characteristic deviates from the base conditions. Generally, CMFs are expressed in terms of the exponential of the model coefficient(s). Equations 4.2 through 4.4 present specific considerations of variables with base conditions.

$$CMF_{ML} = e^{b_{ML}(N_{ML}-2)} \quad (4.2)$$
$$CMF_{SPD} = e^{b_{SPD}(SPD - 55)} \quad (4.3)$$
$$CMF_{LAT} = e^{b_{LAT}(LAT - 2)} \quad (4.4)$$

where,

CMF_{ML}	=	Crash Modification Factor for number of managed lanes,
CMF_{SPD}	=	Crash Modification Factor for the posted speed limit,
CMF_{LAT}	=	Crash Modification Factor for lateral separation width of managed lanes from the general-purpose lanes,
N_{ML}	=	Number of managed lanes,
SPD	=	Posted speed limit (mph),
LAT	=	Lateral separation width (ft), and
b_i	=	SPF coefficient of variable i.

4.7 Develop SDFs

SDFs were used to predict the proportion of crashes in each of the following severity categories: fatal (K), incapacitated injury (A), non-incapacitated injury (B), possible injury (C), or property damage only (PDO). The SDF can be used with the SPF to estimate the expected crash frequency for each severity category. The SDF includes various geometric, operation, and traffic variables that will allow the estimated proportion to be specific to an individual freeway segment, and is developed using a highway safety database that combines crashes with roadway inventory data. Several statistical models are available to develop SDFs.

The MNL model was used in the HSM to predict the probability of crash severity (AASHTO, 2010). An individual crash severity among the given severities was considered to be predicted if the crash severity likelihood function was maximum for that particular severity. Each crash severity likelihood function, which is a dimensionless measure of the likelihood of a crash, was considered a deterministic component and an error/random component. While the deterministic part is assumed to contain variables that can be measured, the random part corresponds to the unaccounted factors that impact injury severity. The deterministic part of the crash severity likelihood is designated as a linear function of the driver, roadway, vehicle, and weather characteristics, as shown in Equation 4.5.

$$V_j = ASC_j + \sum_{k=1}^{K} b_{k,j} X_k \quad (4.5)$$

where,

V_j = systematic component of crash severity likelihood for severity *j*,

ASC_j = alternative specific constant for crash severity *j*,

$b_{k,j}$ = the regression coefficient for crash severity *j* and variable *k*, *k* =1, ..., K,

X_{ki} = independent variable *k*, and

K = a total number of independent variables included in the model.

The logit model was derived assuming that the error components are extreme value (or Gumbel) distributed (McFadden, 1981). The probability for each crash severity is given by Equation 4.6.

$$P_j = \frac{e^{V_j}}{\sum_{j=1}^{J} e^{V_j}} \tag{4.6}$$

where,

P_j = probability of the occurrence of crash severity *j*, and

J = total number of crash severities to be modeled.

4.8 Summary

This chapter discussed the data processing and analysis procedures that were used in the study. Data processing primarily consisted of generating homogeneous segments, assigning crashes to segments, and preparing variables for analysis. Where applicable, the segmentation process was carried out using variables, such as the posted speed limit, AADT, number of general-purpose lanes, median width, inside shoulder width, outside shoulder width, and number of managed lanes. There were a total of 574 segments, with an average segment length of 0.239 miles, totaling 137.6 miles that were included in the analysis. The chapter also highlighted the importance of developing separate models for single-vehicle and multi-vehicle crashes, and for FI and PDO crashes. The chapter discussed the Negative Binomial (NB) regression models that were used to develop SPFs and the Multinomial Logistic (MNL) regression models that were used to develop the SDFs.

CHAPTER 5
RESULTS AND DISCUSSION

This chapter presents SPFs, CMFs, and SDFs developed for reversible and non-reversible managed lanes facilities. The SPFs are presented in Section 5.1 by facility type, with separate models for FI crashes and PDO crashes. Similarly, CMFs and SDFs are presented in Sections 5.2 and 5.3, respectively, by facility type and injury severity. Crashes with the injury severity levels of "K", "A', "B", and "C" were classified as FI crashes. "PDO" crashes included the no-injury crashes (injury severity level of "O"). As discussed in Chapter 4, crashes on the entire facility (including both the managed lanes and the general-purpose lanes) were considered during model development. The crash data ranged from two to five years. After performing outlier analysis and limiting the segment length to a minimum of 0.01 miles, 24,327 and 20,145 crashes were included in the model development for reversible and non-reversible managed lanes facilities, respectively, as noted in Table 5.1. All facilities have at least one managed lane that is currently operational along the general-purpose lanes.

Table 5.1: Number of Crashes Included in Model Development

Facility Type	Injury Severity		Total
	Fatal and Injury (FI) Crashes	Property Damage Only (PDO) Crashes	
Non-reversible Managed Lanes Facilities	4,815	15,330	20,145
Reversible Managed Lanes Facilities	6,904	17,423	24,327
Total	11,719	32,753	44,472
Proportion (%)	26.4%	73.6%	100.0%

Note: The numbers include crashes that occurred on both the managed lanes and the general-purpose lanes.

5.1 SPFs

This study considered two sets of managed lanes facilities: non-reversible and reversible managed lanes facilities. Since PDO crashes are usually under-reported, separate models for FI and PDO crashes were developed. Additionally, previous studies have recommended developing models by collision type, particularly single-vehicle (SV) and multi-vehicle (MV) collisions. The rationale is that the influential variables are unique to each collision type. The research team first examined different functional forms with various combinations of variables while modeling the FI crashes. It was assumed that the FI crash model provides a true relationship between crashes and independent variables. About 14 explanatory variables were considered in various combinations of variables while modeling the FI crashes, as outlined in Section 4.4.2. The formula presented in Equation 5.1 reflects the findings from several preliminary regression analyses that gave the best variables combination. The same formula was also used to model the PDO crashes, even if some variables were strongly insignificant or counter-intuitive. The predicted crash frequency was calculated using Equations 5.1 – 5.3, as follows:

$$N_{i,s} = L \times y \times e^{b_0 + b_{aadt} \ln(AADT)} \times CMF_{ml} \times CMF_{lat} \quad (5.1)$$

with,

$$CMF_{ml} = e^{b_{ml}(N_{ml}-2)} \tag{5.2}$$

$$CMF_{lat} = I_{py}e^{b_{lat\_py}(W_{lat}-2)} + I_{bar}e^{b_{lat\_bar}(W_{lat}-2)} \tag{5.3}$$

where,

$N_{i,s}$	=	Predicted annual average crash frequency for collision type i ($i = SV$ or MV) and crash severity s ($s = FI$ or PDO),
L	=	Segment length (miles),
y	=	Number of years of crash data,
$AADT$	=	Average Annual Daily Traffic (veh per day),
CMF_{ml}	=	Crash Modification Factor for number of managed lanes,
CMF_{lat}	=	Crash Modification Factor for lateral separation width of the managed lanes from the general-purpose lanes,
N_{ml}	=	Number of managed lanes,
b_{ml}	=	Model coefficient for the number of managed lanes,
I_{py}	=	Indicator variable for pylons separation (=1 if pylons are present, = 0 otherwise),
I_{bar}	=	Indicator variable for concrete barrier separation (=1 if concrete barrier is present, =0 otherwise),
b_{lat_py}	=	Model coefficient for lateral separation width when pylons separation is present,
b_{lat_bar}	=	Model coefficient for lateral separation width when concrete barrier separation is present,
W_{lat}	=	Lateral separation width (ft).

5.1.1 Non-reversible Managed Lanes Facilities

5.1.1.1 FI Crash Models

Table 5.2 provides the calibrated coefficients for FI crashes for both the managed lanes and the general-purpose lanes on non-reversible managed lanes facilities. A significance level of 5% was used to include the variables in the model. However, the variable was also considered when the coefficient was not statistically significant, but was intuitive and within logical boundaries. The NLMIXED procedure in the SAS software was used to estimate the proposed model coefficients. This procedure was used because the proposed predictive model is both nonlinear and discontinuous. The log-likelihood function for the NB distribution was used to determine the best-fit model coefficients.

Table 5.2: Calibrated Coefficients for FI Crashes on Non-reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	Standard Error	t-statistic	p-value
$\boldsymbol{b_0}$	**Intercept**	**SV**	**-13.0779**	**5.2284**	**-2.50**	**0.0127**
		MV	**-19.6485**	**4.3618**	**-4.50**	**<0.0001**
$\boldsymbol{b_{aadt}}$	**AADT**	**SV**	**1.1976**	**0.4244**	**2.82**	**0.0050**
		MV	**1.8354**	**0.3555**	**5.16**	**<0.0001**
b_{ml}	Number of managed lanes	SV	-0.0807	0.0992	-0.81	0.4167
		MV	**0.1923**	**0.0859**	**2.24**	**0.0257**
b_{lat_py}	Separation width (pylons)	SV	-0.0174	0.0110	-1.58	0.1152
		MV	**-0.0266**	**0.0084**	**-3.15**	**0.0017**
b_{lat_bar}	Separation width (concrete barrier)	SV	0.0053	0.0256	0.21	0.8373
		MV	-0.0031	0.0187	-0.17	0.8676
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.4336**	**0.1551**	**9.24**	**<0.0001**
		MV	**1.7714**	**0.0952**	**18.62**	**<0.0001**

Note: SV = Single-vehicle; MV = Multi-vehicle; Boldfaced variables are significant at 95% level.

Figure 5.1 shows the fit of the SPF for FI crashes on the non-reversible managed lanes freeway segments. This figure compares the predicted and observed crash frequency in the data. The data were sorted by predicted crashes, and each data point in the figure represents the average predicted and aggregated observed crash frequency for a group of five sites. The data points were grouped to reduce the uncertainty in the prediction at individual sites. In general, the data shown in the figure indicate that the model provides an unbiased estimate of expected crash frequency.

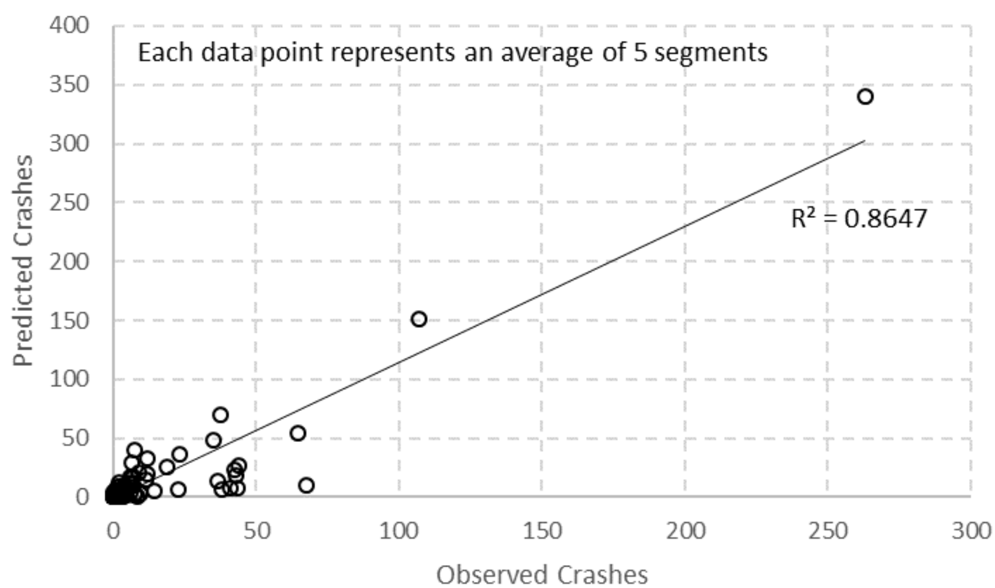


Figure 5.1: Observed vs. Predicted FI Crashes on Non-reversible Managed Lanes Facilities

The model results in Table 5.2 show that most variables are statistically significant at a 95% confidence level. Specifically, the significant variables include AADT, the number of managed lanes, and the interaction between the separation width and pylons. Only the interaction between separation width and the concrete barrier was not significant at 95% for both SV and MV models. The results indicated that the FI crashes (both SV and MV) increased with traffic volume (AADT). In the presence of pylons, as expected, FI crashes decreased with the increase in separation width.

Figure 5.2 presents the calibrated SPFs of non-reversible managed lanes facilities for MV–FI and SV–FI crashes. The equations are plotted for the case of all CMFs equal to 1.0 (representing base conditions). Additional conditions include concrete barrier separation, 2-ft separation width and two managed lanes. The figure shows the relationship between predicted MV–FI and SV–FI crashes (per year per mile) versus AADT. In general, the predicted crash frequency increases with an increase in AADT. However, the rate of increase is greater for MV–FI.

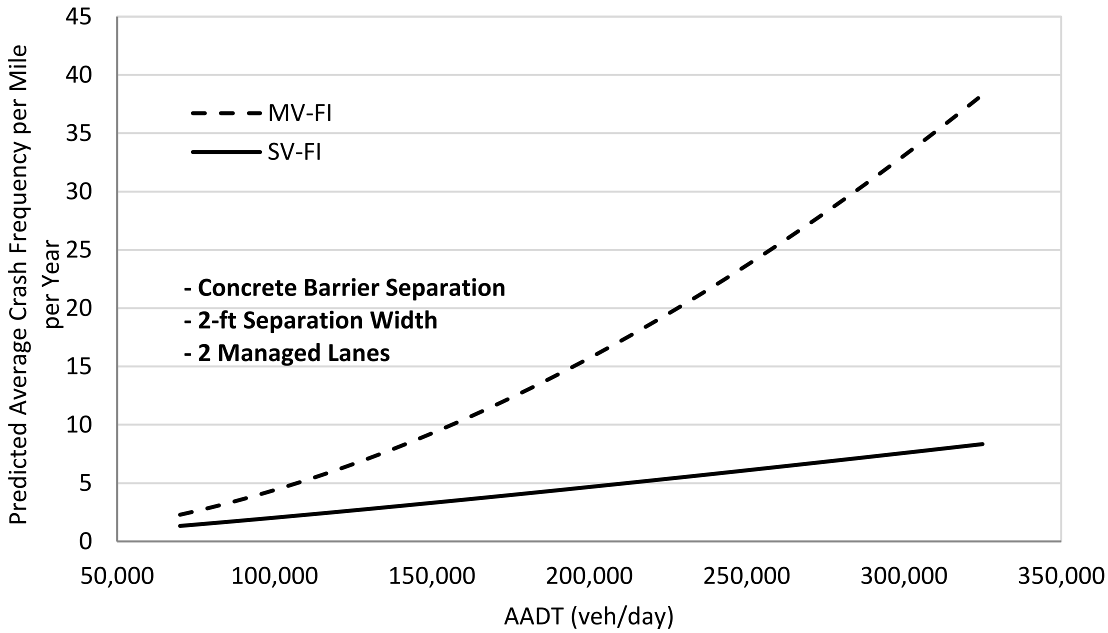


Figure 5.2: Predicted Average MV-FI and SV-FI Crashes per Mile per Year by AADT for Non-reversible Managed Lanes Facilities

5.1.1.2 PDO Crash Models

Table 5.3 presents the models for PDO crashes (that occurred on both the managed lanes and the general-purpose lanes). The table provides calibrated coefficients for PDO crashes on non-reversible managed lanes facilities. Similarly, a significance level of 5% was used to include the variables in the model. The variable was also considered when the coefficient is not statistically significant but is intuitive and within logical boundaries. The NLMIXED procedure in the SAS software was used to estimate the proposed model coefficients because the proposed predictive model is both nonlinear and discontinuous. The log-likelihood function for the NB distribution was used to determine the best-fit model coefficients.

Table 5.3: Calibrated Coefficients for PDO Crashes on Non-reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	Standard Error	t-statistic	p-value
$\boldsymbol{b_0}$	**Intercept**	**SV**	**-14.1066**	**5.0350**	**-2.80**	**0.0053**
		MV	**-32.2862**	**4.0627**	**-7.95**	**<0.0001**
$\boldsymbol{b_{aadt}}$	**AADT**	**SV**	**1.3582**	**0.4095**	**3.32**	**0.0010**
		MV	**2.9176**	**0.3285**	**8.88**	**<0.0001**
$\boldsymbol{b_{spd}}$	**Posted speed limit**	**All**	**0.0704**	**0.0216**	**3.26**	**0.0012**
b_{ml}	Number of managed lanes	SV	-0.0804	0.0988	-0.81	0.4162
		MV	**0.1947**	**0.0682**	**2.86**	**0.0045**
$\boldsymbol{b_{lat\_py}}$	**Separation width (pylons)**	**SV**	**-0.0355**	**0.0101**	**-3.53**	**0.0005**
		MV	**-0.0186**	**0.00828**	**-2.25**	**0.0251**
b_{lat_bar}	Separation width (concrete barrier)	SV	-0.0353	0.0246	-1.43	0.1521
		MV	-0.0216	0.0192	-1.13	0.2607
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.4731**	**0.1147**	**12.85**	**<0.0001**
		MV	**2.0432**	**0.0885**	**23.10**	**<0.0001**

Note: SV = Single-vehicle; MV = Multi-vehicle; Boldfaced variables are significant at 95% level.

Figure 5.3 shows the fit of the SPF for PDO crashes on the non-reversible managed lanes freeway segments. Similarly, the data shown in the figure indicate that the model provides an unbiased estimate of expected crash frequency.

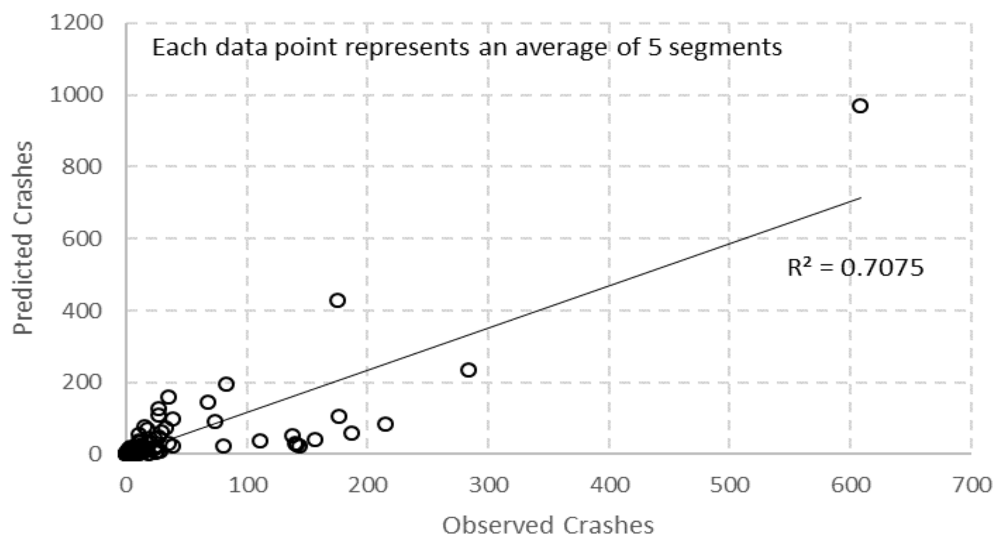


Figure 5.3: Observed vs. Predicted PDO Crashes on Non-reversible Managed Lanes Facilities

The model results in Table 5.3 show that most variables are statistically significant at a 95% confidence level. Specifically, such variables include AADT, the number of managed lanes, posted speed limit, and the interaction between the separation width and pylons. Only the interaction between separation width and the concrete barrier was not significant at 95% for both SV and MV models. The results indicate that the PDO crashes (both SV and MV) increase with traffic volume (AADT). As expected, PDO crashes decrease with an increase in separation width in the presence of pylons.

Figure 5.4 presents the calibrated SPFs for MV–PDO and SV–PDO crashes on non-reversible managed lanes facilities. The equations are plotted for the case of all CMFs equal to 1.0 (representing base conditions). Additional conditions include concrete barrier separation, 2-ft separation width and two managed lanes. The figure reveals that the predicted crash frequency increases with an increase in AADT. However, the rate of increase is greater for MV–PDO.

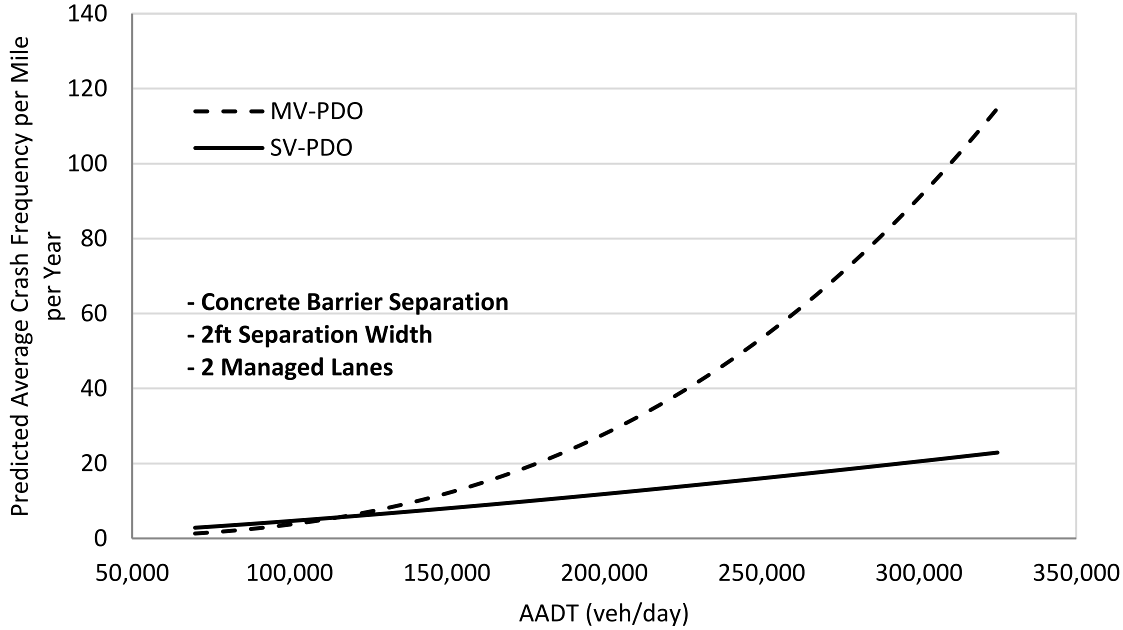


Figure 5.4: Predicted Average MV-PDO and SV-PDO Crashes per Mile per Year by AADT for Non-reversible Managed Lanes Facilities

5.1.2 Reversible Managed Lanes Facilities

5.1.2.1 FI Crash Models

Table 5.4 provides the calibrated coefficients for FI crashes on reversible managed lanes facilities. Note that all segments have managed lanes separated by a concrete barrier only. Note that the procedures discussed in Section 5.1.1 were followed for estimating the proposed model coefficients.

Table 5.4: Calibrated Coefficients for FI Crashes on Reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	Standard Error	t-statistic	p-value
b_0	Intercept	SV	-3.2563	2.8715	-1.13	0.2573
		MV	**-13.7089**	**2.7103**	**-5.06**	**<0.0001**
b_{aadt}	AADT	SV	0.3906	0.2408	1.62	0.1053
		MV	**1.3284**	**0.2262**	**5.87**	**<0.0001**
$\boldsymbol{b_{spd}}$	**Posted speed limit**	**All**	**0.0328**	**0.0106**	**3.10**	**0.0020**
b_{ml}	Number of managed lanes	SV	-0.1048	0.0971	-1.08	0.2809
		MV	**-0.3484**	**0.0871**	**-4.00**	**<0.0001**
b_{lat_bar}	Separation width (concrete barrier)	**SV**	**-0.0268**	**0.0084**	**-3.18**	**0.0015**
		MV	0.0080	0.0072	1.12	0.2637
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.3086**	**0.1282**	**10.21**	**<0.0001**
		MV	**1.2270**	**0.0876**	**14.01**	**<0.0001**

Note: SV = Single-vehicle; MV = Multi-vehicle; Boldfaced variables are significant at 95% level.

Figure 5.5 shows the fit of the SPF for FI crashes on the reversible managed lanes freeway sections. In general, the data shown in the figure indicate that the model provides an unbiased estimate of expected crash frequency.

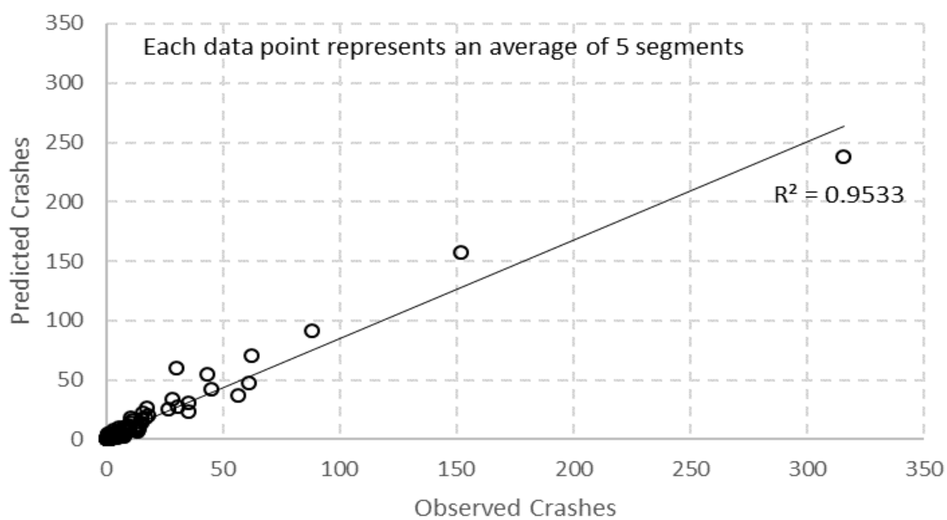


Figure 5.5: Observed vs. Predicted FI Crashes on Reversible Managed Lanes Facilities

Figure 5.6 presents the relationship between predicted MV–FI crashes and AADT for reversible managed lanes facilities. The equations are plotted for the case of all CMFs equal to 1.0 (representing base conditions). Additional conditions include concrete barrier separation, 2-ft separation width, and two managed lanes. In general, the predicted crash frequency increases with an increase in AADT.

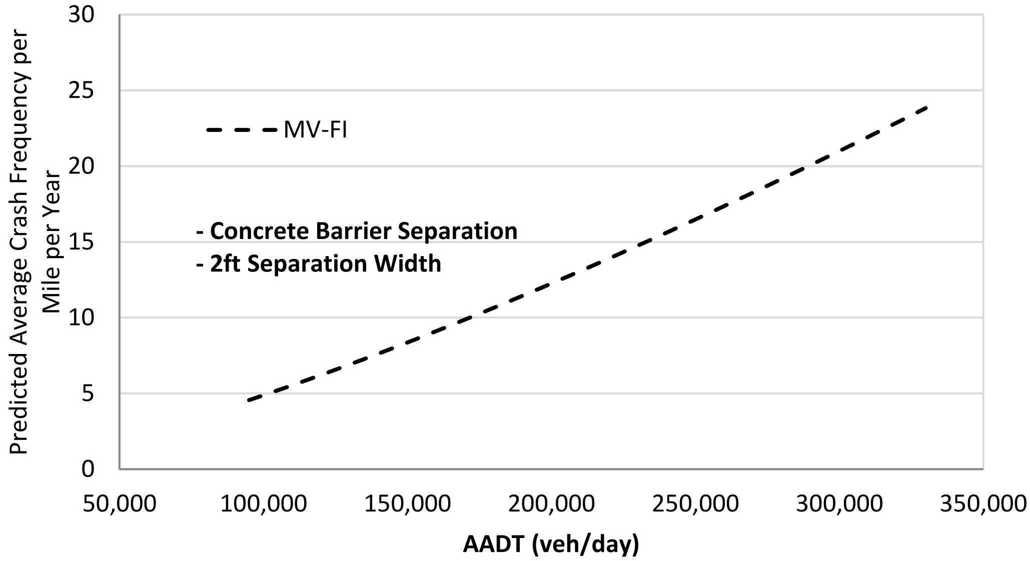


Figure 5.6: Predicted Average MV-FI Crashes per Mile per Year by AADT for Reversible Managed Lanes Facilities

5.1.2.2 PDO Crash Models

Table 5.5 provides the calibrated coefficients for PDO crashes on reversible managed lanes facilities.

Table 5.5: Calibrated Coefficients for PDO Crashes on Reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	Standard Error	t-statistic	p-value
b_0	Intercept	SV	-5.0339	2.7290	-1.84	0.0656
		MV	**-9.9968**	**2.6566**	**-3.76**	**0.0002**
$\boldsymbol{b_{aadt}}$	**AADT**	**SV**	**0.5892**	**0.2282**	**2.58**	**0.0101**
		MV	**1.0998**	**0.2223**	**4.95**	**<0.0001**
$\boldsymbol{b_{spd}}$	**Posted speed limit**	**All**	**0.0504**	**0.0104**	**4.87**	**<0.0001**
b_{ml}	Number of managed lanes	SV	-0.1245	0.0934	-1.33	0.1829
		MV	**-0.4268**	**0.0936**	**-4.56**	**<0.0001**
b_{lat_bar}	Separation width (concrete barrier)	SV	-0.0066	0.0079	-0.83	0.4057
		MV	0.0087	0.0070	1.24	0.2161
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.1485**	**0.0991**	**11.59**	**<0.0001**
		MV	**1.1917**	**0.0801**	**14.88**	**<0.0001**

Note: SV = Single-vehicle; MV = Multi-vehicle; Boldfaced variables are significant at 95% level.

Figure 5.7 shows the fit of the SPF for PDO crashes on the reversible managed lanes freeway sections. In general, the data shown in the figure indicate that the model provides an unbiased estimate of expected crash frequency.

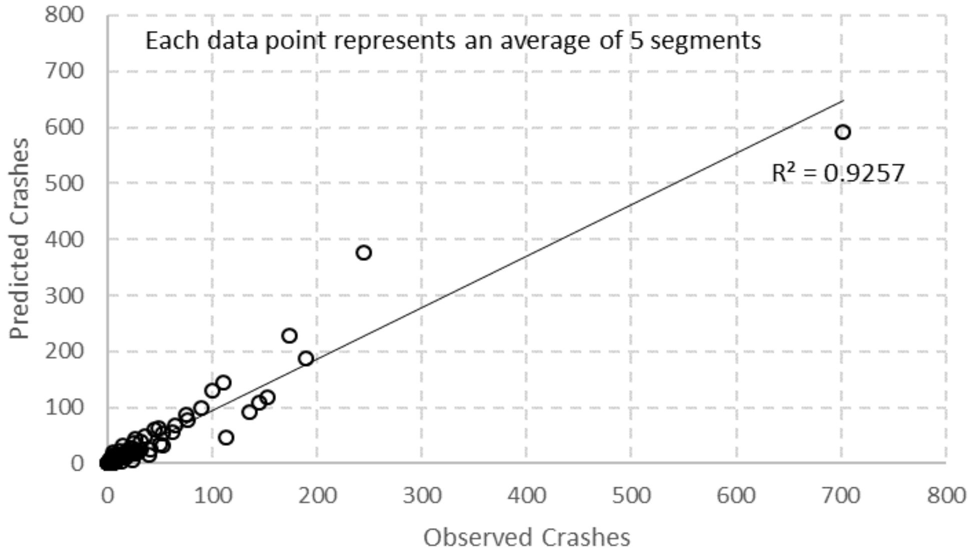


Figure 5.7: Observed vs. Predicted PDO Crashes on Reversible Managed Lanes Facilities

Figure 5.8 presents the calibrated SPFs for the reversible managed lanes facilities for MV–PDO and SV–PDO crashes. The equations are plotted for the case of all CMFs equal to 1.0 (representing base conditions). Additional conditions include concrete barrier separation, 2-ft separation width, and two managed lanes. The figure shows that the predicted crash frequency increases with an increase in AADT. However, the rate of increase is greater for MV–PDO.

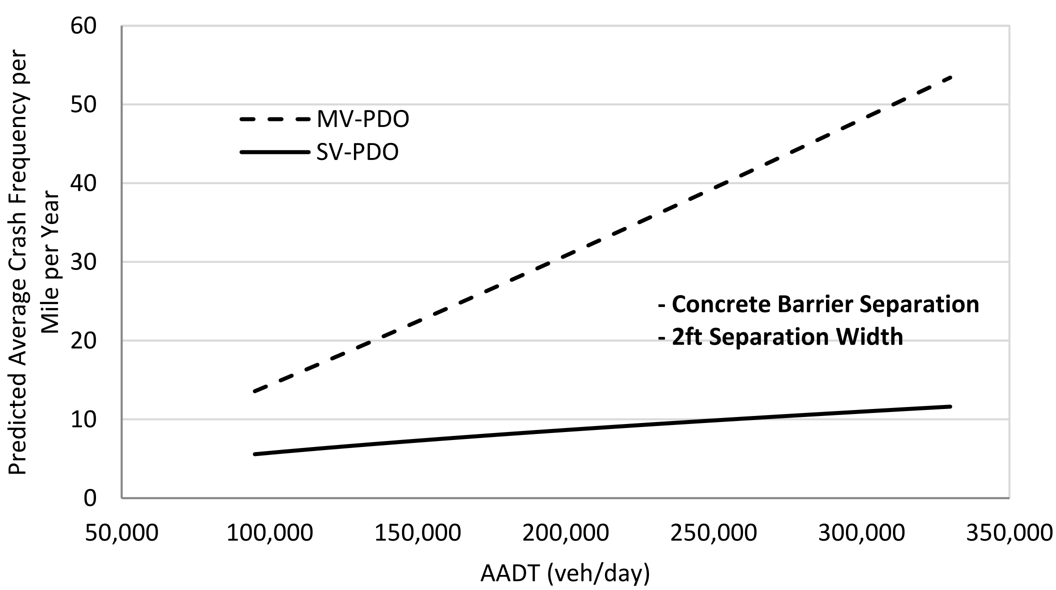


Figure 5.8: Predicted Average MV-PDO and SV-PDO Crashes per Mile per Year by AADT for Reversible Managed Lanes Facilities

5.2 CMFs

As defined earlier, a CMF represents the relative crash frequency change due to a specific condition when all other conditions and location characteristics remain constant. A CMF of less than one (< 1) indicates a reduction in the crash frequency. In contrast, a CMF of greater than one (> 1) indicates an increase in the frequency of crashes when a particular design or operational characteristic or roadway geometric characteristic deviates from the base conditions. In this study, the CMFs for the number of managed lanes and separation width of managed lanes from the general-purpose lanes by collision type ($i = SV$ or MV) and crash injury severity ($s = FI$ or PDO) were calculated using Equations 5.4 and 5.5.

$$CMF_{ml\_i-s} = e^{b_{ml}(N_{ml}-2)} \quad (5.4)$$
$$CMF_{lat\_i-s} = I_{py}e^{b_{lat\_py}(W_{lat}-2)} + I_{bar}e^{b_{lat\_bar}(W_{lat}-2)} \quad (5.5)$$

where,

CMF_{ml_i-s}	=	Crash Modification Factor for number of managed lanes for collision type i ($i = SV$ or MV) and crash injury severity s ($s = FI$ or PDO),
CMF_{lat_i-s}	=	Crash Modification Factor for lateral separation width of managed lanes from the general-purpose lanes for collision type i ($i = SV$ or MV) and crash injury severity s ($s = FI$ or PDO),
b_{ml}	=	Model coefficient for the number of managed lanes,
N_{ml}	=	Number of managed lanes,
I_{py}	=	Indicator variable for pylons separation (=1 if pylons are present, = 0 otherwise),
I_{bar}	=	Indicator variable for concrete barrier separation (=1 if a concrete barrier is present, =0 otherwise),
b_{lat_py}	=	Model coefficient for lateral separation width when pylons separation is present,
b_{lat_bar}	=	Model coefficient for lateral separation width when concrete barrier separation is present, and
W_{lat}	=	Lateral separation width (ft).

5.2.1 Non-reversible Managed Lanes Facilities

The CMFs for the number of managed lanes and the interaction between the separation type and separation width are presented using Equations 5.6 – 5.13:

$$CMF_{ml\_SV-FI} = e^{-0.0807(N_{ml}-2)} \quad (5.6)$$
$$CMF_{ml\_MV-FI} = e^{0.1923(N_{ml}-2)} \quad (5.7)$$
$$CMF_{ml\_SV-PDO} = e^{-0.0804(N_{ml}-2)} \quad (5.8)$$
$$CMF_{ml\_MV-PDO} = e^{0.1947(N_{ml}-2)} \quad (5.9)$$
$$CMF_{lat\_SV-FI} = I_{py}e^{-0.0174(W_{lat}-2)} + I_{bar}e^{0.0053(W_{lat}-2)} \quad (5.10)$$
$$CMF_{lat\_MV-FI} = I_{py}e^{-0.0266(W_{lat}-2)} + I_{bar}e^{-0.0031(W_{lat}-2)} \quad (5.11)$$
$$CMF_{lat\_SV-PDO} = I_{py}e^{-0.0355(W_{lat}-2)} + I_{bar}e^{-0.0353(W_{lat}-2)} \quad (5.12)$$

$$CMF_{lat\_MV-PDO} = I_{py}e^{-0.0186(W_{lat}-2)} + I_{bar}e^{-0.0216(W_{lat}-2)} \quad (5.13)$$

Figures 5.9 through 5.12 present the graphical representations of the annotated CMF equations that are statistically significant at a 95% confidence level. The following key observations can be made from the figures:

- CMFs decrease with an increase in separation width, which means that PDO crashes decrease as the separation width between the general-purpose and the managed lanes increases (Figures 5.9 – 5.11).
- On average, in the presence of pylons, SV–PDO crashes decrease by 3.5% for each additional foot of lateral separation width (Figure 5.9). On the other hand, in the presence of pylons, MV–PDO crashes decrease by an average of 1.8% for each additional foot of lateral separation width (Figure 5.10).
- In the presence of pylons, MV–FI crashes decrease by an average of 2.6% for each additional foot of lateral separation width (Figure 5.11).
- The number of managed lanes presents similar effects on MV–FI and MV–PDO crashes. On average, MV–FI and MV–PDO crashes increase by 21.2% for each additional managed lane (Figure 5.12).

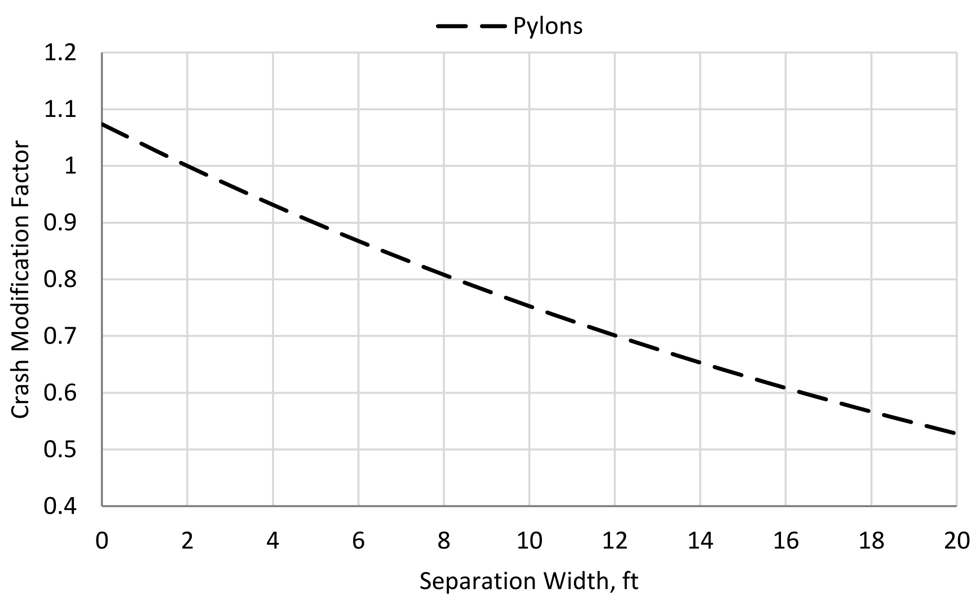


Figure 5.9: CMF by Separation Type and Width for SV-PDO Crashes

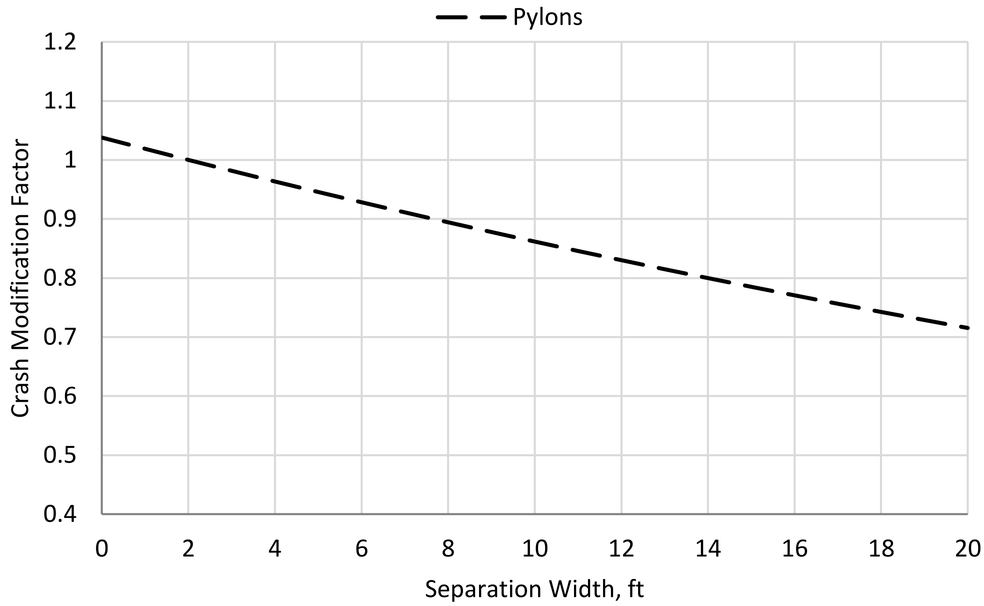


Figure 5.10: CMF by Separation Type and Width for MV-PDO Crashes

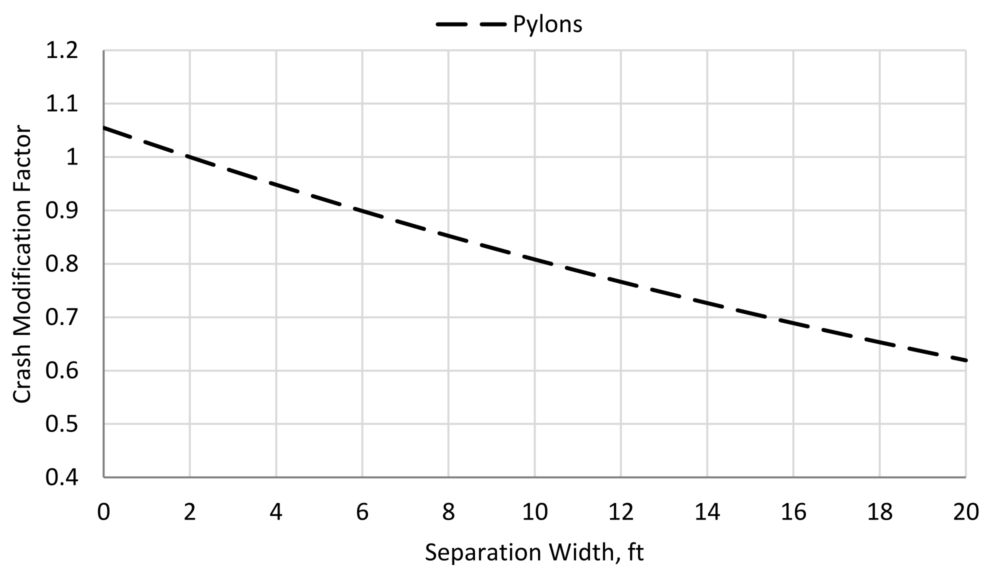


Figure 5.11: CMF by Separation Type and Width for MV-FI Crashes

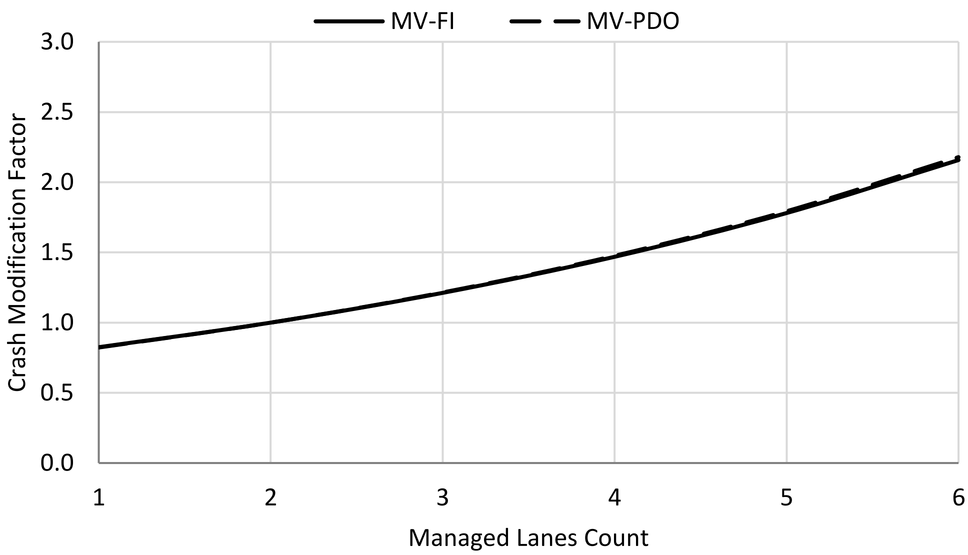


Figure 5.12: CMF by Number of Managed Lanes for MV Crashes

The models in Tables 5.2 and 5.3 indicate that some variables are not statistically significant at a 95% confidence level. Overall, the analysis demonstrates that interaction between the presence of concrete barrier separation and the separation width is not a statistically significant predictor of crashes in the case of non-reversible managed lanes facilities. In addition, the interaction between the presence of pylon separation and the separation width is not a statistically significant predictor of SV–FI crashes. Despite not being statistically significant (at a 95% confidence level), the following observations can be made from the figures:

- On average, in the presence of concrete barrier separation, SV–FI crashes increase by an average of 0.5% for each additional foot of lateral separation width.
- On average, in the presence of concrete barrier separation, SV–PDO crashes decrease by 3.5% for each additional foot of lateral separation width.
- On average, in the presence of concrete barrier separation, MV–FI crashes decrease by 0.3% for each additional foot of lateral separation width.
- On average, in the presence of concrete barrier separation, MV–PDO crashes decrease by 2.1% for each additional foot of lateral separation width.
- The number of managed lanes presents similar effects on SV–FI and SV–PDO crashes. On average, SV–FI and SV–PDO crashes decrease by 7.7% for each additional managed lane.

5.2.2 Reversible Managed Lanes Facilities

The CMFs for the number of managed lanes and the interaction between the separation type and separation width are presented using Equations 5.14 through 5.21:

$$CMF_{ml\_SV-FI} = e^{-0.1048(N_{ml}-2)} \quad (5.14)$$

$$CMF_{ml\_MV-FI} = e^{-0.3484(N_{ml}-2)} \quad (5.15)$$

$$CMF_{ml\_SV-PDO} = e^{-0.1245(N_{ml}-2)} \quad (5.16)$$
$$CMF_{ml\_MV-PDO} = e^{-0.4268(N_{ml}-2)} \quad (5.17)$$

$$CMF_{lat\_SV-FI} = I_{bar}e^{-0.0268(W_{lat}-2)} \quad (5.18)$$
$$CMF_{lat\_MV-FI} = I_{bar}e^{0.0080(W_{lat}-2)} \quad (5.19)$$
$$CMF_{lat\_SV-PDO} = I_{bar}e^{-0.0066(W_{lat}-2)} \quad (5.20)$$
$$CMF_{lat\_MV-PDO} = I_{bar}e^{0.0087(W_{lat}-2)} \quad (5.21)$$

Figures 5.13 and 5.14 present the graphical representations of the annotated CMF equations that are statistically significant at a 95% confidence level. The following key observations can be made from the figures:

- On average, in the presence of the concrete barrier, SV–FI crashes decrease by 2.6% for each additional foot of lateral separation width (Figure 5.13).
- On average, MV–FI crashes decrease by 29.4% for each additional managed lane. On the other hand, MV–PDO crashes decrease by an average of 34.7% for each additional managed lane (Figure 5.14).

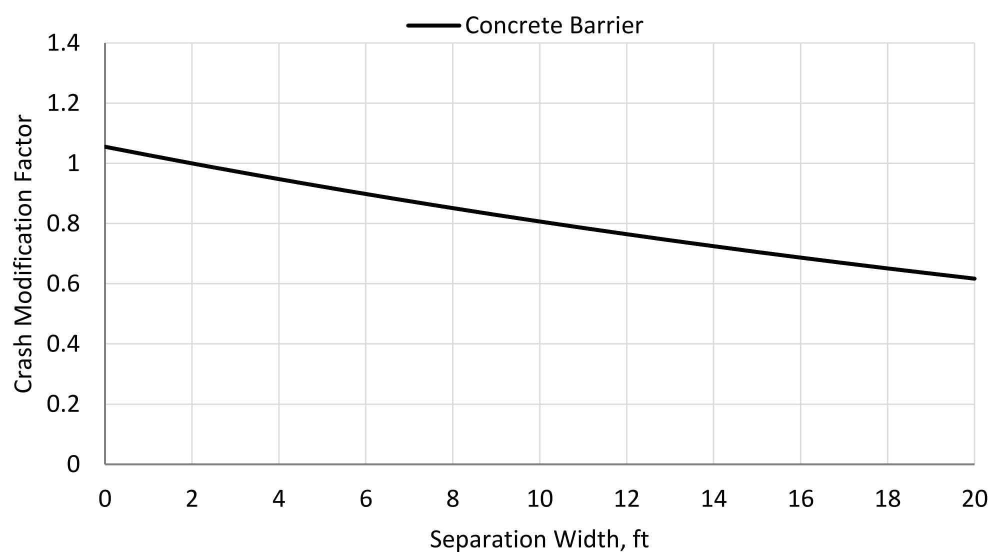


Figure 5.13: CMF by Separation Type and Width for SV-FI Crashes

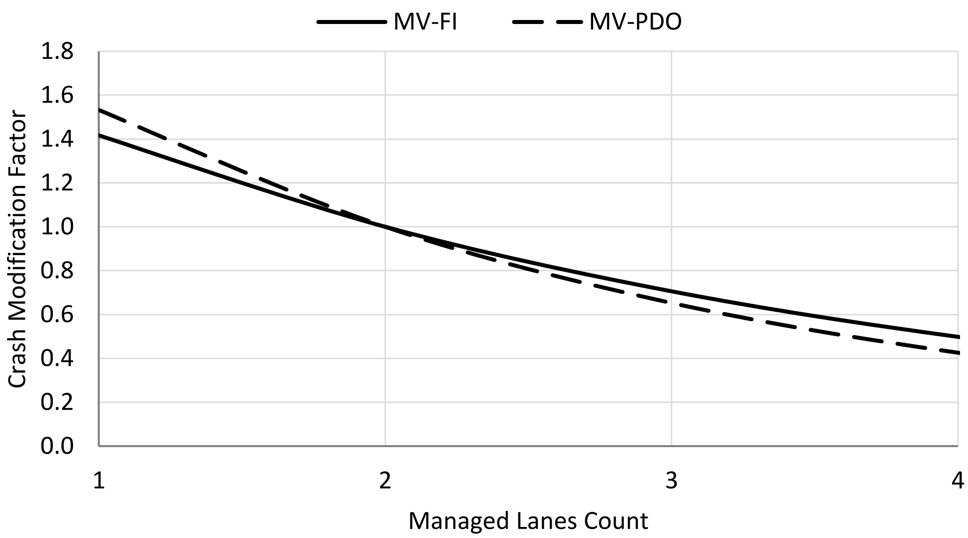


Figure 5.14: CMF by Number of Managed Lanes for MV Crashes

The models in Tables 5.4 and 5.5 indicate that some variables are not statistically significant at a 95% confidence level. Overall, the analysis demonstrates that interaction between the presence of concrete barrier separation and the separation width is not a statistically significant predictor of SV–PDO, MV–FI, and MV–PDO crashes in the case of reversible lane facilities. Despite not being statistically significant at a 95% confidence level, the following observations can be made from the figures:

- On average, in the presence of the concrete barrier, SV–PDO crashes decrease by 0.7% for each additional foot of lateral separation width.
- On average, in the presence of the concrete barrier, MV–FI crashes increase by 0.8% for each additional foot of lateral separation width.
- On average, in the presence of the concrete barrier, MV–PDO crashes increase by 0.9% for each additional foot of lateral separation width.
- On average, SV–FI crashes decrease by 9.9% for each additional managed lane. On the other hand, SV–PDO crashes decrease by an average of 11.7% for each additional managed lane.

5.3 SDFs

The database assembled for calibration included crash severity level as a dependent variable and each site's geometric and traffic variables as independent variables. Each row (i.e., site characteristics) was repeated from the original database to the frequency of each severity level. Thus, a segment with n crashes was repeated n number of times. It should be noted that the segments with PDO crashes were not included in the database. The total sample size of the final dataset for model calibration will be equal to the total number of fatal and injury crashes in the original dataset. The "possible injury" category was set as the base scenario with coefficients restricted at zero during the model calibration.

5.3.1 Non-reversible Managed Lanes Facilities

When a particular category had very few reported crashes, some combination of the severity categories was needed to obtain statistically reliable estimates (e.g., K+A, B, C). In the case of non-reversible managed lanes facilities, there were very few K crashes, so they were combined with A crashes.

The adjusted probability for each severity category was using Equations 5.22 – 5.24, as shown:

$$P_{K+A} = \frac{e^{V_{K+A}}}{1 + e^{V_{K+A}} + e^{V_B}} \tag{5.22}$$

$$P_B = \frac{e^{V_B}}{1 + e^{V_{K+A}} + e^{V_B}} \tag{5.23}$$

$$P_C = 1 - (P_{K+A} + P_B) \tag{5.24}$$

Table 5.6 provides SDFs for crashes on non-reversible managed lanes facilities.

Table 5.6: SDFs for Non-reversible Managed Lanes Facilities

Variable	Fatality (K) + Incapacitating injury (A)		Non-Incapacitating injury (B)	
	Coefficient	t-value	Coefficient	t-value
Alternative specific constant	-2.8759	-3.11	-4.1962	-7.17
Posted speed limit	0.0152	0.99	0.0527	5.45
Presence of ramp	0.2451	1.57	0.2532	2.59
Separation width (pylons)	-0.0494	-4.95	-0.0050	-0.92
Separation width (concrete barrier)	-0.0221	-1.21	-0.0022	-0.21

Figures 5.15 through 5.18 present the distribution of crashes by severity and different explanatory variables. The following key observations can be made from the figures:

- While the proportion of K+A crashes remains nearly the same throughout the 55 – 65 mph posted speed limit window, the proportion of non-incapacitating injury (B) crashes increases with posted speed limit (Figure 5.15).
- The proportions of K+A, and B crashes increase at segments with ramps (Figure 5.16).
- The proportions of K+A, and B crashes decrease as the separation width between the general-purpose lanes and the managed lanes increases in the presence of (Figure 5.17).
- Similarly, the K+A, and B crashes decrease as the separation width between the general-purpose lanes and the managed lanes increases in the presence of concrete barrier (Figure 5.18).

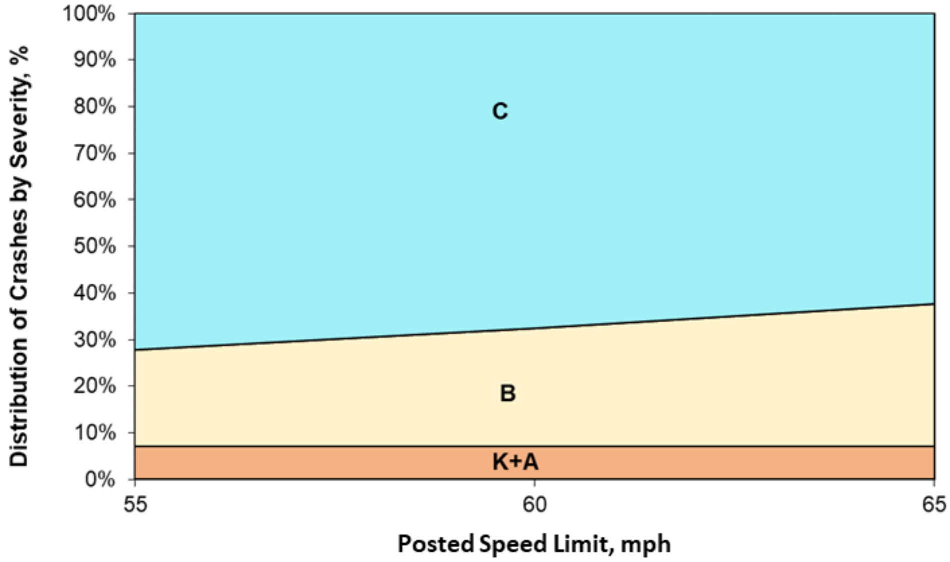


Figure 5.15: Distribution of Crashes by Severity and Posted Speed Limit on Non-reversible Managed Lanes Facilities

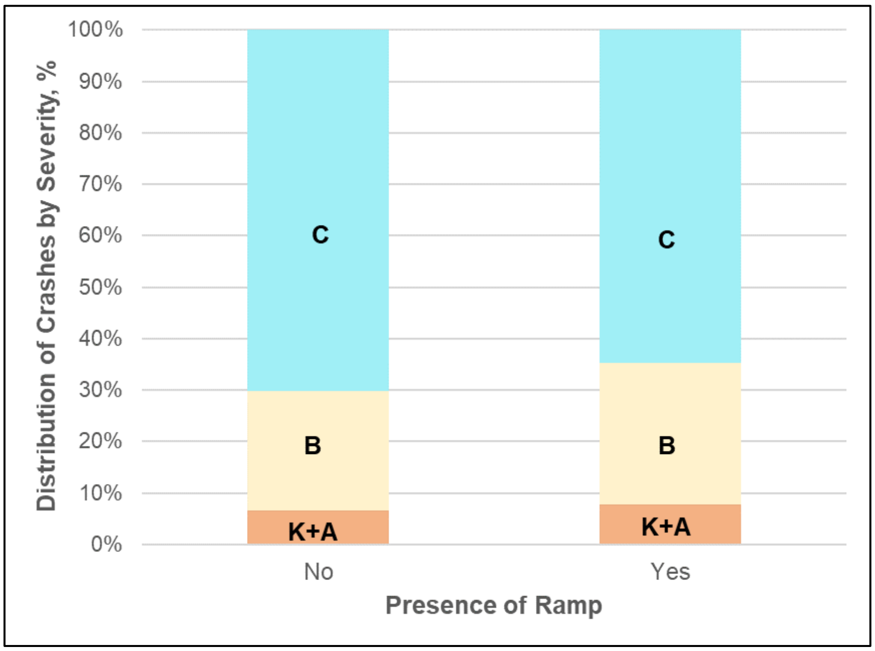


Figure 5.16: Distribution of Crashes by Severity and Presence of Ramp on Non-reversible Managed Lanes Facilities

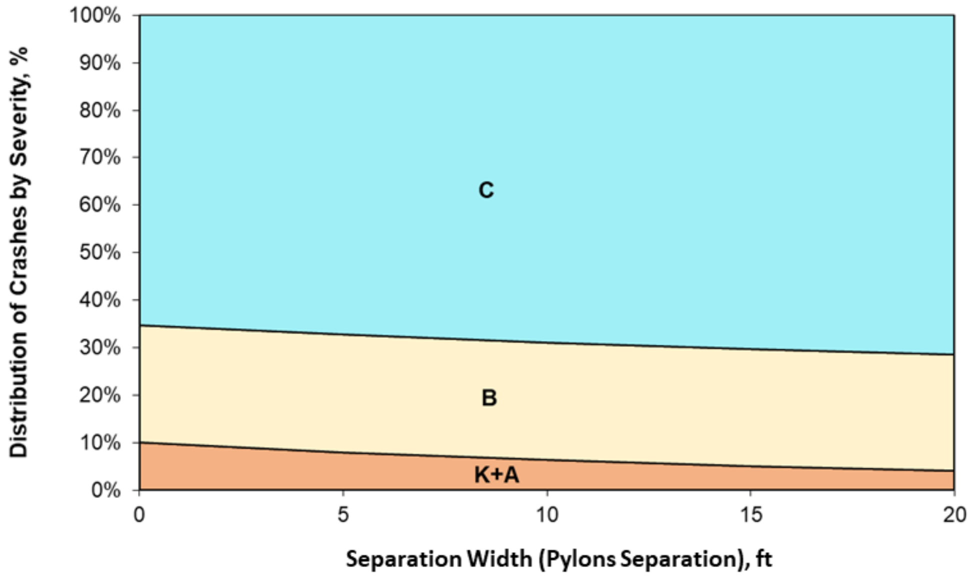


Figure 5.17: Distribution of Crashes by Severity and Separation Width in the Presence of Pylons Separation on Non-reversible Managed Lanes Facilities

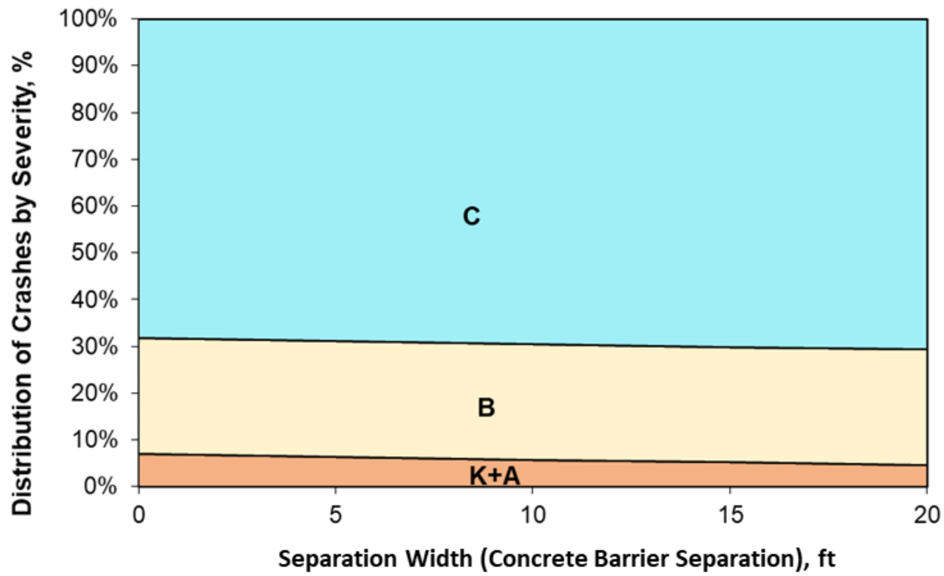


Figure 5.18: Distribution of Crashes by Severity and Separation Width in the Presence of Concrete Barrier Separation on Non-reversible Managed Lanes Facilities

5.3.2 Reversible Managed Lanes Facilities

In the case of reversible managed lanes facilities, the adjusted probability for each severity category was given as:

$$P_K = \frac{e^{V_K}}{1 + e^{V_K} + e^{V_A} + e^{V_B}} \quad (5.25)$$

$$P_A = \frac{e^{V_A}}{1 + e^{V_K} + e^{V_A} + e^{V_B}} \quad (5.26)$$

$$P_B = \frac{e^{V_B}}{1 + e^{V_K} + e^{V_A} + e^{V_B}} \quad (5.27)$$

$$P_C = 1 - (P_K + P_A + P_B) \quad (5.28)$$

Table 5.7 provides the SDFs for crashes on reversible managed lanes facilities. A significance level of 5% was used to include the variables in the model. However, the variable was also considered when the coefficient was not statistically significant, but was intuitive and within logical boundaries. The NLMIXED procedure in the SAS software was used to estimate the proposed model coefficients.

Table 5.7: SDFs for Reversible Managed Lanes Facilities

Variable	Fatality (K)		Incapacitating injury (A)		Non-Incapacitating injury (B)	
	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
Alternative specific constant	-3.2909	-5.24	-2.7828	-6.45	-1.2537	-5.5
Number of managed lanes	0.509	3.71	0.5285	6.06	0.3814	7.24
GPL outside shoulder width	-0.05686	-1.95	-0.03545	-1.95	-0.01483	-1.78
ML inside shoulder width	-0.1706	-3.97	-0.0939	-1.44	-0.05286	-3.97
Presence of ramp	0.2453	1.53	0.2453	1.53	--	--

Figures 5.19 through 5.22 present the distribution of crashes by severity and different explanatory variables. The following key observations can be made from the figures:

- The proportions of K, A, and B crashes increase with the number of managed lanes (Figure 5.19).
- The proportions of K, A, and B crashes slightly increase at segments with ramps (Figure 5.20).
- The proportions of K, A, and B crashes decrease with the outside shoulder width on the general-purpose lanes (Figure 5.21).
- The proportions of K, A, and B crashes decrease with the inside shoulder width on managed lanes (Figure 5.22).

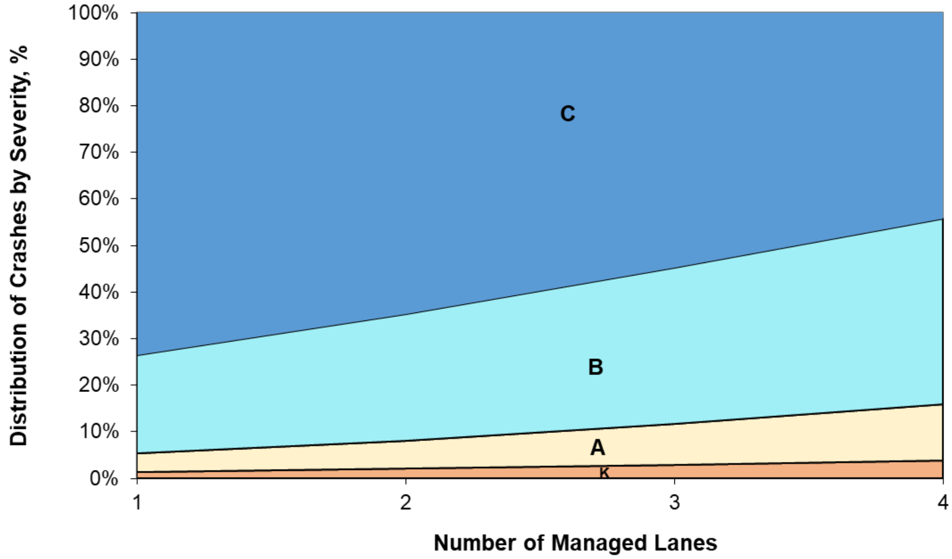


Figure 5.19: Distribution of Crashes by Severity and Number of Managed Lanes on Reversible Managed Lanes Facilities

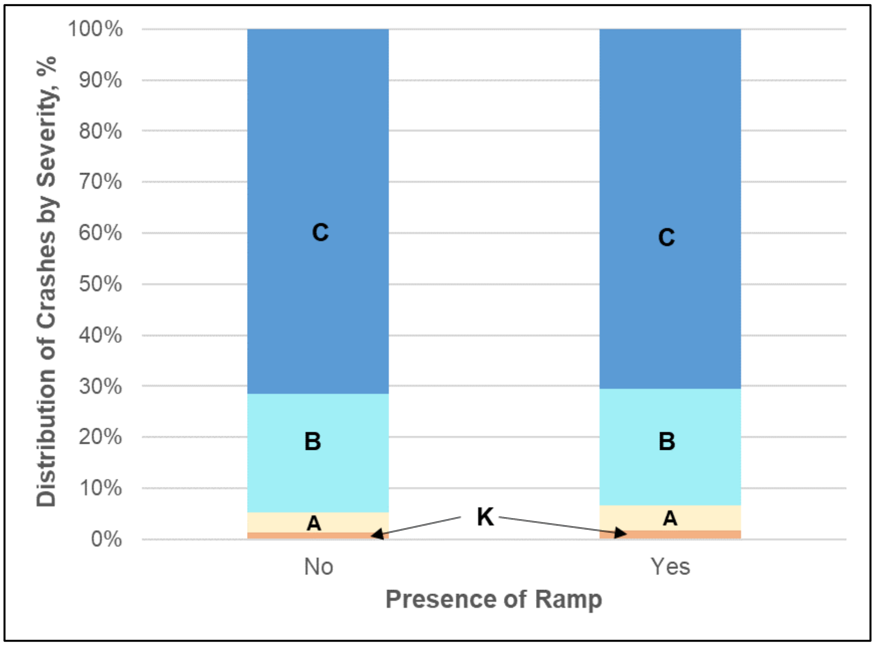


Figure 5.20: Distribution of Crashes by Severity and Presence of Ramp on Reversible Managed Lanes Facilities

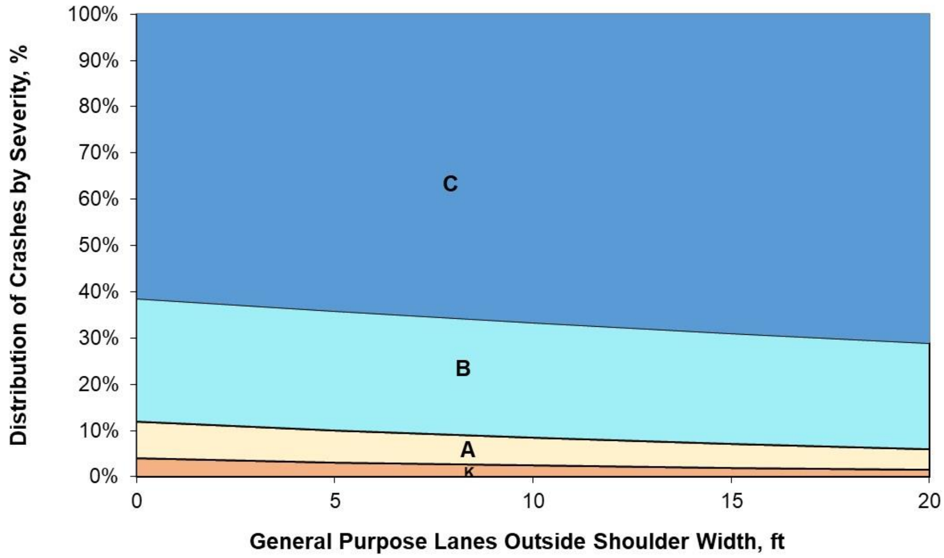


Figure 5.21: Distribution of Crashes by Severity and Outside Shoulder Width on General-purpose Lanes on Reversible Managed Lanes Facilities

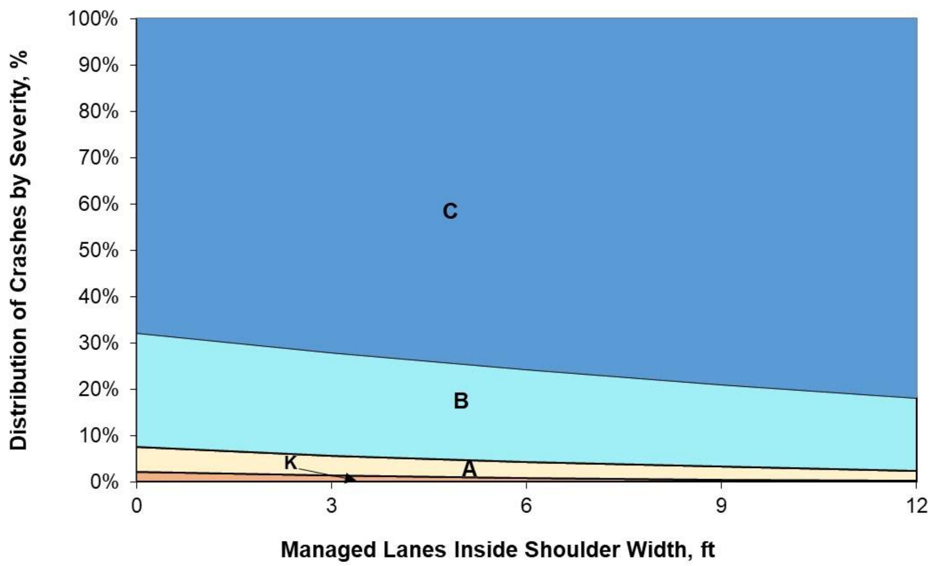


Figure 5.22: Distribution of Crashes by Severity and Inside Shoulder Width on Managed Lanes on Reversible Managed Lanes Facilities

5.4 Summary

This chapter presented SPFs, CMFs, and SDFs for reversible and non-reversible managed lanes facilities. The SPFs were presented by facility type, collision type (SV and MV) and by injury severity (FI and PDO crashes). Similarly, CMFs were presented by facility type, collision type (SV and MV) and by injury severity (FI and PDO crashes). Crashes with the injury severity levels of “K”, “A’, “B”, and “C” were classified as FI crashes. “PDO” crashes included the no-injury crashes (injury severity level of “O”). The SDFs were presented by facility type.

CHAPTER 6
TECHNOLOGY TRANSFER ACTIVITIES

The technology transfer outputs include sample problems, a spreadsheet application, a GIS inventory of managed lanes in Florida, and two one-page summary sheets. These outputs aim to ease the understanding and use of the research outcomes presented in this report. The outputs would also be helpful to share the research outcomes with practitioners. The summary sheets, provided in Appendix E, provide a one-page information source on separation treatments for reversible and non-reversible managed lanes facilities. This chapter provides additional details on the following outputs:

- Sample problems
- Spreadsheet application
- GIS inventory

6.1 Sample Problems

The following sections focus on the high-level steps and illustrative sample problems to determine the total crash frequency on reversible and non-reversible managed lanes facilities. Three sample problems are provided for guidance.

6.1.1 Steps and Specific Considerations

The developed prediction model yields an estimate of the predicted average crash frequency for a managed lanes facility. As illustrated in Equations. 6.1 through 6.3, the model gives predicted annual average crash frequency for a segment with length "L".

$$N_{i,s} = L \times 1 \times e^{b_0 + b_{aadt} \ln(AADT)} \times CMF_{ml} \times CMF_{lat} \tag{6.1}$$

with,

$$CMF_{ml} = e^{b_{ml}(N_{ml}-2)} \tag{6.2}$$

$$CMF_{lat} = I_{py} e^{b_{lat\_py}(W_{lat}-2)} + I_{bar} e^{b_{lat\_bar}(W_{lat}-2)} \tag{6.3}$$

where,

$N_{i,s}$	=	Predicted annual average crash frequency for collision type i ($i = SV$ or MV) and crash injury severity s ($s = FI$ or PDO),
L	=	Segment length (miles),
y	=	Number of years of crash data,
$AADT$	=	Average Annual Daily Traffic (veh per day),
CMF_{ml}	=	Crash Modification Factor for number of managed lanes,
CMF_{lat}	=	Crash Modification Factor for lateral separation width of managed lanes from the general-purpose lanes,
N_{ml}	=	Number of managed lanes,
b_{ml}	=	Model coefficient for number of managed lanes,

I_{py} = Indicator variable for pylons separation (=1 if pylons are present, = 0 otherwise),

I_{bar} = Indicator variable for concrete barrier separation (=1 if concrete barrier is present, =0 otherwise),

b_{lat_py} = Model coefficient for lateral separation width when pylons separation is present,

b_{lat_bar} = Model coefficient for lateral separation width when concrete barrier separation is present, and

W_{lat} = Lateral separation width (ft).

The following paragraphs explain the details of each step of the method as applied to complete an analysis. The steps are also presented in an evaluation flowchart in Figure 6.1.

Step 1 - *Define the limits of the roadway facility or site for which the predicted average crash frequency is to be estimated.*

The method can be undertaken for a roadway facility or an individual site. A site is a homogeneous roadway segment. The method can be applied to an existing roadway, a design alternative for an existing roadway, or a design alternative for a new roadway (which may be either not constructed or yet to experience enough traffic to have observed crash data). The limits of the roadway of interest will depend on the nature of the study. The study may be limited to only one specific site or a group of contiguous sites.

Step 2 - *Define the period of interest.*

The method can be undertaken for either the past or future period measured in years. Years of interest will be determined by the availability of observed or forecast AADT volumes and geometric design data and may not necessarily be full calendar years. Whether the method is used for the past, or future, period depends on the purpose of the study.

Step 3 - *For the study period, determine the availability of annual average daily traffic volumes and other data.*

Step 4 - *Determine geometric design features and site characteristics for all sites in the study corridor.*

The following geometric features are used to select an appropriate SPF:

- Segment length (miles)
- AADT (vehicles per day)
- Number of managed lanes
- Separation type
- Lateral separation width – the buffer that separates the managed lanes from the general-purpose lanes
- Injury severity

Step 5 - *Divide the roadway facility under consideration into individual homogenous roadway segments, which are referred to as sites.*

Using the information from Step 1 through Step 4, the corridor is divided into individual sites, consisting of individual homogenous roadway segments. When dividing roadway facilities into shorter homogenous roadway segments, limit the segment length to a minimum of 0.01 miles to decrease data collection and management efforts. The following variables could be used in dividing the roadway into homogenous roadway segments:

- Facility type (non-reversible and reversible managed lanes facility)
- Posted speed limit
- AADT
- Number of managed lanes
- Separation type
- Lateral separation width

Step 6 - *Select the first or next individual site in the study corridor. If there are no more sites to be evaluated, proceed to Step 11.*

In Step 5, the roadway within the study limits is divided into individual homogenous sites (roadway segments). The outcome of the method is the predicted average crash frequency of the entire study corridor, which is the sum of all of the individual sites for each year in the study.

Step 7 - *For the selected site, select the first or next year in the period of interest. If there are no more years to be evaluated for that site, proceed to Step 10.*

Steps 7 through 9 are repeated for each site in the study corridor and each year in the study period. The individual years of the evaluation period may have to be analyzed one year at a time for any particular roadway segment because AADT and other features may change from year to year.

Step 8 - *For the selected site, determine and apply the appropriate safety performance function (SPF) for the site's facility type.*

As indicated earlier, the facility type is either a non-reversible or reversible managed lanes facility. These two different facilities bear different safety performance functions. In addition, within each facility type, there are separate SPFs for SV and MV crashes and for FI and PDO crash frequencies. If the total predicted crash frequency is needed, the analyst should add all four values: SV–FI, SV–PDO, MV–FI, and MV–PDO.

Step 9 - *If there is another year to be evaluated in the study period for the selected site, return to Step 7. Otherwise, proceed to Step 10.*

This step creates a loop through Steps 7 through 9 that is repeated for each year of the evaluation period for the selected site.

Step 10 - *If there is another site to be evaluated, return to Step 6. Otherwise, proceed to Step 11.*

This step creates a loop through Steps 6 to 10 that is repeated for each roadway segment within the facility.

Step 11 – *Sum the results from all sites, injury severities, and years in the study, to estimate the total crash frequency.*

The total estimated number of crashes within the facility limits during a study period of *n* years is calculated using Equation 6.4, follows:

$$N_{total} = \sum_{\substack{All \\ roadway \\ segments}} N_{rs} \tag{6.4}$$

where,

N_{total} = total predicted number of crashes within the limits of a facility for the period of interest, or the sum of the predicted average crash frequency for each year for each site within the defined roadway limits within the study period.

N_{rs} = predicted average crash frequency for a roadway segment for one specific year.

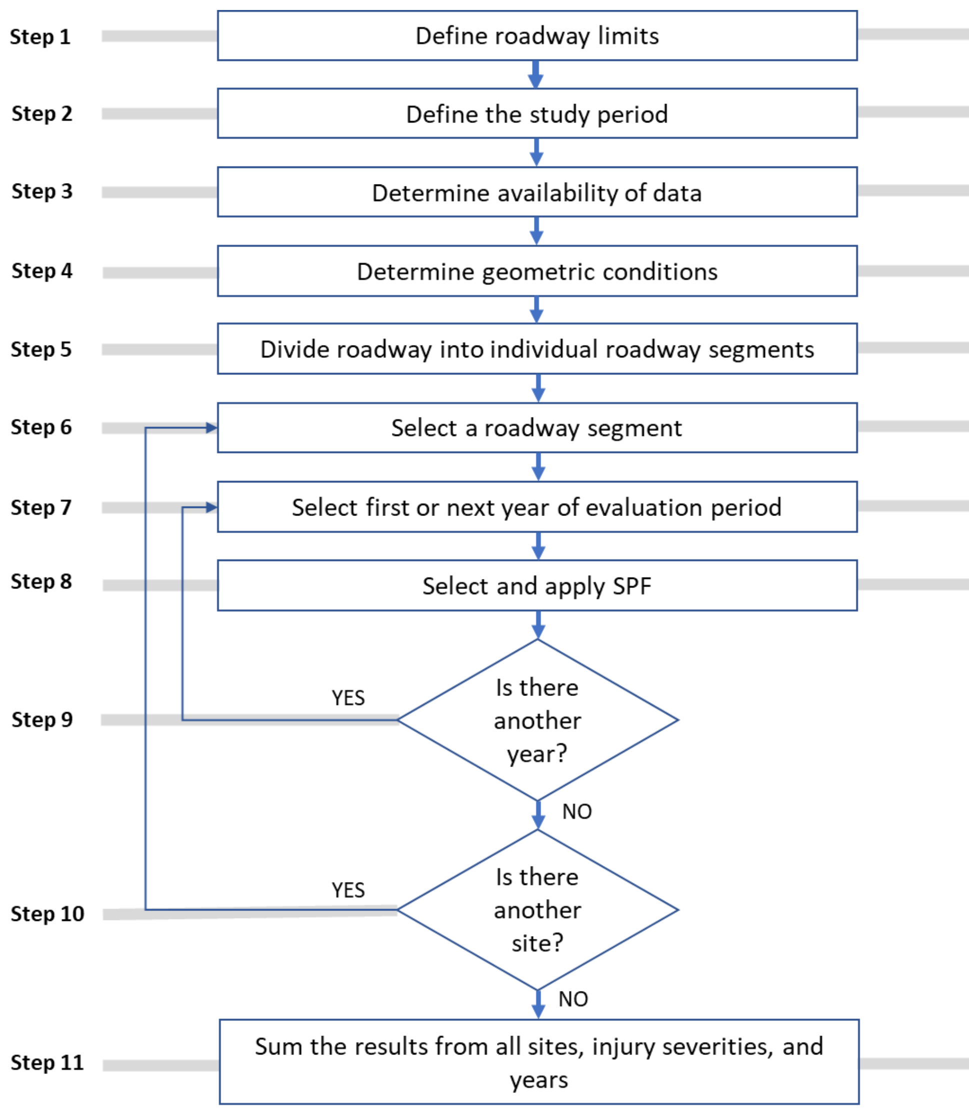


Figure 6.1: Evaluation Flowchart

6.1.2 Sample Problem I

The Site/Facility
A roadway segment with managed lanes in a non-reversible managed lanes facility.

The Question

a) What is the predicted average SV–FI crash frequency of the roadway segment for a particular year?

b) What is the predicted average MV–FI crash frequency of the roadway segment for a particular year?

c) What is the predicted average SV–PDO crash frequency of the roadway segment for a particular year?

d) What is the predicted average MV–PDO crash frequency of the roadway segment for a particular year?

e) What is the predicted average total crash frequency of the roadway segment for a particular year?

The Facts

- Segment length: 1.0 mile
- AADT: 255,000 veh/day
- Number of managed lanes: 4
- Separation type: pylons
- Lateral separation width: 3-ft
- Posted speed limit: 60 mph

Steps
Step 1 through 7
To determine the predicted average crash frequency of the roadway segment in Sample Problem I, only Step 8 is conducted. No other steps are necessary because only one roadway segment is analyzed.

Step 8 - *For the selected site, determine and apply the appropriate safety performance function (SPF) for the site's facility type.*

a) Predicted annual average SV–FI crash frequency of the roadway segment:

$$N_{FI,SV} = L * y * e^{-13.0779 + 1.1976 * Ln(AADT) - 0.0807 * (ML-2) - 0.0174 * (Lat-2)}$$

$$N_{FI,SV} = 1.0 * 1 * e^{-13.0779 + 1.1976 * Ln(255{,}000) - 0.0807 * (4-2) - 0.0174 * (3-2)}$$

$$N_{FI,SV} = 5.22 \text{ crashes/year}$$

b) Predicted annual average MV–FI crash frequency of the roadway segment:

$$N_{FI,MV} = L * y * e^{-19.6485 + 1.8354*Ln(AADT) + 0.1923*(MNL-2) - 0.0266*(Lat-2)}$$

$$N_{FI,MV} = 1.0 * 1 * e^{-19.6485 + 1.8354*Ln(255{,}000) + 0.1923*(4-2) - 0.0266*(3-2)}$$

$$N_{FI,MV} = 35.11 \text{ crashes/year}$$

c) Predicted annual average SV–PDO crash frequency of the roadway segment:

$$N_{PDO,SV} = L * y * e^{-14.1066 + 1.3582*Ln(AADT) + 0.0704*(SPD-55) - 0.0804*(ML-2) - 0.0355*(Lat-2)}$$

$$N_{PDO,SV} = 1.0 * 1 * e^{-14.1066 + 1.3582*Ln(255{,}000) + 0.0704(60-55) - 0.0804*(4-2) - 0.0355*(3-2)}$$

$$N_{PDO,SV} = 19.25 \text{ crashes/year}$$

d) Predicted annual average MV–PDO crash frequency of the roadway segment:

$$N_{PDO,MV} = L * y * e^{-19.6485 + 1.8354*Ln(AADT) + 0.0704*(SPD-55) + 0.1923*(ML-2) - 0.0266*(Lat-2)}$$

$$N_{PDO,MV} = 1.0 * 1 * e^{-19.6485 + 1.8354*Ln(255{,}000) + 0.0704*(60-55) + 0.1923*(4-2) - 0.0266*(3-2)}$$

$$N_{PDO,MV} = 116.50 \text{ crashes/year}$$

e) Predicted annual average total crash frequency of the roadway segment:

$$N_{Total} = N_{FI,SV} + N_{FI,MV} + N_{PDO,SV} + N_{PDO,MSV}$$

$$N_{Total} = 176.07 \text{ crashes/year}$$

Results

Using the steps as outlined above, the predicted average crash frequencies for the roadway segment in Sample Problem I are determined (rounded to one decimal place) to be:

- 5.2 SV–FI crashes per year
- 35.1 MV–FI crashes per year
- 19.3 SV–PDO crashes per year
- 116.5 MV–PDO crashes per year
- 176.1 total crashes per year

6.1.3 Sample Problem II

The Site/Facility
A roadway segment with managed lanes in a reversible managed lanes facility.

The Question

a) What is the predicted average SV–FI crash frequency of the roadway segment for a particular year?

b) What is the predicted average MV–FI crash frequency of the roadway segment for a particular year?

c) What is the predicted average SV–PDO crash frequency of the roadway segment for a particular year?

d) What is the predicted average MV–PDO crash frequency of the roadway segment for a particular year?

e) What is the predicted average total crash frequency of the roadway segment for a particular year?

The Facts

- Segment length: 1.0 mile
- AADT: 180,000 veh/day
- Number of managed lanes: 4
- Separation type: concrete barrier
- Lateral separation width: 10-ft
- Posted speed limit: 60 mph

Steps
Step 1 through 7
To determine the predicted average crash frequency of the roadway segment in Sample Problem II, only Step 8 is conducted. No other steps are necessary because only one roadway segment is analyzed.

***Step 8** - For the selected site, determine and apply the appropriate safety performance function (SPF) for the site's facility type.*

a) Predicted annual average SV–FI crash frequency of the roadway segment:

$$N_{FI,SV} = L * y * e^{-3.2563+0.3906*Ln(AADT)+0.0328*(SPD-55)-0.1048*(ML-2)-0.268*(Lat-2)}$$

$$N_{FI,SV} = 1 * 1 * e^{-3.2563+0.3906*Ln(180{,}000)+0.0328*(60-55)-0.1048*(4-2)-0.268*(10-2)}$$

$$N_{FI,SV} = 3.35 \text{ crashes/year}$$

b) Predicted annual average MV–FI crash frequency of the roadway segment:

$$N_{FI,MV} = L * y * e^{-13.7089+ 1.3284*Ln(AADT)+0.0328*(SPD-55)-0.3484*(ML-2)+0.008*(Lat-2)}$$

$$N_{FI,MV} = 1 * 1 * e^{-13.7089+ 1.3284*Ln(180,000)+0.0328*(60-55)-0.3484*(4-2)+0.008*(10-2)}$$

$N_{FI,MV} =$ 6.67 crashes/year

c) Predicted annual average SV–PDO crash frequency of the roadway segment:

$$N_{PDO,SV} = L * y * e^{-5.0339+ 0.5892*Ln(AADT)+0.0504*(SPD-55)-0.1245*(ML-2)-0.0066*(Lat-2)}$$

$$N_{PDO,SV} = 1 * 1 * e^{-5.0339+ 0.5892*Ln(180,000)+0.0504*(60-55)-0.1245*(4-2)-0.0066*(10-2)}$$

$N_{PDO,SV} =$ 7.74 crashes/year

d) Predicted annual average MV–PDO crash frequency of the roadway segment:

$$N_{PDO,MV} = L * y * e^{-9.9968+ 1.0998*Ln(AADT)+0.0504*(SPD-55)-0.4268*(ML-2)+0.0087*(Lat-2)}$$

$$N_{PDO,MV} = 1 * 1 * e^{-9.9968+ 1.0998*Ln(180,000)+0.0504*(60-55)-0.4268*(4-2)+0.0087*(10-2}$$

$N_{PDO,MV} =$ 16.11 crashes/year

e) Predicted annual average total crash frequency of the roadway segment:

$$N_{Total} = N_{FI,SV} + N_{FI,MV} + N_{PDO,SV} + N_{PDO,MSV}$$

$N_{Total} =$ 33.87 crashes/year

Results

Using the steps as outlined above, the predicted average crash frequencies for the roadway segment in Sample Problem II are determined (rounded to one decimal place) to be:

- 3.4 SV–FI crashes per year
- 6.7 MV–FI crashes per year
- 7.7 SV–PDO crashes per year
- 16.1 MV–PDO crashes per year
- 33.9 total crashes per year

6.1.4 Sample Problem III

The Site/Facility

A 3.0 mi roadway corridor with managed lanes in a non-reversible managed lanes facility. The corridor is divided into three homogenous segments, as listed in Table 6.1.

The Question

a) What is the predicted average SV–FI crash frequency of the roadway corridor for a particular analysis period?

b) What is the predicted average MV–FI crash frequency of the roadway corridor for a particular analysis period?

c) What is the predicted average SV–PDO crash frequency of the roadway corridor for a particular analysis period?

d) What is the predicted average MV–PDO crash frequency of the roadway corridor for a particular analysis period?

e) What is the predicted average total crash frequency of the roadway corridor for a particular analysis period?

The Facts

- Analysis period: 3 years (2017 – 2019)
- Table 6.1

Table 6.1: Sample Problem III – Homogenous Segments

Segment #		S1	S2	S3
Segment length (mi)		0.5	1.0	1.5
AADT (veh/day)	2017	255,000	260,000	265,000
	2018	250,000	270,000	275,000
	2019	260,000	280,000	285,000
Number of managed lanes		4	4	4
Separation type		Pylons	Pylons	Pylons
Lateral separation width (ft)		3	6	12
Posted speed limit (mph)		55	55	55

Steps

Step 1 through 5

These steps are not necessary because they are already completed.

Steps 6 through 10

- Analyze each segment (e.g., S1) as illustrated in Sample Problem I
- Analyze each segment (e.g., S1) in each year (e.g., 2017)

- For each segment (e.g., S1), determine and apply the appropriate SPF for the site's facility type
- Continue until all segments are analyzed
- Steps 6 through 10 are summarized in Table 6.2

Table 6.2: Sample Problem III – Summary of Results from Steps 6 through 10

Year	Collision Type	S1	S2	S3
2017	SV – FI	2.61	5.34	8.20
	MV – FI	17.55	36.38	56.51
	SV – PDO	6.77	13.90	21.39
	MV – PDO	40.96	86.70	137.49
2018	SV – FI	2.55	5.59	8.57
	MV – FI	16.93	38.99	60.49
	SV – PDO	6.59	14.63	22.50
	MV – PDO	38.66	96.80	153.18
2019	SV – FI	2.67	5.84	8.94
	MV – FI	18.19	41.68	64.59
	SV – PDO	6.95	15.37	23.62
	MV – PDO	43.35	107.63	170.01
	Total	203.78	468.85	735.49

Step 11
Sum the results from all sites, injury severities, and years in the study to estimate the total crash frequency. Table 6.3 summarizes the results from Step 11 for Sample Problem III.

Table 6.3: Sample Problem III – Summary of Results from Step 11

Collision Type	S1	S2	S3	Total
SV – FI	7.83	16.77	25.71	**50.31**
MV – FI	52.67	117.05	181.59	**351.31**
SV – PDO	20.31	43.9	67.51	**131.72**
MV – PDO	122.97	291.13	460.68	**874.78**
Total	203.78	468.85	735.49	**1,408.12**

Results
Using the steps as outlined above, the predicted average crash frequencies for the roadway segment in Sample Problem III are determined (rounded to one decimal place) to be:

- 50.3 SV–FI crashes per analysis period
- 351.3 MV–FI crashes per analysis period
- 131.7 SV–PDO crashes per analysis period
- 874.8 MV–PDO crashes per analysis period
- 1408.1 total crashes per analysis period

6.2 Spreadsheet Application

This Microsoft Excel spreadsheet application automatically estimates the facilities' safety performance. It is a decision support application intended to provide support and guidance to transportation practitioners wanting to quantify the safety benefits and compare scenarios with different managed lanes features. The application uses the prediction models developed in this research. In short, the application contains four worksheets with the following contents:

1. **WELCOME** worksheet includes a foreword, final report details, list of worksheets, acknowledgment of sponsorship, and a disclaimer. This is an information hub for the analyst.

2. **NON-REVERSIBLE LANES** worksheet provides the data inputs and analysis of non-reversible managed lane facilities. The analyst needs to fill in the highlighted cells of the general and location information. To conduct an analysis, the analyst should key-in the required input data of each segment against the following variables:

   - Begin milepost,
   - End milepost,
   - AADT (veh/day),
   - Number of managed lanes,
   - Separation width (ft),
   - Separation type, and
   - Posted speed limit.

3. **REVERSIBLE LANES** worksheet provides the data inputs and analysis of reversible managed lane facilities. The analyst needs to fill in the highlighted cells of the general and location information. To conduct an analysis, the analyst should key-in the required input data of each segment against the variables outlined above.

4. **MODELS** worksheet includes the model results for both reversible and non-reversible managed lane facilities. This is a read-only worksheet.

Figure 6.2 presents a sample input-output of a non-reversible managed lanes facility analysis. A 9.66 mi roadway corridor with 12 segments is predicted to have total of 1,401 crashes per year with the given roadway characteristics and traffic volume.

ANALYSIS OF NON-REVERSIBLE MANAGED LANES FACILITIES			
GENERAL AND LOCATION INFORMATION			
General Information		Location Information	
Analyst	Priyanka Alluri	Roadway	95 Express / IH10
Agency or Company	FIU	Roadway Section	
Date Performed	3/30/2022	Jurisdiction	FDOT / TXDOT
Analysis Year	2022	Remark(s)	

OVERALL RESULTS	
Total length of the study corridor(s) (mi.)	9.66
Predicted annual single vehicle Fatal and Injury crashes on study corridor(s)	41.69
Predicted annual multi vehicle Fatal and Injury crashes on the study corridor(s)	270.47
Predicted annual single vehicle Property Damage Only crashes on the study corridor(s)	109.24
Predicted annual multi vehicle Property Damage Only crashes on the study corridor(s)	979.67
Predicted annual Total Crashes on the study corridor(s)	1,401.07

INPUT DATA									RESULTS PER SEGMENT				
Segment ID	Begin Milepost	End Milepost	Segment Length (mi)	AADT (veh/day)	Number of Managed Lanes	Separation Width (ft)	Separation Type	Posted Speed Limit (mph)	SV-FI Crashes	MV-FI crashes	SV-PDO Crashes	MV-PDO Crashes	Total Crashes
									41.69	270.47	109.24	979.67	1401.07
S1	749.288	750.288	1.000	255,000	4	3.0	Pylons	60	5.22	35.11	19.25	116.50	176.07
S2	750.288	751.727	1.439	214,150	6	8.5	Pylons	55	4.71	46.54	10.76	94.40	156.41
S3	751.727	751.912	0.185	214,150	4	17.5	Pylons	55	0.61	3.21	1.18	6.95	11.95
S4	751.912	753.557	1.645	230,952	4	24.0	Pylons	55	5.29	27.54	9.24	68.31	110.38
S5	753.557	753.904	0.347	302,062	4	22.0	Pylons	55	1.59	10.03	3.01	32.73	47.36
S6	753.904	754.296	0.392	302,062	4	16.5	Pylons	55	1.98	13.11	4.14	40.95	60.18
S7	754.296	755.186	0.890	302,062	4	22.0	Pylons	60	4.09	25.72	10.98	119.35	160.14
S8	755.186	755.188	0.002	302,218	4	21.0	Pylons	60	0.01	0.06	0.03	0.27	0.37
S9	755.188	757.346	2.158	302,218	4	21.0	Pylons	60	10.09	64.11	27.61	295.27	397.09
S10	757.346	757.765	0.419	302,218	2	14.0	Pylons	60	2.60	10.21	8.07	44.24	65.12
S11	757.765	758.108	0.343	302,218	4	20.5	Pylons	60	1.62	10.33	4.47	47.37	63.78
S12	758.108	758.944	0.836	302,218	4	21.5	Pylons	60	3.88	24.51	10.51	113.33	152.22

Figure 6.2: Non-reversible Managed Lanes Facility Sample Input-Output

6.3 GIS Inventory of Managed Lanes in Florida

The GIS Inventory output consists of seven managed lanes facilities that are currently operational in Florida. The inventory includes the following facilities:

- 295 Express
- 75 Express
- 595 Express
- 95 Express
- Palmetto Express
- Beachline Expressway
- Veterans Expressway

Table 6.4 presents the list of attributes included in the inventory.

Table 6.4: Attributes of a GIS Inventory of Managed Lanes in Florida

Attribute	Definition	Alias, Type, Width, Precision, Scale	Attribute Values	Attribute Definition Source
SID	Sequential identification number	*Alias:* SID *Type:* Double *Width:* 4 *Precision:* 0 *Scale:* 0	Sequential unique whole numbers that identify each record.	Research team
Shape	Feature geometry	*Alias:* Shape *Type:* Geometry *Width:* 0 *Precision:* 0 *Scale:* 0	Coordinates defining the features.	ESRI
ROADWAY	A unique 8-character identification number assigned to a roadway or section of a roadway either On or Off the State Highway System for which information is maintained in the Department's RCI	*Alias:* ROADWAY *Type:* String *Width:* 8 *Precision:* 0 *Scale:* 0	8-character ID, the first two characters are the county code, the next 3 are the section code, and the final 3 characters are the subsection code.	FDOT, Transportation Data & Analytics Office
ROUTE	Route number of the interstate	*Alias:* ROUTE *Type:* String *Width:* 8 *Precision:* 0 *Scale:* 0	Route number of the interstate	FDOT, Transportation Data & Analytics Office
RouteNUM	Route number (number only)	*Alias:* RouteNum *Type:* String *Width:* 8 *Precision:* 0 *Scale:* 0	Route number (number only)	FDOT, Transportation Data & Analytics Office
DISTRICT	FDOT District Number	*Alias:* DISTRICT *Type:* String *Width:* 1 *Precision:* 0 *Scale:* 0	FDOT District number	FDOT, Transportation Data & Analytics Office
COUNTY	The county that contains the roadway	*Alias:* COUNTY *Type:* String *Width:* 12 *Precision:* 0 *Scale:* 0	Florida county name	FDOT, Transportation Data & Analytics Office RCI Planning Data Handbook
BEGIN_POST	Denotes the lowest milepost for the record	*Alias:* BEGIN_POST *Type:* Double *Width:* 19 *Precision:* 18 *Scale:* 4	Lowest milepost for the record	FDOT, Transportation Data & Analytics Office
END_POST	Denotes the highest milepost for the record	*Alias:* END_POST *Type:* Double *Width:* 19 *Precision:* 18 *Scale:* 4	Highest milepost for the record	FDOT, Transportation Data & Analytics Office
Shape_Leng	Length in meters of the geometry for the record	*Alias:* Shape_Leng *Type:* Double *Width:* 19 *Precision:* 18 *Scale:* 4	Shape length in meters	ESRI - Internally generated

CHAPTER 7
SAFETY PERFORMANCE OF FLORIDA EXPRESS LANES – ADDITIONAL INSIGHTS

This chapter presents descriptive statistics of two managed lanes facilities in Florida. The data included crashes on 15.3 miles of 95 Express (non-reversible managed lanes facility) and 8.0 miles of 595 Express (reversible managed lanes facility). The express lanes on the 95 Express are separated from the general-purpose lanes by pylons, while concrete barriers separate the express lanes from the general-purpose lanes on the 595 Express. The following sections present the details.

7.1 95 Express

From 2015 through 2019, about 20,794 crashes occurred along the 15.3 miles of the 95 Express. Table 7.1 presents the distribution of crashes by crash occurrence lane against the first harmful event. The results reveal that most crashes occurred on the general-purpose lanes only (71.7%). This phenomenon was expected since general-purpose lanes carry a significant portion of the traffic. About 7.9% of crashes involved crossing over the pylons (started from ELs to GPLs or vice versa). Such crashes involved vehicles crossing over as a result of collision impact or drivers deliberately crossing over the pylons and ending up colliding with other vehicles. Vehicle to vehicle collisions were the predominant first harmful events (88%). About 4.7% of crashes involved hitting the pylons as the first harmful event.

Table 7.1: Distribution of Crashes by Crash Occurrence Lane and First Harmful Event on 95 Express

Crash Occurrence Lane	First Harmful Event					Total	Proportion (%)
	Hitting other roadside object(s)	Hitting the median concrete barrier	Hitting the pylons	Vehicle-to-vehicle collision	Unknown		
Express lanes only (ELs)	68	273	113	1,734	16	2,204	10.6%
General-purpose lane only (GPLs)	609	124	101	13,967	99	14,900	71.7%
Started on ELs and ended on GPLs (EL_GPL)	14	39	227	170	5	455	2.2%
Started on GPLs and ended on ELs (GPL_EL)	27	59	543	543	7	1,179	5.7%
Within EL facility but on the ramp	146	17	2	1,878	13	2,056	9.9%
Total	864	512	986	18,292	140	20,794	100%
Proportion (%)	4.2%	2.5%	4.7%	88.0%	0.7%	100%	

N = 20,794

Figure 7.1 shows the distribution of the crashes by different time periods. About 68.4% of crashes occurred between 7:00 AM and 6:00 PM. Nearly half (53%) of crashes occurred during peak hours, i.e., morning peak, 6:00 AM to 10:00 AM, and evening peak, 3:00 PM to 7:00 PM. Specifically, 20.8% of crashes occurred during the morning peak, while the remaining 32.2% occurred during the evening peak. The highest proportion of crashes occurred during the evening peak hours at 6:00 PM (7.1%).

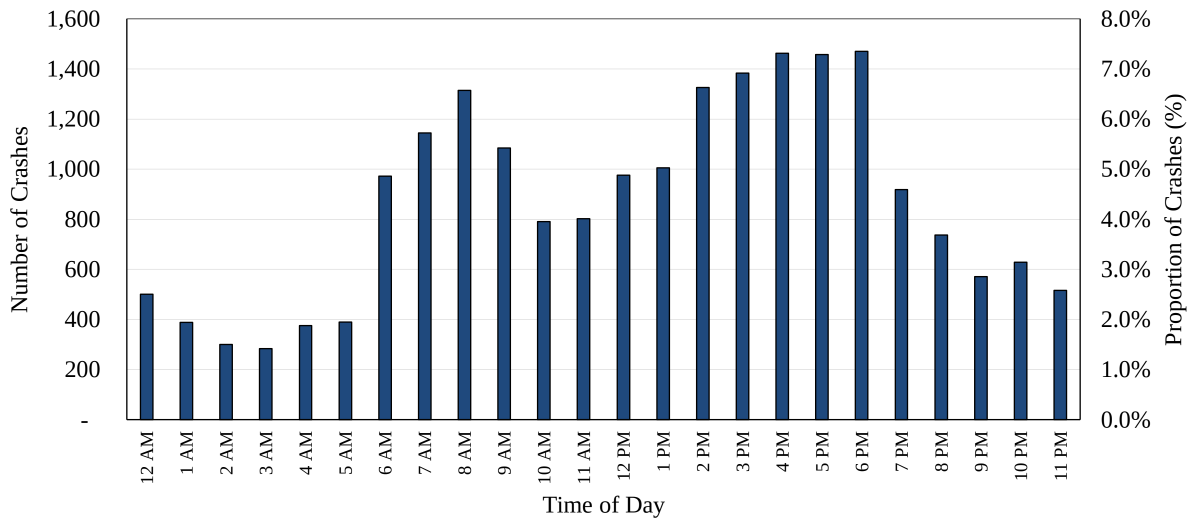


Figure 7.1: Distribution of Crashes by Time of Day on 95 Express

Table 7.2 presents the distribution of crashes by first harmful event and crash severity. The results in Table 7.2 reveal that most crashes had no injury severity (78.9%). Generally, the crash severity trends are similar across all types of first harmful events, with the highest proportion of crashes bearing no injury severity and the lowest proportion of crashes resulting in either a fatality or an injury.

Table 7.2: Distribution of Crashes by First Harmful Event and Crash Severity on 95 Express

First Harmful Event	Crash Severity					Total	Proportion (%)
	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Possible Injury	No Injury		
Hitting other roadside object(s)	11	28	63	116	646	864	4.2%
Hitting the median concrete barrier	3	18	51	82	358	512	2.5%
Hitting the pylons	2	33	106	189	656	986	4.7%
Vehicle-to-vehicle collision	14	275	884	2,458	14,661	18,292	88.0%
Unknown	4	7	23	17	89	140	0.7%
Total	34	361	1,127	2,862	16,410	20,794	100.0%
Proportion (%)	0.2%	1.7%	5.4%	13.8%	78.9%	100.0%	

Table 7.3 presents the distribution of crashes by crash occurrence lane against the number of vehicles involved. Most crashes involved two vehicles (72.6%). While single-vehicle crashes account for only 9.5%, multi-vehicle crashes account for a more significant share of about 90.4%.

Table 7.3: Distribution of Crashes by Crash Occurrence Lane and Number of Vehicles Involved on 95 Express

Crash Occurrence Lane	Number of Vehicles Involved			Total	Proportion (%)
	Single Vehicle	Two Vehicles	Three Plus Vehicles		
Express lanes only (ELs)	428	1,413	363	2,204	10.6%
General-purpose lanes only (GPLs)	937	1,197	2,766	14,900	71.7%
Started on ELs and ended on GPLs (EL_GPL)	70	259	126	455	2.2%
Started on GPLs and ended on ELs (GPL_EL)	342	560	277	1,179	5.7%
Within ELs facility but on the ramp	200	1,673	183	2,056	9.9%
Total	1,977	15,102	3,715	20,794	100%
Proportion (%)	9.5%	72.6%	17.9%	100.0%	

7.2 595 Express

From 2015 through 2019, about 1,057 crashes occurred along the 8 miles of the 595 Express. Tables 7.4 through 7.6 provide the statistics on the number of crashes against crash occurrence lane, crash severity, first harmful event, and the number of vehicles involved. Table 7.4 presents the distribution of crashes by crash occurrence lane against the first harmful events. The results reveal that most crashes occurred only on the general-purpose lanes (95.8%) and only 3.4% occurred on the express lanes. About 0.8% of crashes occurred at express lanes entry or exit points.

Table 7.4: Distribution of Crashes by Crash Occurrence Lane and First Harmful Event on 595 Express

Lane Where a Crash Occurred	First Harmful Event				Total	Proportion (%)
	Hitting concrete barrier	Hitting other roadside objects	Vehicle-to-vehicle collision	Unknown		
Express lanes (ELs)	17	10	9	0	36	3.4%
General-purpose lanes (GPLs)	164	92	751	6	1,013	95.8%
ELs Entry/Exit	2	4	2	0	8	0.8%
Total	183	106	762	6	1,057	100.0%
Proportion (%)	17.3%	10.0%	72.1%	0.6%	100.0%	

Figure 7.2 shows the distribution of the crashes by different time periods. About 68.0% of crashes occurred between 7:00 AM and 6:00 PM. More than half (59.5%) of crashes occurred during peak hours, i.e., morning peak, 6:00 AM to 10:00 AM, and evening peak, 3:00 PM to 7:00 PM. Specifically, 33.8% of crashes occurred during the morning peak, while the remaining 25.7% occurred during the evening peak. The highest proportion of crashes occurred during the morning peak hours at 8 AM (10.5%).

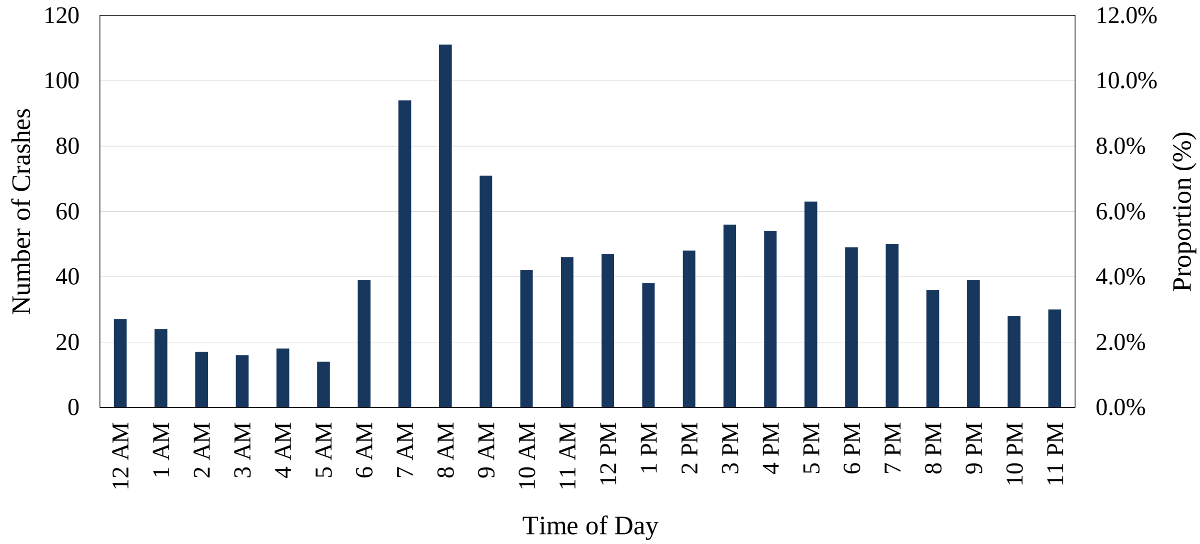


Figure 7.2: Distribution of Crashes by Time of Day on 595 Express

Table 7.5 presents the distribution of crashes by first harmful event and crash severity. Most crashes were found to be PDO (72.8%). Generally, the crash severity trends are similar across all types of first harmful events, with the highest proportion of crashes bearing no injury severity and the lowest proportion of crashes resulting in either a fatality or an injury.

Table 7.5: Distribution of Crashes by First Harmful Event and Crash Severity on 595 Express

First Harmful Event	Crash Severity					Total	Proportion (%)
	Fatal	Incapacitating Injury	Non-Incapacitating Injury	Possible Injury	No Injury		
Hitting concrete barrier	0	5	36	25	117	183	17.3%
Hitting other roadside objects	0	4	6	6	90	106	10.0%
Vehicle-to-vehicle collision	1	26	85	93	557	762	72.1%
Unknown	0		1		5	6	0.6%
Total	1	35	128	124	769	1,057	100.0%
Proportion (%)	0.1%	3.3%	12.1%	11.7%	72.8%	100.0%	

Table 7.6 presents the distribution of crashes by crash occurrence lane against the number of vehicles involved. Most crashes involved two vehicles (63.7%). While single-vehicle crashes account for only 26.0%, multi-vehicle crashes constitute a more significant share (74%).

Table 7.6: Distribution of Crashes by Crash Occurrence Lane and Number of Vehicles Involved on 595 Express

Lane Where a Crash Occurred	Number of Vehicles Involved			Total	Proportion (%)
	Single Vehicle	Two Vehicles	Three Plus Vehicles		
Express lanes (ELs)	26	10		36	3.4%
General-purpose lanes (GPLs)	244	660	109	1013	95.8%
ELs Entry/Exit	5	3		8	0.8%
Total	275	673	109	1057	100.0%
Proportion (%)	26.0%	63.7%	10.3%	100.0%	

7.3 Summary

This chapter provided additional insights on two managed lanes facilities in Florida, 95 Express and 595 Express. The 95 Express facility operates as a non-reversible variable toll managed lanes facility, separated from the general-purpose lanes by pylons (i.e., tubular delineators). On the other hand, the 595 Express facility operates as a reversible variable toll managed lanes facility, separated from the general-purpose lanes by concrete barrier. Descriptive statistics on the number of crashes against crash occurrence lane, crash severity, first harmful event, and the number of vehicles involved were provided. Findings for each facility include:

95 Express

- Most crashes occurred on the general-purpose lanes only (71.7%).
- About 7.9% of crashes involved crossing over the pylons.
- Vehicle-vehicle collisions were the predominant first harmful events (88.0%).
- About 4.7% of crashes involved hitting the pylons as the first harmful event.
- Nearly half (53.0%) of crashes occurred during peak hours.
- Most crashes were PDO (78.9%).
- Most crashes involved two vehicles (72.6%).
- Single-vehicle crashes account for only 9.5%, and multi-vehicle crashes account for 90.5% of crashes.

595 Express

- Most crashes occurred on the general-purpose lanes only (95.8%), while 3.4% of the crashes occurred on the express lanes.
- About 0.8% of crashes occurred at express lanes entry or exit points.
- More than half (59.5%) of crashes occurred during peak hours.
- Most crashes were PDO (72.8%).
- Most crashes involved two vehicles (63.7%).
- Single-vehicle crashes account for 26.0%, and multi-vehicle crashes account for 74.0% of crashes.

CHAPTER 8
SUMMARY AND CONCLUSIONS

The goal of this project was to quantify the effects of separation type selection on the safety performance of freeway facilities with managed lanes. The data collection, processing, and analysis efforts were explained in detail to lay out a foundation of procedures. The project developed quantitative measures to compare alternatives for the managed lanes separation treatments. Two separation treatments were studied: pylons (also called tubular delineators or tubular markers) and the concrete barrier separation types.

The research analyzed 137.6 miles of high-occupancy toll (HOT) lanes and express lanes (ELs) facilities, collectively placed under the term *priced managed lanes*. The study used data from the states of Florida, Texas, and Georgia for both non-reversible and reversible managed lanes facilities. The following criteria were considered while selecting the study sites:

- availability of crash data for three to five years between the years 2015 and 2019,
- diversity in the roadway geometric cross-section of the managed lanes facilities, particularly the separation types, and
- inclusion of different managed lanes operation strategies (i.e., non-reversible managed lanes and reversible managed lanes).

Following the data collection, the data processing step was carried out. The data processing primarily constituted segmentation, assignment of crashes to segments, and variables preparation. Segmentation, which involved dividing the sites into individual homogeneous segments, was the most critical, resource-intensive step, and necessary to ensure homogeneity of segments in the analysis variables. The processed data were then analyzed further to obtain inferences. The analysis provided the following:

- Safety performance functions (SPFs): negative binomial models for non-reversible and reversible managed lanes facilities, fatal and injury (FI) and property damage only (PDO) crashes, single-vehicle and multi-vehicle crashes.
- Crash modification factors (CMFs): estimated from SPFs.
- Severity distribution functions (SDFs): multinominal logistic regression for non-reversible and reversible managed lanes facilities.

8.1 Model Results

Tables 8.1 through 8.4 present the developed SPFs for all the facility types and crash types analyzed. The estimate values in bold font are significant at a 95% confidence level. Equations 8.1 through 8.12 are SPFs by facility type (reversible and non-reversible managed lanes), collision type (SV and MV) and by injury severity (FI and PDO crashes).

Table 8.1: SPFs and CMFs for FI Crashes on Non-reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	p-value	CMF
$\boldsymbol{b_0}$	**Intercept**	**SV**	**-13.0779**	**0.0127**	**-**
		MV	**-19.6485**	**<0.0001**	**-**
$\boldsymbol{b_{aadt}}$	**AADT**	**SV**	**1.1976**	**0.0050**	**3.312**
		MV	**1.8354**	**<0.0001**	**6.268**
b_{ml}	Number of managed lanes	SV	-0.0807	0.4167	$e^{-0.0807(N_{ml}-2)}$
		MV	**0.1923**	**0.0257**	$\boldsymbol{e^{0.1923(N_{ml}-2)}}$
b_{lat_py}	Separation width (pylons)	SV	-0.0174	0.1152	$e^{-0.0174(W_{lat}-2)}$
		MV	**-0.0266**	**0.0017**	$\boldsymbol{e^{-0.0266(W_{lat}-2)}}$
b_{lat_bar}	Separation width (concrete barrier)	SV	0.0053	0.8373	$e^{0.0053(W_{lat}-2)}$
		MV	-0.0031	0.8676	$e^{-0.0031(W_{lat}-2)}$
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.4336**	**<0.0001**	**-**
		MV	**1.7714**	**<0.0001**	**-**

Note: SV = Single-vehicle; MV = Multi-vehicle; N_{ml} = Number of managed lanes; W_{lat} = Lateral separation width (ft); Boldfaced variables are significant at 95% level.

SPFs for Non-reversible Managed Lanes Facilities with Pylons

$$N_{SV-FI} = L \times 1 \times EXP(-13.0779 + 1.1976\,\mathrm{Ln}(AADT) - 0.0807(N_{ml} - 2) - 0.0174(W_{lat} - 2)) \quad (8.1)$$

$$N_{MV-FI} = L \times 1 \times EXP(-19.6485 + 1.8354\,\mathrm{Ln}(AADT) + 0.1923(N_{ml} - 2) - 0.0266(W_{lat} - 2)) \quad (8.2)$$

SPFs for Non-reversible Managed Lanes Facilities with Concrete Barrier

$$N_{SV-FI} = L \times 1 \times EXP(-13.0779 + 1.1976\,\mathrm{Ln}(AADT) - 0.0807(N_{ml} - 2) + 0.0053(W_{lat} - 2)) \quad (8.3)$$

$$N_{MV-FI} = L \times 1 \times EXP(-19.6485 + 1.8354\mathrm{Ln}(AADT) + 0.1923(N_{ml} - 2) - 0.0031(W_{lat} - 2)) \quad (8.4)$$

Table 8.2: SPFs and CMFs for PDO Crashes on Non-reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	p-value	CMF
$\boldsymbol{b_0}$	**Intercept**	**SV**	**-14.1066**	**0.0053**	**-**
		MV	**-32.2862**	**<0.0001**	**-**
b_{aadt}	AADT	**SV**	**1.3582**	**0.0010**	**3.889**
		MV	**2.9176**	**<0.0001**	**18.497**
b_{spd}	Posted speed limit	**All**	**0.0704**	**0.0012**	$\boldsymbol{e^{0.0704(SPD-55)}}$
b_{ml}	Number of managed lanes	SV	-0.0804	0.4162	$e^{-0.0804(N_{ml}-2)}$
		MV	**0.1947**	**0.0045**	$\boldsymbol{e^{0.1947(N_{ml}-2)}}$
b_{lat_py}	Separation width (pylons)	**SV**	**-0.0355**	**0.0005**	$\boldsymbol{e^{-0.0355(W_{lat}-2)}}$
		MV	**-0.0186**	**0.0251**	$\boldsymbol{e^{-0.0186(W_{lat}-2)}}$
b_{lat_bar}	Separation width (concrete barrier)	SV	-0.0353	0.1521	$e^{-0.0353(W_{lat}-2)}$
		MV	-0.0216	0.2607	$e^{-0.0216(W_{lat}-2)}$
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.4731**	**<0.0001**	**-**
		MV	**2.0432**	**<0.0001**	**-**

Note: SV = Single-vehicle; MV = Multi-vehicle; N_{ml} = Number of managed lanes; W_{lat} = Lateral separation width (ft); SPD = Posted speed limit (mi/h); Boldfaced variables are significant at 95% level

SPFs for Non-reversible Managed Lanes Facilities with Pylons

$$N_{SV-PDO} = L \times 1 \times EXP(-14.1066 + 1.3582\,\mathrm{Ln}(AADT) - 0.0804(N_{ml} - 2) - 0.0355(W_{lat} - 2) + 0.0704(SPD - 55)) \quad (8.5)$$

$$N_{MV-PDO} = L \times 1 \times EXP(-32.2862 + 2.9176\,\mathrm{Ln}(AADT) + 0.1947(N_{ml} - 2) - 0.0186(W_{lat} - 2) + 0.0704(SPD - 55)) \quad (8.6)$$

SPFs for Non-reversible Managed Lanes Facilities with Concrete Barrier

$$N_{SV-PDO} = L \times 1 \times EXP(-14.1066 + 1.3582\,\mathrm{Ln}(AADT) - 0.0804(N_{ml} - 2) - 0.0353(W_{lat} - 2) + 0.0704(SPD - 55)) \quad (8.7)$$

$$N_{MV-PDO} = L \times 1 \times EXP(-32.2862 + 2.9176\mathrm{Ln}(AADT) + 0.1947(N_{ml} - 2) - 0.0216(W_{lat} - 2) + 0.0704(SPD - 55)) \quad (8.8)$$

Table 8.3: SPFs and CMFs for FI Crashes on Reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	p-value	CMF
b_0	Intercept	SV	-3.2563	0.2573	-
		MV	**-13.7089**	**<0.0001**	**-**
b_{aadt}	AADT	SV	0.3906	0.1053	1.478
		MV	**1.3284**	**<0.0001**	**3.775**
b_{spd}	Posted speed limit	**All**	**0.0328**	**0.0020**	$\boldsymbol{e^{0.0328(SPD-55)}}$
b_{ml}	Number of managed lanes	SV	-0.1048	0.2809	$e^{-0.1048(N_{ml}-2)}$
		MV	**-0.3484**	**<0.0001**	$\boldsymbol{e^{-0.3484(N_{ml}-2)}}$
b_{lat_bar}	Separation width (concrete barrier)	**SV**	**-0.0268**	**0.0015**	$\boldsymbol{e^{-0.0268(W_{lat}-2)}}$
		MV	0.0080	0.2637	$e^{0.0080(W_{lat}-2)}$
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.3086**	**<0.0001**	**-**
		MV	**1.2270**	**<0.0001**	**-**

Note: SV = Single-vehicle; MV = Multi-vehicle; N_{ml} = Number of managed lanes; W_{lat} = Lateral separation width (ft); SPD = Posted speed limit (mi/h); Boldfaced variables are significant at 95% level

SPFs for Reversible Managed Lanes Facilities with Concrete Barrier

$$N_{SV-FI} = L \times 1 \times EXP(-3.2563 + 0.3906\,\mathrm{Ln}(AADT) - 0.1048(N_{ml} - 2) - 0.0268(W_{lat} - 2) + 0.0328(SPD - 55)) \tag{8.9}$$

$$N_{MV-FI} = L \times 1 \times EXP(-13.7089 + 1.3284\mathrm{Ln}(AADT) - 0.3484(N_{ml} - 2) + 0.0080(W_{lat} - 2) + 0.0328(SPD - 55)) \tag{8.10}$$

Table 8.4: SPFs and MCFs for PDO Crashes on Reversible Managed Lanes Facilities

Parameter	Variable	Collision Type	Estimate	p-value	CMF
b_0	Intercept	SV	-5.0339	0.0656	
		MV	**-9.9968**	**0.0002**	
b_{aadt}	AADT	**SV**	**0.5892**	**0.0101**	**1.803**
		MV	**1.0998**	**<0.0001**	**3.004**
b_{spd}	Posted speed limit	**All**	**0.0504**	**<0.0001**	$\boldsymbol{e^{0.0504(SPD-55)}}$
b_{ml}	Number of managed lanes	SV	-0.1245	0.1829	$e^{-0.1245(N_{ml}-2)}$
		MV	**-0.4268**	**<0.0001**	$\boldsymbol{e^{-0.4268(N_{ml}-2)}}$
b_{lat_bar}	Separation width (concrete barrier)	SV	-0.0066	0.4057	$e^{-0.0066(W_{lat}-2)}$
		MV	0.0087	0.2161	$e^{0.0087(W_{lat}-2)}$
$\boldsymbol{k}$	**Inverse dispersion parameter**	**SV**	**1.1485**	**<0.0001**	
		MV	**1.1917**	**<0.0001**	

Note: SV = Single-vehicle; MV = Multi-vehicle; N_{ml} = Number of managed lanes; W_{lat} = Lateral separation width (ft); SPD = Posted speed limit (mi/h); Boldfaced variables are significant at 95% level.

SPFs for Reversible Managed Lanes Facilities with Concrete Barrier

$$N_{SV-PDO} = L \times 1 \times EXP(-5.0339 + 0.5892\,\mathrm{Ln}(AADT) - 0.1245(N_{ml} - 2) - 0.0066(W_{lat} - 2) + 0.0504(SPD - 55)) \quad (8.11)$$

$$N_{MV-PDO} = L \times 1 \times EXP(-9.9968 + 1.0998\mathrm{Ln}(AADT) - 0.4268(N_{ml} - 2) + 0.0087(W_{lat} - 2) + 0.0504(SPD - 55)) \quad (8.12)$$

The following key observations are worth mentioning from the results regarding the non-reversible managed lanes facilities:

- On average, in the presence of pylons, SV–PDO crashes decrease by 3.5% for each additional foot of lateral separation width. On the other hand, in the presence of pylons, MV–PDO crashes decrease by an average of 1.8% for each additional foot of lateral separation width.
- Similarly, in the presence of pylons, MV–FI crashes decrease by an average of 2.6% for each additional foot of lateral separation width.
- The number of managed lanes presents similar effects on MV–FI and MV–PDO crashes. On average, MV–FI and MV–PDO crashes increase by 21.2% for each additional managed lane.
- While the proportion of fatal and incapacitating injury (K + A) crashes remains nearly the same throughout the 55 – 65 mph posted speed limit window, the proportion of non-incapacitating injury (B) crashes increases with posted speed limit.
- The proportions of fatal (K), incapacitating injury (A), and non-incapacitating injury (B) crashes:
    - increase at segments with ramps.
    - decrease as the separation width between the general-purpose lanes and the managed lanes increases in the presence of pylons.
    - decrease as the separation width between the general-purpose lanes and the managed lanes increases in the presence of concrete barrier.

In addition, the following key observations are worth mentioning from the results regarding the reversible managed lanes facilities:

- On average, in the presence of the concrete barrier, SV–FI crashes decrease by 2.6% for each additional foot of lateral separation width.
- On average, MV–FI crashes decrease by 29.4% for each additional managed lane. On the other hand, MV–PDO crashes decrease by an average of 34.7% for each additional managed lane.
- The proportions of fatal (K), incapacitating injury (A), and non-incapacitating injury (B) crashes:
    - increase with the number of managed lanes.
    - slightly increase at segments with ramps.
    - decrease with the outside shoulder width on the general-purpose lanes.
    - decrease with the inside shoulder width on managed lanes.

8.2 Technology Transfer Activities

Additional products were also developed to help practitioners better understand and use the research outcomes. These supplementary tools focus on reversible and non-reversible managed lanes facilities and include the following:

- Sample problems
  - Provide a step-by-step procedure for determining the total crash frequency on managed lanes facilities.
- Spreadsheet application
  - Provides a Microsoft Excel spreadsheet application to estimate the safety performance of a managed lanes facility.
- Geographic information systems (GIS) inventory
  - Provides an attribute-based inventory of seven managed lanes facilities in Florida.
- One-page summary sheets
  - Provide a one-page information source on separation treatments for reversible and non-reversible managed lanes facilities.

8.3 Additional Insights into the Safety Performance of Florida Express Lanes

Additional insights were provided into two managed lanes facilities in Florida, 95 Express (15.3 miles) and 595 Express (8.0 miles). The 95 Express is a non-reversible managed lanes facility separated from the general-purpose lanes by pylons, while the 595 Express is a reversible managed lanes facility separated from the general-purpose lanes by concrete barriers. Descriptive statistics on the number of crashes against crash occurrence lane, crash severity, first harmful event, and the number of vehicles involved were provided. Findings for each facility include:

95 Express Statistics

- Most crashes occurred on the general-purpose lanes only (71.7%).
- About 7.9% of crashes involved crossing over the pylons.
- Vehicle-vehicle collisions were the predominant first harmful events (88.0%).
- About 4.7% of crashes involved hitting the pylons as the first harmful event.
- Nearly half (53.0%) of crashes occurred during peak hours.
- Most crashes were PDO (78.9%).
- Most crashes involved two vehicles (72.6%).
- Single-vehicle crashes account for only 9.5%, and multi-vehicle crashes account for 90.5% of crashes.

595 Express Statistics

- Most crashes occurred on the general-purpose lanes only (95.8%), while 3.4% of the crashes occurred on express lanes.
- About 0.8% of crashes occurred at express lanes entry or exit points.
- More than half (59.5%) of crashes occurred during peak hours.
- Most crashes were PDO (72.8%).
- Most crashes involved two vehicles (63.7%).
- SV crashes account for only 26.0%, and MV crashes account for 74.0% of crashes.

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APPENDIX A: Reversible versus Bi-directional Managed Lanes

(Source (GDOT, 2010a)

	Operational Issues		Cost	
	Advantages	Disadvantages	Advantages	Disadvantages
Reversible	• Efficient for moving vehicles longer distances • Isolation from GP lanes improves flow • Maximizes V/C ratio utility by putting lanes in the direction of greatest flow	• Not well known to drivers • Complex operations • Requires studies to determine optimal hours of operation • Some proportion of demand will not be served • Less suited to short trips	• Potentially Less expensive than a bi-directional facility • May require less right-of-way • May require less overpass, bridge, and interchange construction	• Trade-off between cost and total access
Bi-Directional	• Can allow for buffer or alternative lane separation configurations • Can be operational 24 hours per day • Can be designed for short or long trips	• Provides more facility than demand requires in most off-peak hours	• Trade-off between cost and total access	• More expensive than reversible facility • More overpass, bridge and interchange construction often required • Requires more right-of-way

	Transferability		Environmental	
	Advantages	Disadvantages	Advantages	Disadvantages
Reversible	• During system to-system transfers between facilities with similar hours of operation and flow directions, the disadvantages are negligible, but the costs and operational improvements remain in place	• System-to system interchanges may require additional engineering due to variations in peak hour directional flow • Transference onto a radial corridor may not be possible • Variations in hours of operation can complicate access	• May require less right-of-way • May provide air quality improvements	• Does not maximize potential air quality benefits from both directions of traffic flow in locations with lower directional splits
Bi-Directional	• No hours of operations or one-way flows • Normal routing and directional conditions • Allows for continued access and transference along the managed lanes regardless of corridor shift	• Bi-directional system-to system interchanges may require more system connections than reversible system interchanges	• Potentially maximizes air quality improvements	• May require more right-of-way

APPENDIX A: Reversible versus Bi-directional Managed Lanes (continued)

(Source (GDOT, 2010a)

	Safety		Social	
	Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Reversible	• Requires a barrier separated system which reduces risks due to traffic speed turbidity	• Requires additional signage and gates to prevent access to vehicles during off hours • Requires more enforcement • Requires extra development to ensure safety at system-to-system interchanges	• May require less right-of way • May have less impact on neighboring land uses • Shorter construction period has less impacts on surroundings	• Provides access in only one direction at a time
Bi-Directional	• Never utilizes the same corridor for flow in opposite directions	• Does not require barrier systems which can reduce the risk of collision due to traffic speed turbidity	• Provides access in both directions at potentially all hours	• May require more right-of-way • May have higher impact on neighboring land uses • Longer construction period's adverse impacts on surroundings

APPENDIX B: Express Lanes in Florida

(Source: Alluri et al., 2020)

Phase	Roadway	Description
		Southeast Florida
In operation	I-95	• Phase 1—Junction of I-95 and SR-836/I-395 in downtown Miami to Golden Glades interchange (7 miles): 2 express lanes/direction • Phase 2—Golden Glades interchange to Broward Boulevard (14 miles): 1 to 2 express lanes/direction
	I-595	• I-75/Sawgrass Expressway to Turnpike Mainline (10 miles): 3 reversible lanes
	I-75	• I-595 to the north of Griffin Road (5 miles): 2 express lanes per direction • North of Griffin Rd. to Sheridan St. (4 miles): 2 express lanes per direction • Sheridan St. to Miramar Pkwy (4 miles): 2 express lanes per direction • Miramar Pkwy to the north of NW 138th St. (6 miles): 2 express lanes/ direction • North of NW 138th St. to Palmetto Expressway (3 miles): 1 express lane/ direction
Under construction	Turnpike Extension (HEFT)	• Biscayne Drive to Killian Pkwy (14 miles): 1 express lane/direction • Killian Pkwy to SR-836 (7 miles): 2 express lanes/direction Opens in sections starting in spring 2018 through spring 2020
	I-95	• Broward Boulevard to Commercial Blvd (10 miles): 2 express lanes/direction • Commercial Blvd to SW 10th St. (9 miles): 2 express lanes/direction • SW 10th St. to Glades Rd. (5 miles): 2 express lanes/direction • Broward Blvd to SW 10th St. - 2020, SW 10th St. to Glades Road Expected Completion: - 2022
	Palmetto Expressway / SR-826	• West Flagler St. to NW 154th St. (10 miles): 2 express lanes/ direction Expected Completion: Early 2019
In planning/design	Turnpike Mainline	• Golden Glades to Turnpike Extension (3 miles): 1 express lane/direction • Turnpike Extension to the north of Johnson St. (4 miles): 2 express lanes/direction • North of Johnson St. to Griffin Rd. (3 miles): 2 express lanes/direction • I-595 to Atlantic Blvd (10 miles): 2 express lanes/direction • Atlantic Blvd to Wiles Rd. (5 miles): 2 express lanes/direction • North of Sawgrass Expressway / SR-869 to Glades Road (4 miles): 2 express lanes/direction • Glades Rd. to Atlantic Avenue (6 miles): 2 express lanes/direction • Atlantic Avenue to Boynton Beach Blvd (5 miles): 2 express lanes/direction • Boynton Beach Blvd to Lake Worth Rd. (7 miles): 2 express lanes/direction • West Palm Beach Service Plaza to SR-710 (12 miles): 2 express lanes/direction • SR-710 to Jupiter (10 miles): 2 express lanes/direction • Stuart to Fort Pierce (19 miles): 2 express lanes/direction
	I-95	• Glades Rd. to the south of Linton Blvd (6 miles): 1 to 2 express lanes/direction • Stirling Rd. to Broward Blvd (8 miles): 1 additional express lane/direction • I-95 Express direct connect to I-595 (1 mile): 1 additional lane per direction to ramp flyover connection
	Sawgrass Expressway / SR-869	• South of Sunrise Blvd to Atlantic Blvd (7 miles): 2 express lanes/direction • Atlantic Blvd to US 441 (10 miles): 2 express lanes/direction • US 441 to Powerline Rd. (4 miles): 2 express lanes/direction
	Palmetto Expressway / SR-826	• The junction at I-75 to Golden Glades interchange (9 miles): 1 to 2 express lanes/direction • SR-836 to US 1 (6 miles): 1 to 2 express lanes/direction

APPENDIX B: Express Lanes in Florida (continued)

(Source: Alluri et al., 2020)

Phase	Roadway	Description
Northeast Florida		
Under construction	I-295	• I-95 to Buckman Bridge (5 miles): 2 express lanes/direction • SR-9B to J. Turner Butler Blvd (5 miles): 2 express lanes/direction Expected completion: I-95 to Buckman Bridge: fall 2018, SR-9B to J. Turner Butler Blvd: spring 2019
In planning/design	I-295	• J. Turner Butler to the south of Dames Point Bridge (9 miles): 1 to 2 express lanes/direction
	I-95	• North of International Golf Pkwy to I-295 (14 miles): 2 express lanes/direction • I-295 to J. Turner Butler Blvd (6 miles): 2 to 3 express lanes/direction • J. Turner Butler Blvd to Atlantic Blvd (6 miles): 2 express lanes/direction
Central Florida		
Under construction	Beachline West Expressway / SR-528	• I-4 to Turnpike Mainline (4 miles): 2 express lanes/direction • Turnpike Mainline to McCoy Road (4 miles): 1 express lane/direction Expected Completion: I-4 to McCoy Rd: Tentatively opening in Summer 2019
	Turnpike Mainline	• Osceola Pkwy to Beachline West Expressway/SR-528 (6 miles): 2 express lanes/direction Expected Completion: 2021
	I-4	• SR-434 to Kirkman Rd. (21 miles): 2 express lanes/direction Expected Completion: 2021
In planning/design	Turnpike Mainline	• Kissimmee / St. Cloud south to Osceola Pkwy (7 miles): 2 express lanes/direction • Beachline West Expressway / SR-528 to I-4 (4 miles): 1 express lane/direction • Clermont / SR-50 to Minneola (6 miles): 2 express lanes/direction • Minneola to Leesburg North / US 27 (10 miles): 2 express lanes/direction • Leesburg North / US 27 to CR 468 (12 miles): 2 express lanes/direction • CR 468 to I-75 (7 miles): 2 express lanes/direction
	I-4	• West of Kirkman Road / SR-435 to west of Beachline West Expressway / SR-528 (4 miles): 2 express lanes/direction • West of Beachline West Expressway / SR-528 to east of Osceola Pkwy / SR-522 (6 miles): 2 express lanes/direction • East of Osceola Pkwy / SR-522 to west of Champions Gate Blvd / CR 532 (8 miles): 2 express lanes/direction • West of Champions Gate Blvd / CR 532 to west of US 27 (4 miles): 2 express lanes/direction • East of SR-434 to east of US 17-92 (9 miles): 2 express lanes/direction • East of US 17-92 to east of SR-472 (10 miles): 2 express lanes/direction
	Seminole Expressway / SR-417	• Aloma Avenue to SR-434 (6 miles): 2 express lanes/direction • SR-434 to Lake Mary Blvd / CR 427 (5 miles): 2 express lanes/direction • Lake Mary Blvd / CR 427 to Rinehart Rd. (6 miles): 2 express lanes/direction
In design	I-275	• 4th St. N to east of Howard Frankland Bridge (6 miles): 2 express lane/direction
	I-4	• Downtown (east of 50th St.) to Polk Pkwy (22 miles): 1-2 express lanes/direction.

APPENDIX B: Express Lanes in Florida (continued)

(Source: Alluri et al., 2020)

Phase	Roadway	Description
West Central Florida		
In operation	Veterans Expressway / SR-589	• Hillsborough Ave. to Dale Mabry Hwy. (9 miles): 1 express lane/direction
Under construction	I-275	• Gandy Blvd to 4th St. N (4 miles): 1 express lane/direction Expected Completion: 2022
In design	I-275	• 4th St. N to east of Howard Frankland Bridge (6 miles): 2 express lane/direction
	I-4	• Downtown (east of 50th St.) to Polk Pkwy (22 miles): 1-2 express lanes/direction.

APPENDIX C: Existing Managed Lanes in Texas

Name	Length (miles)	From	To	Separation Type	Year Opened	No. of Lanes	Operational hours
US-75	10.5	W Bethany Dr.	Beltline Rd.	Pylons		1 (4)1	24/7
US-75	0.5	Beltline Rd.	I-635	Pylons		1 (5)1	24/7
I-635	9	Oates Dr. /I-30	Greenville Ave.	Pylons	2017	1 (4)	24/7
I-635	9	Greenville Ave.	Luna Rd.	Concrete Barrier	2016	3 (4)	24/7
I-35E	12	Tuberville Rd.	PGBT	Concrete Barrier	2018	2(4) *	SB 3–11 AM; NB 1 PM–1 AM
I-35E	5.5	PGBT	I-635	Concrete Barrier	2018	2(3) *	SB 3–11 AM; NB 1 PM–1 AM
I-35E	3.5	I-635	LP12	Concrete Barrier	2018	1(5)	24/7
I-35W	7.5	N Tarrant Pkwy.	SH183	Concrete Barrier		2(2)	24/7
I-35W	2.5	SH183	US280	Concrete Barrier		2(3)	24/7
SH-26	1	Cotton Belt Trail	SH-114	Concrete Barrier		2(2)	24/7
SH-114	1.5	SH-26	Texan Trail	Concrete Barrier		2(6)	24/7
SH-114	1	Texan Trail	International Pkwy	Concrete Barrier		2(3)	24/7
SH-114	4.5	International Pkwy.	PGBT	Concrete Barrier		1(3) WB	24/7
SH-114	1.5	PGBT	NW Hwy	Concrete Barrier		1(3)	24/7
SH-114	2	NW Hwy.	Rochelle Blvd.	Concrete Barrier		1(2)	24/7
I-820	6	SH183	I-35W	Concrete Barrier		2(2)	24/7
SH-183	6	I-820	Industrial Blvd.	Concrete Barrier		2(3 to 4)	24/7
SH-183	8	Industrial Blvd.	McArthur Blvd.	Concrete Barrier		1(3 to 4)	24/7
SH-183	5	McArthur Blvd.	Regal Row	Concrete Barrier		2(3 to 4)	24/7
LP-12	2	NW Hwy.	SH-183	Concrete Barrier		1(3)	24/7
I-30	10	Duncan Perry Rd.	Postal Way	Concrete Barrier	2017	2(4) *	EB: 9 PM–11 AM WB: 12 PM–8 PM (M-F)
I-30	10	Postal Way	Hardwick St.	Concrete Barrier	2017	1(4) *	EB: 9 PM–11 AM WB: 12 PM–8 PM (M-F)
I-30	10	I-45	NW Hwy.	Concrete Barrier		1(4) *	WB: 6–10 AM; EB 3:30–7 PM (M-F)
I-10	5.5	Westgreen Blvd.	SH-6	Pylons		1(4)1	24/7
I-10	12	SH-6	1-610	Pylons		2(5)	5–11 AM; 2–8 PM (M-F)
I-45	15.5	River Plantation	Parramatta Ln.	Flush		1(4)1	24/7
I-45	18.5	Parramatta Ln.	I-10	Concrete Barrier		1(4 to 5) *	
I-45	20	I-69	Medical center Blvd.	Concrete Barrier		1(4 to 5) *	
I-45	1	Medical center Blvd.	S Texas Ave.	Flush		1(4)1	24/7
I-69	13	Reading Rd.	W Airport Blvd.	Flush		1(4)1	24/7
I-69	14	W Airport Blvd.	Alabama St.	Concrete Barrier		1(2 to 6) *	
I-69	20	McClellan Rd.	I-10	Concrete Barrier		1(3 to 5) *	
US-290	22	Mason Rd.	I-610	Concrete Barrier		1(3 to 5) *	
SL-1	11	Lake Austin Blvd.	Parmer Ln.	Pylons		1(3)	

APPENDIX D: Pros and Cons of Different Managed Lanes Separation Types

(Source: Michael, 2011)

		Barrier Separation	Pylon Separation	Buffer Separation (Pavement Marking)	Wide Buffer Separation
Safety • Incident avoidance • Incident management • Lane clearance	Pros	• Reduces GPLs and MLs sideswipes • MLs traffic is separated from incidents in GPLs	• Easier access for emergency vehicles since pylons can be driven over	• Easy access for emergency vehicles since there is no physical separation • Easy for MLs traffic to vacate the lanes in case of an emergency or incident	• Less opportunity for sideswipes • Wide buffers create a substantial sense of separation
	Cons	• Access to lanes is restricted, therefore Incident Management response may take longer • The impact on MLs traffic is high in case of an incident • More difficult to vacate lanes in case of an emergency or incident	• Can create roadway debris when plugged off • Vehicles in the GPLs are not physically separated from MLs if an incident does occur	• More opportunity for GPLs and MLs sideswipes • Vehicles in the GPLs are not physically separated from MLs if an incident does occur	• Emergency vehicles access may be difficult especially with soft grassed buffers
Right-of-way right-of-way in addition to the space needed for the device placement	Pros	None	• No right of way typically needed for installation	• No right of way typically needed for installation	None
	Cons	• Extra right-of-way typically needed for access points installation • Right-of-way typically needed for shoulders	None	None	• Extra right-of-way is needed
Cost • Initial installation • Maintenance	Pros	• Low maintenance • Allows for overhead sign structure uprights to be placed within the barrier, which reduces sign structure spans	• Easy installation • Low installation cost	• Easy installation • Low installation cost	• Easy installation • Low installation cost
	Cons	• Higher cost for installation than other at-grade separation methods	• High maintenance costs due to frequent replacement of unplugged pylons • No location for overhead sign structure uprights within area separating GPLs & MLs, which results in longer sign structure spans	• No location for overhead sign structure uprights within area separating GPLs & MLs, which results in longer sign structure spans	• May require longer overhead sign structures spans

ML is managed lanes; GPL is general-purpose lanes.

APPENDIX D: Pros and Cons of Different Managed Lanes Separation Types (continued)

(Source: Michael, 2011)

		Barrier Separation	Pylon Separation	Buffer Separation (Pavement Marking)	Wide Buffer Separation
Features and Operational Characteristics • Concurrent flow • Mixed mode • Level of service	Pros	• Allows for higher operating speeds in concurrent flow Operations • Reduces toll avoidance • Better enforcement areas due to limited access points	• Provides some physical separation which can help reduce toll avoidance • Reduces illegal lane changes	• Easy to operate in mixed mode during non-peak times	• Easy to operate in mixed mode during non-peak times • Reduces illegal lane changes
	Cons	• When installed within existing roadway cross-sections, design constraints may be involved • Mixed-mode operations in non-peak times are not applicable • Special openings or devices may be needed for emergency vehicles during incident responses	• Hard to operate in mixed mode during non-peak times • Easily traversed • Hard to establish enforcement areas • Operating speeds may be lower than posted because of limited physical separation • Frequent maintenance on pylons replacements	• Illegal lane changes are not deterred • Hard to enforce illegal maneuvers and other infractions because enforcement areas are hard to establish • Operating speeds within MLs are typically lower than posted during congested times because of no physical separation	• Some illegal maneuvers and other infractions may occur because of limited physical separation
Access Points	Pros	• Access points are controlled by physical separation making them easier to enforce and limits violators	• Easy adjustment of access points after initial installation • Access points are controlled by visual /soft separation limiting violators	• Easy adjustment of access points after initial installation	• Easy adjustment of access points after initial installation
	Cons	• Possible flyovers or extra ramps required for GPLs exits	• GPLs traffic may have to merge with MLs traffic for left exits	• GPLs traffic may have to merge with MLs for left exits	• GPLs traffic may have to merge with MLs for left exits

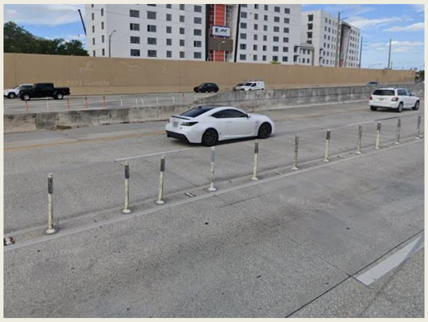
ML is managed lanes; GPL is general-purpose lanes.

APPENDIX E:
One-page Summaries

MANAGED LANES

Non-Reversible Managed Lanes Facilities

Managed lanes are highway lanes where operational strategies are proactively implemented and managed in response to changing traffic conditions. The managed lanes concept is typically a *"freeway-within-a-freeway"* where a set of lanes within the freeway cross-section is separated from the general-purpose lanes. Common separation treatments that separate managed lanes from general-purpose lanes include barrier separation, buffer separation with pylons, buffer separation with pavement marking, wide buffer separation, and grade separation. These separation treatments have varying impacts on the overall safety and operational performance of the managed lane facilities.



Managed lanes
with pylons separation

Specific Considerations

- Performance measure: crash frequency
- Study areas: 20 miles in Florida and 22 miles in Texas
- Study period: 2015 – 2019
- Data: Crash data, AADT, Roadway geometric characteristics
- Separation type: pylons and concrete barrier
- Separate crash prediction models were developed for single-vehicle (SV) and multi-vehicle (MV) crashes by crash severity (fatal and injury (FI) and property damage only (PDO) crashes)

Results and Findings

- On average, in the presence of pylons, SV–PDO crashes decrease by 3.5% for each additional foot of lateral separation width between the general-purpose and managed lanes.
- In the presence of pylons, MV–PDO crashes decrease by an average of 1.8% for each additional foot of lateral separation width between the general-purpose and managed lanes.
- In the presence of pylons, MV–FI crashes decrease by an average of 2.6% for each additional foot of lateral separation width between the general-purpose and managed lanes.
- The number of managed lanes presents similar effects on MV–FI and MV–PDO crashes. On average, MV–FI and MV–PDO crashes increase by 21.2% for each additional managed lane.
- Descriptive statistics of crashes on the 95 Express in Florida revealed that:
  - Most crashes occurred on the general-purpose lanes only (71.7%).
  - About 7.9% of crashes involved crossing over the pylons.

For more information, please refer to the report BE975

MANAGED LANES

Reversible Managed Lanes Facilities

Managed lanes are highway lanes where operational strategies are proactively implemented and managed in response to changing traffic conditions. The managed lanes concept is typically a *"freeway-within-a-freeway"* where a set of lanes within the freeway cross section is separated from the general-purpose lanes. Common separation treatments that separate managed lanes from general-purpose lanes include barrier separation, buffer separation with pylons, buffer separation with pavement marking, wide buffer separation, and grade separation. These separation treatments have varying impacts on the overall safety and operational performance of the managed lane facilities.

Managed lanes with concrete barrier separation

Specific Considerations

- Performance measure: crash frequency
- Study areas: 8 miles in Florida, 11.5 miles in Georgia, and 80.8 miles in Texas
- Study period: 2015 - 2019
- Data: Crash data, AADT, Roadway geometric characteristics
- Separation type: concrete barrier
- Separate crash prediction models were developed for single-vehicle (SV) and multi-vehicle (MV) crashes by crash severity (fatal and injury (FI) and property damage only (PDO) crashes)

Results and Findings

- On average, in the presence of the concrete barrier, SV–FI crashes decrease by 2.6% for each additional foot of lateral separation width.
- On average, MV–FI crashes decrease by 29.4% for each additional managed lane. On the other hand, MV–PDO crashes decrease by an average of 34.7% for each additional managed lane.
- Descriptive statistics of crashes on the 595 Express in Florida revealed that:
  - Most crashes occurred on the general-purpose lanes only (95.8%).
  - About 0.8% of crashes occurred at express lanes entry or exit points.
  - Single-vehicle crashes accounted for 26.0%, and multi-vehicle crashes accounted for 74% of crashes.

For more information, please refer to the report BE975