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A Corridor Level GIS-Based Decision Support Model to Evaluate Truck Diversion Strategies

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A CORRIDOR LEVEL GIS-BASED DECISION SUPPORT MODEL TO EVALUATE TRUCK DIVERSION STRATEGIES

by

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ABSTRACT

Increased urbanization, population growth, and economic development within the U.S. have led to an increased demand for freight travel to meet the needs of individuals and businesses. Consequently, freight transportation has grown significantly over time and has expanded beyond the capacity of infrastructure, which has caused new challenges in many regions. To maintain quality of life and enhance public safety, more effort must be dedicated to investigating and planning in the area of traffic management and to assessing the impact of trucks on highway systems. Traffic diversion is an effective strategy to reduce the impact of incident-induced congestion, but alternative routes for truck traffic must be carefully selected based on a route's restrictions on the size and weight of commercial vehicles, route's operational characteristics, and safety considerations. This study presents a diversion decision methodology that integrates the network analyst tool package of the ArcGIS platform with regression analysis to determine optimal alternative routes for trucks under nonrecurrent delay conditions. When an incident occurs on a limited-access road, the diversion algorithm can be initiated. The algorithm is embedded with an incident clearance prediction model that estimates travel time on the current route based on a number of factors including incident severity; capacity reduction; number of lanes closed; type of incident; traffic characteristics; temporal characteristics; responders; and reporting, response, and clearance times. If travel time is expected to increase because of the event, a truck alternative route selection module is activated. This module evaluates available routes for diversion based on predefined criteria including roadway characteristics (number of lanes and lane width), heavy vehicle restrictions (vertical clearance, bridge efficiency ranking, bridge design load, and span limitations), traffic conditions (level of service and speed limit), and

neighborhood impact (proximity to schools and hospitals and the intensity of commercial and

residential development). If any available alternative routes reduce travel time, the trucks are

provided with a diversion strategy. The proposed decision-making tool can assist transportation

planners in making truck diversion decisions based on observed conditions. The results of a

simulation and a feasibility analysis indicate that the tool can improve the safety and efficiency

of the overall traffic network.

It is my greatest pleasure to dedicate this achievement
to my late father, Mahmoud Younes

ACKNOWLEDGMENT

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LIST OF ABBREVIATIONS

AADT Annual Average Daily Traffic

ATIS   Advanced Traveler Information System

ATMS Advanced Transportation Management System

ATRI American Transportation Research Institute

CAV   Connected and Automated Vehicles

CORSIM   Corridor Simulation

DSS   Decision Support System

DTA   Dynamic Traffic Assignment

DTR   Dynamic Traffic Re-routing

ESRI   Environmental Research Institute

FHWA Federal Highway Administration

FITM Freeway Incident Management

FMTP Freight Mobility and Trade Plan

GIS-T Geographic Information Systems for Transportation

GIS   Geographic Information System

ITS   Intelligent Transport Systems

LOS   Level of Service

NBI   National Bridge Inventory

NFSP Freight Strategic Plan

RTRDS   Real-Time Route Diversion Management System

TRB   Transportation Research Board

VOT   Value of Time

VRP   Vehicle Routing Problem

CHAPTER 1: INTRODUCTION

1.1 Background

The extent of road travel in the U.S. has substantially increased due to various disruptive effects. These include the impact of technology, the emergence of connected and automated vehicles (CAVs), social and demographic changes, urbanization and globalization, environmental and energy trends, economic and workforce changes, and political and fiscal trends.

The increase in vehicle miles traveled, together with limited roadway infrastructure expansion, has led to severe traffic congestion. Traffic congestion creates significant economic losses and negative environmental impacts. As a result of congestion, according to the Urban Mobility Scorecard (Schrank, Lomax, Fellow, Bak, & Analyst, 2015), in 2014, people in the U.S. traveled an extra 6.9 billion hours and purchased an additional 3.1 billion gallons of fuel, resulting in congestion costs of up to $160 billion. Thus, traffic congestion is a critical issue for traffic managers, decision-makers, and road users.

By 2045, the U.S. population is anticipated to rise from the existing 321 million to 389 million, and the size of the U.S. economy is projected to double from its 2017 size (National Freight Strategic Plan, NFSP 2015). With the growth of the population and economic activity within the U.S., freight transportation has also grown significantly. In 2015, the U.S. transportation system carried a daily average of approximately 49.3 million tons of freight, with a worth of more than $52.5 billion. One study, the Freight Analysis Framework, estimated that the tonnage would increase at approximately 1.4% per year between 2015 and 2045. A strong economy and the evolution of time-sensitive freight services have significantly increased the

number of trucks on the nation's highways. According to the Texas A&M Transportation Institute (2017), truck trips are predicted to increase from 557,000 per day in 2014 to over 1 million per day by 2040. These higher truck volumes have a significant effect on the level of congestion and air quality in many regions.

Despite the availability of other transportation modes, trucks are the principal means for moving freight, and about 69% of the total tonnage shipped nationally is carried by truck (U.S. Department of Transportation 2010). According to the American Transportation Research Institute (ATRI) (Murray, 2015), traffic congestion impacted the trucking industry and caused over 996 million hours of delay on the National Highway System, which is comparable to having 362,243 commercial truck drivers inactive for a whole year. This significant loss of productivity costs the trucking industry about $63 billion annually. Additionally, due to the differences in size and operation between trucks and cars, trucks have negative impacts on surrounding traffic and contribute to increases in crash severity, driver frustration, and vehicular emissions. Hence, new approaches are needed to improve the flow of traffic and accommodate heavy vehicles safely under incident-induced congestion.

According to the ATRI 2015 report, Florida is the most congested state in the U.S., bearing 8.4% of the total nationwide cost of congestion (or more than $5.3 billion). Florida's population is growing and is expected to reach 33.5 million by 2060. Additionally, Florida is expecting 157 million more visitors between now and 2025 (Office of Economic and Demographic Research). Florida relies on freight mobility and international trade, and its economy is significantly affected by the movement of goods and commodities. According to the Florida Department of Transportation Office of Freight and Multimodal Operations, total freight

imports to Florida in 2011 were 146 million tons. Figure 1 shows Florida's total freight flow in 2011.

Figure 1: Florida Total Freight Flow, 2011 (Freight Analysis Framework (FAF))

This already significant movement of freight to, from, and within the state is expected to grow by 69% in weight and 174% in value by 2040. Figure 2 illustrates the routes of significant freight flows by truck to, from, and within Florida. The map indicates the maximum truck tonnage movement is between Florida and the adjacent states of Georgia and Alabama.
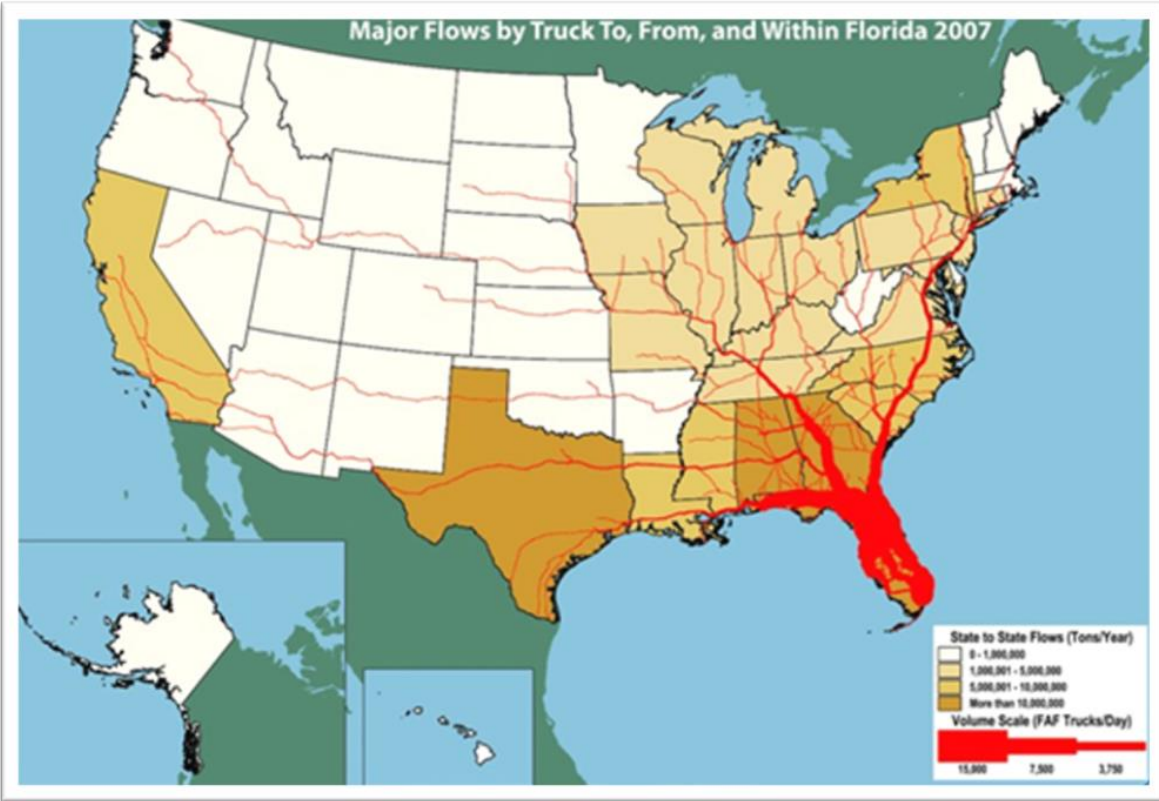
Figure 2: Major flows by Trucks to, from, and within Florida, 2007 (FHWA)

Moreover, based on the ATRI 2015 report, Florida is the most congested state in the U.S., with 8.4% of the total nationwide cost of congestion (or more than $5.3 billion). As shown in table 1, Florida and Texas were ranked as the top two states by total congestion cost. The two States combined caused 16.5% of the national cost of congestion. Table 1 lists the top ten states by the total cost of congestion and each state's share of the total national cost of congestion (Torrey & Research Associate, 2015).

Table 1: Top ten States by the total cost of congestion, 2015

2015 Rank	State	Total Cost	Share of Total Cost	2014 Rank
1	Florida	$ 5,316,892,950.00	8.40%	1
2	Texas	$ 5,134,297,806.00	8.10%	2
3	California	$ 4,195,916,467.00	6.60%	3
4	New York	$ 3,902,164,040.00	6.10%	5
5	New Jersey	$ 2,991,619,160.00	4.70%	4
6	Illinois	$ 2,677,465,331.00	4.20%	6
7	Pennsylvania	$ 2,592,540,683.00	4.10%	7
8	Ohio	$ 2,496,281,123.00	3.90%	21
9	Tennessee	$ 2,335,201,607.00	3.70%	12
10	North Carolina	$ 2,012,954,818.00	3.20%	8

The purpose of the current study is to build on previous studies related to incident management, address the limitation that has been identified, and contribute to the research on traffic rerouting, as outlined in the following sections.

1.2 Problem Statement

Generally, traffic congestion can be classified as recurrent or nonrecurrent congestion. Recurrent congestion is usually triggered by a high level of traffic demand that regularly exceeds the road capacity, whereas nonrecurrent congestion is a temporary interruption of the normal flow of traffic that triggers an unpredicted reduction in roadway capacity, which leads to more lengthy travel delays than usual. According to a 2006 Federal Highway Administration (FHWA) report, nearly 60% of all delays are caused by nonrecurring congestion.

One of the leading causes of nonrecurrent congestion is traffic incidents. Traffic incident management plays an essential role in effectively and efficiently mitigating the impacts of incident-induced congestion. The process of traffic incident management includes several main

phases: detection and verification, response, clearance, and recovery. All stages of the incident management process are vital in reducing the magnitude of incident-induced congestion. Each phase features a set of techniques and requires organized decision-making strategies coordinated between the involved agencies.

Highway agencies in the U.S. have implemented several truck rerouting strategies. Rerouting strategies are intended to divert truck traffic from congested facilities, expedite traffic flow, decrease conflicts between passenger vehicles and trucks, and improve the operation and safety of limited urban highways.

Traffic diversion strategies that channel truck traffic to a potential alternative route can mitigate congestion. The alternative route then carries both the diverted traffic and its regular traffic load. Therefore, the evaluation of truck traffic diversion options should consider the safety and efficiency of the overall network. Although traffic diversion strategies are implemented in many regions, only limited attention has been paid to identifying criteria for selecting the optimal alternative route for truck traffic. Current traffic diversion strategies do not consider whether an alternative route can accommodate truck characteristics and meet maneuverability requirements. The selection criteria for alternative truck routes should be carefully defined so that they consider truck characteristics, and optimal routes should be selected that can efficiently accommodate truck traffic.

Most previous studies of traffic diversion have focused on enhancing traffic conditions for passenger vehicles rather than on enhancing conditions for trucks. Hence, limited consideration has been given to assessing the economic, social, and environmental impacts of truck traffic diversion strategies on the performance of the selected alternative routes.

A competent truck rerouting operation requires precise planning and substantial resources throughout the implementation. Given declining resources for traffic management, it has become increasingly crucial in practice to ensure there is valid justification before implementing a rerouting strategy. This study develops a decision-support system to aid traffic managers in efficiently making such decisions by considering several factors: (a) the predicted incident clearance time, (b) the predefined alternative route selection criteria, and (c) the resultant benefits from reduced delays and lower fuel consumption. The proposed decision-making tool assists transportation planners in reaching truck diversion decisions that are based on observed traffic conditions and that improve the safety and efficiency of the traffic network.

The limitations noted above, together with the infrastructure expansion investment gap in the U.S., indicate a need to embrace alternative strategies to detect, manage, and efficiently mitigate traffic congestion. The use of an efficient truck traffic diversion strategy during incident-induced congestion provides safety and mobility benefits to highway users. A reliable and comprehensive framework is needed for evaluating such traffic diversion strategies during nonrecurrent congestion.

The application of appropriate diversion criteria that include truck value-of-time (VOT) analysis, fuel consumption measures, safety studies, environmental impact analysis, and noise control considerations can lead to the selection of an alternative route that reduces travel time, meets truck operations restrictions and sustains an acceptable level of service on the alternative route. The proposed framework provides a decision-support tool to help decision-makers and traffic management centers cope more efficiently and effectively with nonrecurrent congestion on highway networks.

1.3   Research Objectives

The objective of this research is to develop a framework to evaluate whether and how to implement truck traffic diversion strategies that, by considering an alternate route's truck restriction policies (e.g., speed and weight restrictions) and geometric limitations (e.g., lane width and vertical clearance), do not negatively affect the operation of that alternate route. The framework should also assess the impacts of the diverted truck traffic on all possible measurements of overall network performance.

1.4   Dissertation Organization

This dissertation consists of 7 chapters. A brief outline of the chapters in this reserach is given below.

Chapter 2: This chapter presents a review of the literature related to traffic incident management, different incident management phases, and incident timelines. It also reviews the literature on traffic diversion strategies and the various processes for mitigating congestion problems. Finally, the chapter discusses the application of geographic information systems in transportation.

Chapter 3: Chapter 3 describes the methods for collecting and cleaning the data and for preparing them for analysis. Suitable statistical approaches and techniques used for analyzing the performance of the developed framework based on the available data are also discussed.

Chapter 4: Chapter 4 describes the methodology for the statistical analysis of incident clearance prediction times, which includes incident data collection, data cleaning, and data processing, and defines the variables with the greatest impact on incident duration. This chapter

also presents methods for preparing a road network dataset and historical traffic data and for setting the alternative route selection criteria.

Chapter 5: This chapter details the statistical analysis of the collected incident data to predict incident clearance duration and determine how different explanatory variables affect incident clearance duration. This chapter also presents the network model development process and describes how alternative route selection criteria are incorporated into the developed network model.

Chapter 6: This chapter presents five case studies based on real-world data to validate the model. Results from the developed model are also presented and discussed. Finally, the chapter summarizes the study findings and limitations and offers recommendations for future work.

Chapter 7: This chapter summarizes the findings of this study, draws conclusions, and offers recommendations for future work.

Figure 3 illustrates the organization of this dissertation.
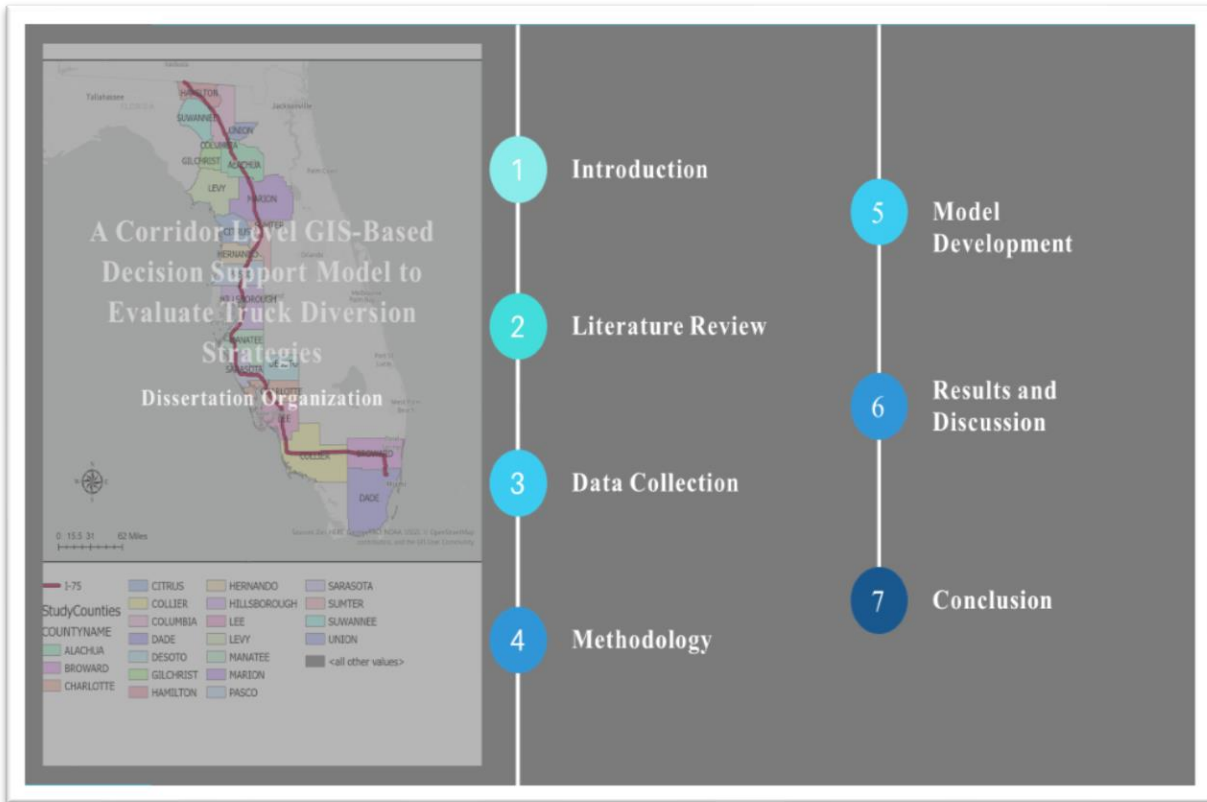
Figure 3: Dissertation Organization

CHAPTER 2: LITERATURE REVIEW

There are three sections in this chapter. First, a summary of previous incident duration prediction models is presented. The second section reviews state-of-the-art truck diversion strategies. Finally, the last section presents tools for supporting traffic operations decisions.

2.1   Introduction

The first chapter of this dissertation discusses the current and future conditions of transportation mobility, and the disrupting forces endangering it. There is a need to study strategies to mitigate disruptive effects and manage this complex dynamic system more efficiently. This literature review includes five sections: First, traffic congestion types are presented, including recurrent and nonrecurrent congestion. Next, studies of the traffic incident management process are reviewed; this section helps lay the foundation for examining the relevant congestion mitigation studies. The third section of this chapter first explores various diversion strategies and then summarizes the criteria for selecting an alternative route. In the fourth section, various network simulation tools are reviewed, with a focus on the application of a geographic information system (GIS) in transportation.

The final section of this chapter discusses decision-support methods in transportation. These systems include the cost-benefit analysis, which can quantify the benefits of mitigation strategies, monetize the costs versus benefits, and finally, be applied in developing a decision-support tool to assist policy-makers. Table 2 summarizes the reviewed literature on truck diversion studies.

Table 2: A summary of a literature review of related studies

Study	Evaluation Method	Findings
Cragg and Demetsky, 1995	Corridor Simulation Software Package (CORSIM)	While traffic diversion might reduce travel time on the freeways, it can increase delays on the detour route by 64%. The inclusion of ramps and weaving sections with sufficient capacity to accommodate diverted traffic is crucial.
Aden and Nageli, 1999	Corridor Simulation Software Package (CORSIM)	The authors stressed the importance of testing signal-timing plans for alternate routes to relieve bottlenecks and reduce network delays.
Backfrieder, 2014	Traffic Simulator Platform (TraffSim)	The authors presented a microscopic simulation platform with the capability of integrating OpenStreetMap to generate a better simulation scenario and to simulate real traffic in a real environment.
Güner et al., 2012	Stochastic dynamic programming	The results confirmed that travel time savings were higher during peak times and lower when the traffic tended to be static.
Lin and Kou, 2003	Microscopic simulation	The modeling results of the case study offered several advantages for drivers using an alternate route. The findings evaluated the effectiveness of alternative route operations in reaction to a major highway accident.
Huaguo, 2008	CORSIM	Road diversion strategies could significantly reduce network delays—by an estimated 21%. A 10% redirected traffic volume has a significant effect on the average delay of the entire system.
Dia et al., 2008	Large-scale micro-simulation	The optimum diversion rate reached was 30%. This decreased the delay of 9%, the number of stops by 22%, and travel times by 3%.
Cuneo et al., 2014	Microscopic traffic simulation	The optimal diversion rate depends on the current traffic demand. This suggests the need to carry out a thorough assessment to determine the impacts of diversion techniques before they are introduced in the field.

Study	Evaluation Method	Findings
Fries et al., 2007	Paramics	Only specific configurations of incident duration and simulation precision fulfilled the decision-time constraints for supporting real-time decision-making.
Luo et al. (2016)	Support vector regression	The study found a 15% difference between the model forecasts and the simulation, indicating the efficiency of the decision support system.
Li and Khattak (2018)	TransModeler	Their study assessed the impact of different Advanced Travel Management System(ATMS) technologies on en-route diversion and investigated the delay decrease and cost savings for both passenger vehicles and trucks.
Aleksandr et al. (2018)	Conceptual diagram	The authors presented and explained all the steps of dynamic traffic rerouting (DTR) using a conceptual diagram. They determined a traffic flow threshold condition that can be used as a start for DTR.

2.2   Traffic Congestion

The forces threatening the performance of the transportation network must be carefully examined. Otherwise, congestion can have unacceptable consequences for the quality of the life of citizens. Without proper planning, congestion occurs and negatively influences the economy.

The demand for solutions to traffic congestion in the U.S. increases each year, and in many parts of the nation, congestion has escalated to distressing levels. The impact of increased congestion on the economy includes many adverse effects on transportation systems, such as a decline in the reliability of transportation infrastructure. Additionally, freight vehicles are forced to devote more time to ensuring on-time delivery, and vehicle operating costs increase, as do environmental and safety costs. Vehicles are also more likely to operate less efficiently, and

roadway conditions may deteriorate. These are all effects of increased congestion on different aspects of daily life.

Generally, traffic congestion can be categorized as recurrent or nonrecurrent congestion. Recurrent congestion is usually triggered by a high level of traffic demand that regularly exceeds the road capacity. Nonrecurrent congestion is a temporary interruption of the normal flow of traffic, and it triggers an unpredicted reduction in roadway capacity that leads to travel delays. One of the leading causes of nonrecurrent congestion is traffic incidents.

As illustrated in Figure 4, the FHWA reported in 2006 that nearly 60% of all delays were caused by nonrecurring congestion.
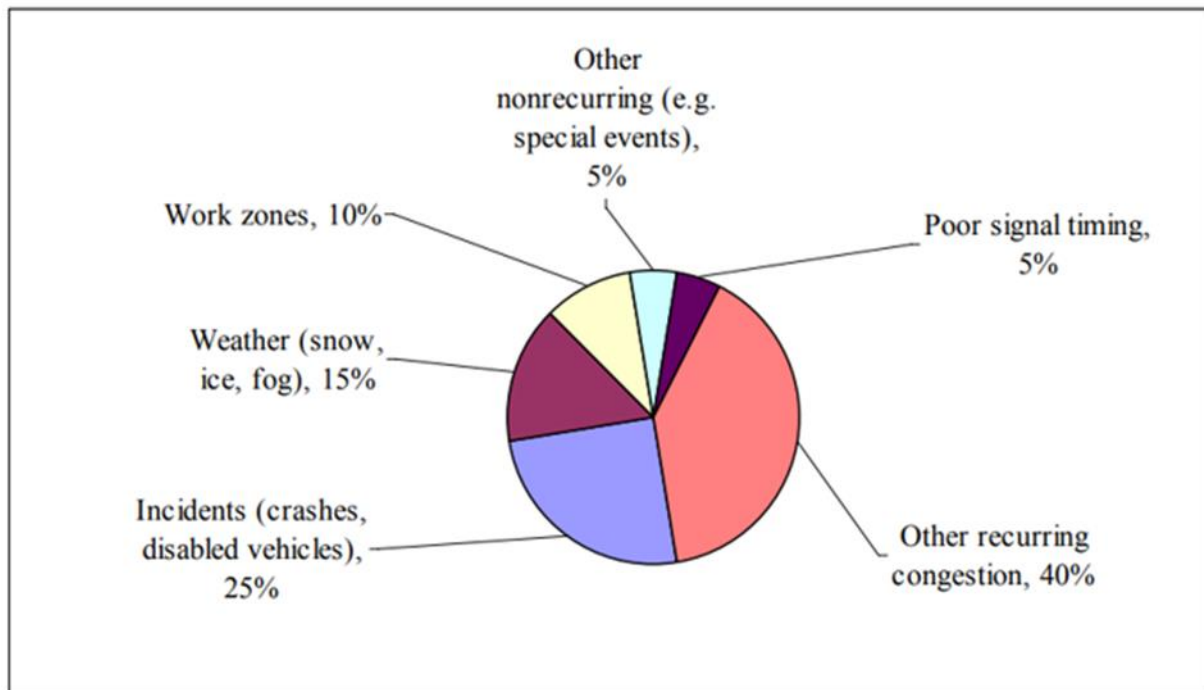
Figure 4: Causes of Highway Congestion

Source: Federal Highway Administration, 2005

2.3   Incident Management

Incident management support systems have attracted significant attention over recent years. These systems play an essential role in supporting decision-makers in situations where they must deal with uncertainties stemming from nonrecurrent congestion and multiple operations. Incident management plays an essential role in efficiently mitigating the impact of incident-induced congestion. The process of traffic incident management features several vital phases, including detection and verification, response, clearance, and recovery. Each phase is essential in reducing the magnitude of incident-induced congestion and involves a set of techniques and decision-making strategies used by the agencies involved.

The recovery phase starts when the incident has been completely cleared from the roadway, and traffic capacity is restored when the traffic flow reaches normal conditions. Diversion of traffic to alternate routes is one technique that can be employed to mitigate congestion in the recovery phase.

Because an alternative route to which traffic is diverted carries both the diverted traffic and the route's regular traffic load, truck traffic diversion options should be carefully evaluated with the goal of improving the safety and efficiency of the overall network. Although traffic diversion strategies are implemented in many states, the consideration of optimal truck traffic criteria in selecting alternative routes has been limited.

Most previous studies in this area have focused more on enhancing traffic conditions for passenger vehicles than on the conditions for trucks. Moreover, to the best of our knowledge, insufficient attention has been paid to assessing the economic and environmental impacts of truck traffic diversion on selected alternate routes. Consequently, a reliable framework is needed

to evaluate truck traffic diversion strategies deployed for nonrecurrent congestion and to assess

the impact of diverted truck traffic on the performance of the network as a whole.

2.4   Traffic Diversion Strategies

The rapid growth in truck traffic on U.S. highways has intensified safety, operational, and

environmental concerns. A variety of truck rerouting strategies have been executed throughout

the U.S. to facilitate traffic flow and reduce conflicts between trucks and cars. When properly

implemented, truck rerouting strategies can improve the operational performance of highways

and can enhance traffic safety.

The Advanced Traveler Information System (ATIS) and the Advanced Traveler

Management System (ATMS) are essential components in the incident management process.

They use real-time information to assist drivers in making better decisions about their departure

times, route choices, and alternate routes to avoid congested facilities. Moreover, dynamic traffic

assignment (DTA) is a critical approach that provides route assignment answers for various types

of vehicles, giving them a minimum average trip time.

2.4.1   Microscopic Rerouting Simulation

Rerouting strategies have been broadly assessed in many studies (Cragg & Demetsky,

1995; Alexander Aved et al., 2007; Anastasia Spiliopoulou et al., 2013; and Constantinos

Antonioua et al., 2011). Cragg and Demetsky (1995) developed a microscopic traffic simulation

model using the CORridor SIMulation (CORSIM) software package to evaluate various traffic

diversion strategies. The researchers examined incident scenarios of different severities and

durations, and they conducted a signal-time optimization plan along the proposed alternate route.

The authors found that, while traffic diversion might reduce travel time on the freeways, it can increase delays on the detour route by 64%. They concluded that the inclusion of ramps and weaving sections with sufficient capacity to accommodate diverted traffic is crucial. Aden and Nageli (1999) utilized a CORSIM simulation model to examine signal timing for preplanned diversion routes during an incident. They stressed the importance of testing signal-timing plans for alternate routes to relieve bottlenecks and reduce network delays.

Aved et al. (2007) used real-time data and a historical traffic database to develop a real-time route diversion management system that was able to identify optimal route diversions. Braekers (2016) presented a review of 277 articles related to the vehicle routing problem (VRP) published between 2009 and 2015 that included detailed characterization of the VRP; the classification taxonomy for this study was adopted from Eksioglu et al. (2009). The authors presented a VRP classification table that researchers can use as a tool to find relevant literature. This table allows for the analysis of the most popular VRP characteristics.

2.4.2 Dynamic Traffic Routing

Dynamic traffic rerouting (DTR) forms a substantial part of the Advanced Transportation Management System (ATMS) and intelligent transport systems (ITSs). Several studies have examined DTR and have considered how its application can enhance the effectiveness of traffic management systems. Most of the studies noted above were dedicated to discovering alternative routes and assessing the impact of traffic information on roadway users. Aleksandr et al. (2018) stated that DTR from congested road segments to alternative routes remains limited. The authors

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presented and explained all the steps of DTR using a conceptual diagram. They determined a traffic flow threshold condition that can be used as a start for DTR.

Li and Khattak (2018) developed microscopic simulation models using TransModeler software to simulate eight diversion locations along highway I-40. Their study assessed the impact of different ATMS technologies on en-route diversion and investigated the delay decrease and cost savings for both passenger vehicles and trucks. The authors considered lane blockage, CAVs, incident duration, incident information availability, number of intersections, and average annual daily traffic (AADT) as their simulation model parameters. They confirmed that few studies had investigated truck en-route diversion using a nonrecurrent large-scale incident scenario on the freeways together with CAV technology. They also suggested that truck and passenger vehicle operation should be modeled separately. Their study proposed several future areas of research, such as incorporating signal-timing plans into the process of diverting traffic to alternative routes, comparing different alternate routes for trucks, and assessing the impact of the behavior of truck drivers on the diversion decision.

Wang et al. (2018) reviewed recent advances in DTA models and investigated their environmental impact. They also assessed traffic signal control for emission pricing and investigated the integration of DTA models with emission estimation models. Moreover, they highlighted several areas for future research on environmentally sustainable transportation. Pell et al. (2017) presented a state-of-the-art study that compares 17 simulation software tools and evaluates their adaptability and versatility in real-time simulations in a heterogeneous road network. They concluded that there is a shortage of online traffic simulation software applications specifically designed for use with multiple road transportation networks. The

authors recommended that future research should focus on improving traffic simulation systems to increase their capabilities and enable them to provide real-time traffic information.

When congestion is detected, vehicle navigation systems and services such as Google Maps and Bing can provide alternative paths for affected vehicles. However, they offer the same routes for all vehicles, which could lead to an imbalance in global traffic behavior. By contrast, DTA can assign each vehicle a route based on either system equilibrium or user optimization. However, the calculation is not done quickly enough to notify drivers of the availability of new routes and assist them in avoiding congestion.

2.4.3   Real-time Diversion Strategies

Pan et al. (2013) presented proactive rerouting strategies based on a traffic supervision system that monitors the traffic and reroutes vehicles once congestion is detected. Their outcomes revealed that the recommended algorithms mitigate traffic congestion effectively. Pan et al. (2017) discussed two limitations to the feasibility of their previous rerouting model. First, drivers' privacy concerns were not considered, as they were required to share information about their origins and destinations. Second, the initial 2013 model did not account for the need for intensive computation, which is necessary to reassign vehicles to a new route in real-time based on the road conditions. The authors proposed an updated distributed vehicular system that is capable of making faster and more efficient rerouting decisions. Moreover, they developed privacy enhancement mechanisms for vehicles that enable them to upload their locations when they are in less sensitive areas. The simulation results demonstrated a significant positive impact on user privacy and a minimal effect on rerouting effectiveness.

Luo et al. (2016) developed an en-route, real-time diversion control strategy in a predictive control structured model. They evaluated the network's performance and investigated the impact of total driving time on traffic efficiency, fuel economy, and emissions reductions. Their study concluded that the application of route diversion control is not as practical during peak hours as it is during off-peak hours. This knowledge can help traffic management to better manage multiple scenarios in a route diversion control application. Backfrieder (2014) introduced TraffSim, a microscopic simulation platform, and demonstrated its ability to integrate OpenStreetMap to generate a robust simulation scenario and to simulate real traffic in a real environment. Backfrieder (2014) also explained the simulator congestion detection components and rerouting algorithms used in TraffSim.

Güner et al. (2012) introduced a stochastic dynamic programming formulation for dynamic routing in a nonstationary stochastic network under conditions of recurrent and nonrecurrent congestion. The researchers integrated real-time ITS information into their model to dynamically divert traffic around congested road segments. The results confirmed that travel-time savings were more significant during peak times.

2.4.4   Diversion Decision Framework

The Alternate Route Handbook of the Highway Administration and Federal Highway Administration (2006) provided thorough guidelines for traffic diversion strategies. Additionally, the Alternative Route Handbook presented the process of development and deployment of diversion strategies. Moreover, the handbook noted the criteria that are currently used in various states to make reliable diversion decisions according to predefined alternate route plans. Most of

the transportation agencies considered incident duration and lane blockage as the principal factors in making a diversion decision.

Liu (2013) presented a diversion decision framework to assess the benefits of implementing a detour strategy for managing nonrecurrent congestion on urban freeways. The author noted that the literature contains minimal information and few tools that can assist policy-makers and traffic managers in making a firm decision on traffic diversion during significant incidents. He also generated simulation scenarios using a combination of critical parameters, such as incident duration, flow rate on a main-line detour route, and number lanes and number signals on the detour route, to define whether and when a detour decision should be made. The results revealed that the proposed logistic decision model could be used in the real-time management of nonrecurrent congestion.

Hu (2005) introduced a systematic framework based on traffic assignment models and analyzed the value of traffic information in performing route diversion strategies for online traffic management objectives under the impact of traffic incidents. The author confirmed the importance of real-time traffic information in alleviating nonrecurrent congestion. The results of his simulation analysis indicated that the proposed framework was able to assess the cost-effectiveness of information provision strategies.

2.5   GIS Applications in Transportation

Geographical information system (GIS) technology contributes to notable strength in transportation modeling. The use of GIS accelerates the practical and portable collection, updating, and encoding of spatial data. In addition, the GIS system enhances model

compatibility, database management and updating, and the visualization of model performance, significantly improving the functionality of the transportation model as a decision support system (DSS) in transportation planning and policy-making.

2.6   Summary

This chapter reviewed research on traffic management and truck rerouting to identify and analyze truck traffic rerouting strategies meant to avoid nonrecurrent congestion. Strategies that divert truck traffic to an alternative route can be used as congestion mitigation strategies. The alternative route consequently carries both the diverted traffic and its regular traffic load. Therefore, the alternative route should be carefully selected, and the safety and efficiency of the overall network should be considered when evaluating truck traffic diversion options. While traffic diversion strategies are deployed in many regions, there is minimal consideration of alternative route requirements when the optimal diversion route for trucks is chosen. Nonetheless, the criteria for choosing alternative truck routes should be carefully defined to consider truck characteristics and to select routes that can efficiently accommodate truck traffic. Most previous studies of this issue focused more on enhancing traffic conditions for passenger vehicles than on conditions for trucks. Hence, limited consideration has been given to the evaluation of the economic, social, and environmental impacts of truck traffic diversion on the performance of the selected alternative routes.

The rapid growth of truck traffic has raised safety and operational concerns. Truck diversion strategies have been executed throughout the U.S. to diminish the impact of incident-

induced congestion. Proper truck rerouting strategies can improve the operational efficiency of freeways and enhance traffic safety on these roadways.

The present study does not claim that existing models are incorrect; instead, it demonstrates that they are incomplete. This study aims to build upon developed methods and findings of prior research to develop a new model to address the discussed problems in traffic planning practicality and efficiency. This research proposes the enhancement of current frameworks with empirical data and conceptual supplements to improve traffic diversion strategies by incorporating uncertainties such as nonrecurrent congestion to assist decision-makers in strategy planning.

CHAPTER 3: DATA COLLECTION

3.1   Introduction

As presented in Chapter 1, the main goal of this research is to develop a framework that can be used to assist traffic control centers in evaluating truck diversion strategies during nonrecurrent congestion. When an incident occurs and is detected, the duration of the incident is predicted based on the available incident characteristics. The delay caused by the incident is then compared with a threshold. If it is found to be higher than the threshold, the diversion algorithm is initiated to divert the truck traffic to an alternative route based on predefined alternative route selection criteria.

The process of developing the framework was segmented into four main phases. First, a hotspot analysis was conducted to define the spatial incident distribution. Second, an incident clearance prediction model was developed, and the variables impacting the incident clearance time were statistically tested. Third, a truck route selection model was developed to select alternative routes that accommodate truck characteristics and restrictions. Finally, a cost-benefit analysis was performed to estimate economic and environmental benefits engendered by implementing the diversion decision model.

Extensive data collection was required for each step of this research. This chapter describes the methods for collecting and cleaning the data and for preparing them for analysis. Suitable statistical approaches and techniques used for analyzing the performance of the developed framework based on the available data are also discussed.

The overall process used to achieve the objectives of this study is summarized in the flowchart in Figure 5. The flow chart shows the data analysis approach and the techniques used

in addressing each objective. It is important to note that this section offers an overview of the

process; the details of each analysis are provided in the relevant chapter.

Phase		Input Data	Tool	Output
Phase 1	**Spatial-Temporal Crash Analysis**	Crash Data for the years of (2014 to 2017) including crash location, date, and time	ArcGIS Pro 2.5, Geographic Information System (GIS) Spatial Analyst	Statistically significant space-time crash trends, Description of hotspot and crash trends categories over time, High-rate crash segments, 3D visualization of crash clusters locations over time
		Roadway Segments		
Phase 2	**Incident Clearance Prediction Model**	Incident data for the year of (2018-2019), including: **Temporal characteristics** (Incident date, incident time, day of week, month of year, incident notification, verification, and response time) **Incident characteristics** (Incident type, incident location, number of blocked lanes, incident severity) **Road characteristics** (median type, median width, functional classification, number of lanes) **Traffic characteristics** (AADT, maximum speed, capacity reduction, truck percentage)	Multiple Linear Regression Statistical Package of Social Science (SPSS)	Prediction of incident clearance duration, Significant explanatory variables were identified
Phase 3	**GIS network Analysis and Truck Diversion Feasibility Analysis**	**Street dataset**, elevation, turn restrictions, one-way restrictions **Traffic data**: Historical traffic data, Live traffic data, Time one table, TMC table, Speed profiles table, Street profiles table **Alternative route selection criteria including**: **Roadway geometry** (lane width, number of lanes) **Traffic conditions** (Level of Service, speed limit) **Heavy vehicle restrictions** (vertical clearance, bridge design load) **Neighborhood impact** (Proximity to schools and hospitals)	ArcGIS Network Analyst, Python for ArcGIS, Arcpy for Geoprocessing	Dynamic routable network, All potential alternative routes (base scenario) , Optimal truck alternative routes, turn by turn direction on each route, travel time, route length
Phase 4	**Diversion Decision-Making**	Predicted incident clearance duration	National Highway Traffic Safety Administration (NHTSA), Commercial Medium and Heavy-Duty Truck Fuel Efficiency Technology Report	Benefits in terms of delay savings, fuel consumption savings
		Travel time and route length on both base scenario and alternative route		Monetary equivalents of time and fuel consumption
		AADT, truck volume, speed limit		Decision-making tool to select optimal alternative route for truck diversion

Figure 5: Overall Structure of the Research

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3.2 Study Area

The Interstate 75 (I-75) corridor is a limited access facility and is one of the most critical transportation facilities in the state of Florida. It facilitates freight movement to, from, and within the state, starting from the south in Miami south to north in approximately 272 miles of I-75 cross through the Florida Department of Transportation (FDOT) Districts 6, 1, 7, 5, and 2.

Interstate 75 is mostly a four-lane highway, but there is a six-lane section with 12-foot lane widths and a minimum 40-foot median. I-75 is an integral part of the strategic intermodal system (SIS), a system of significant roadways intended to provide high-speed travel connections between major population centers throughout the states.

Due to the growth in freight miles traveled, I-75 has experienced a significant increase in traffic volume, which has resulted in operational deficiencies and additional congestion. Given the importance of the I-75 corridor, it was selected as a study area for this research with the purpose of congestion mitigation. The study corridor evaluated includes 20 counties through north, central, and southeast Florida, with a total population of over 5 million residents, which represents approximately 25% of Florida's population. Figure 6 shows the spatial extent of the study area selected for this research.
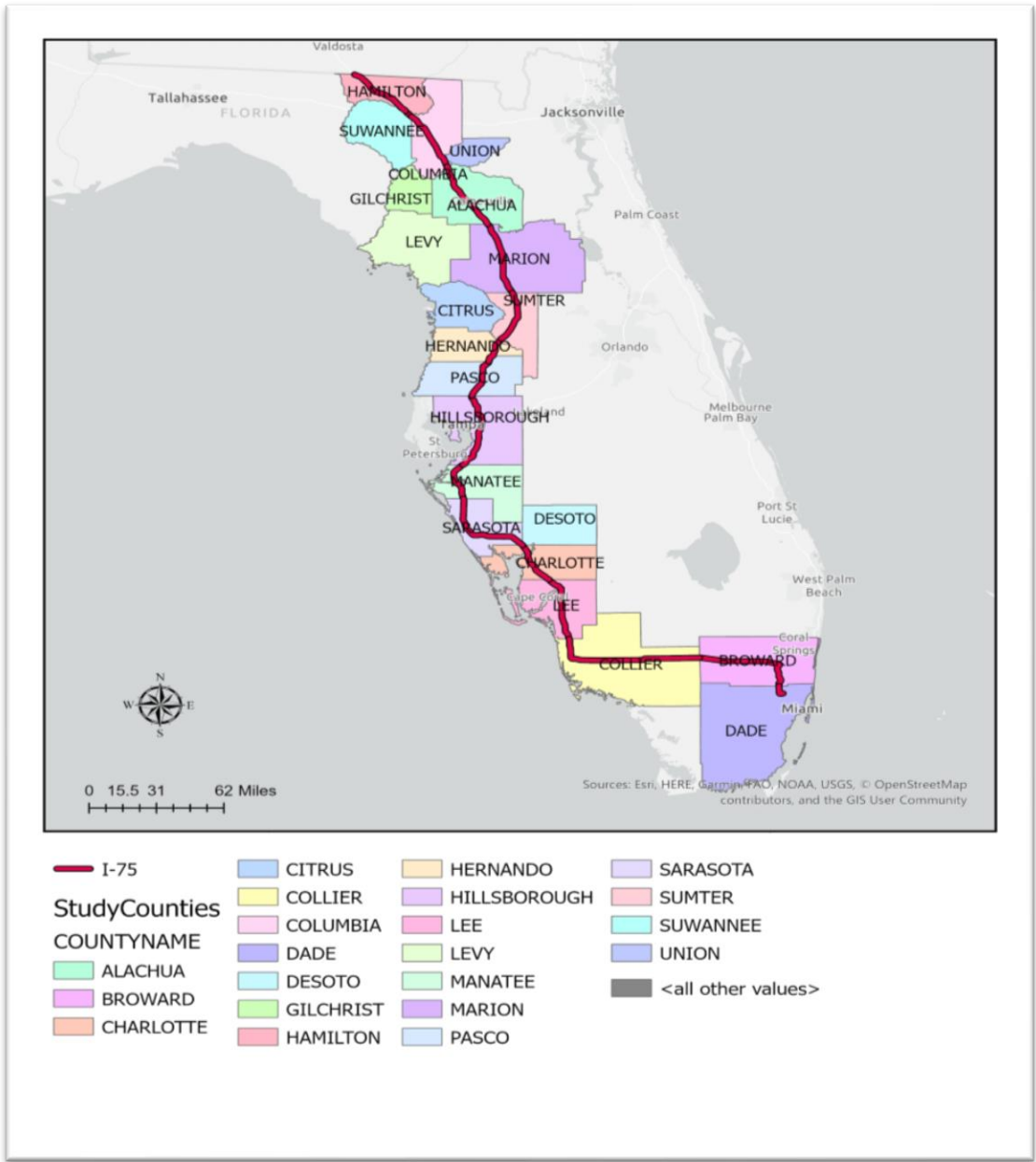
Figure 6: Study Area, Counties Along the I-75 Corridor

The study corridor under evaluation includes the 20 counties through the north, central, and southeast Florida. The subject counties are Alachua, Suwannee, Columbia, Union, Gilchrist, Levy, Marion, Sumter, Citrus, Hernando, Pasco, Hillsborough, Manatee, Sarasota, Desoto,

Charlotte, Lee, Collier, Broward, and Miami-Dade counties. Figure 7 presents a comparison of

the population by Florida county.
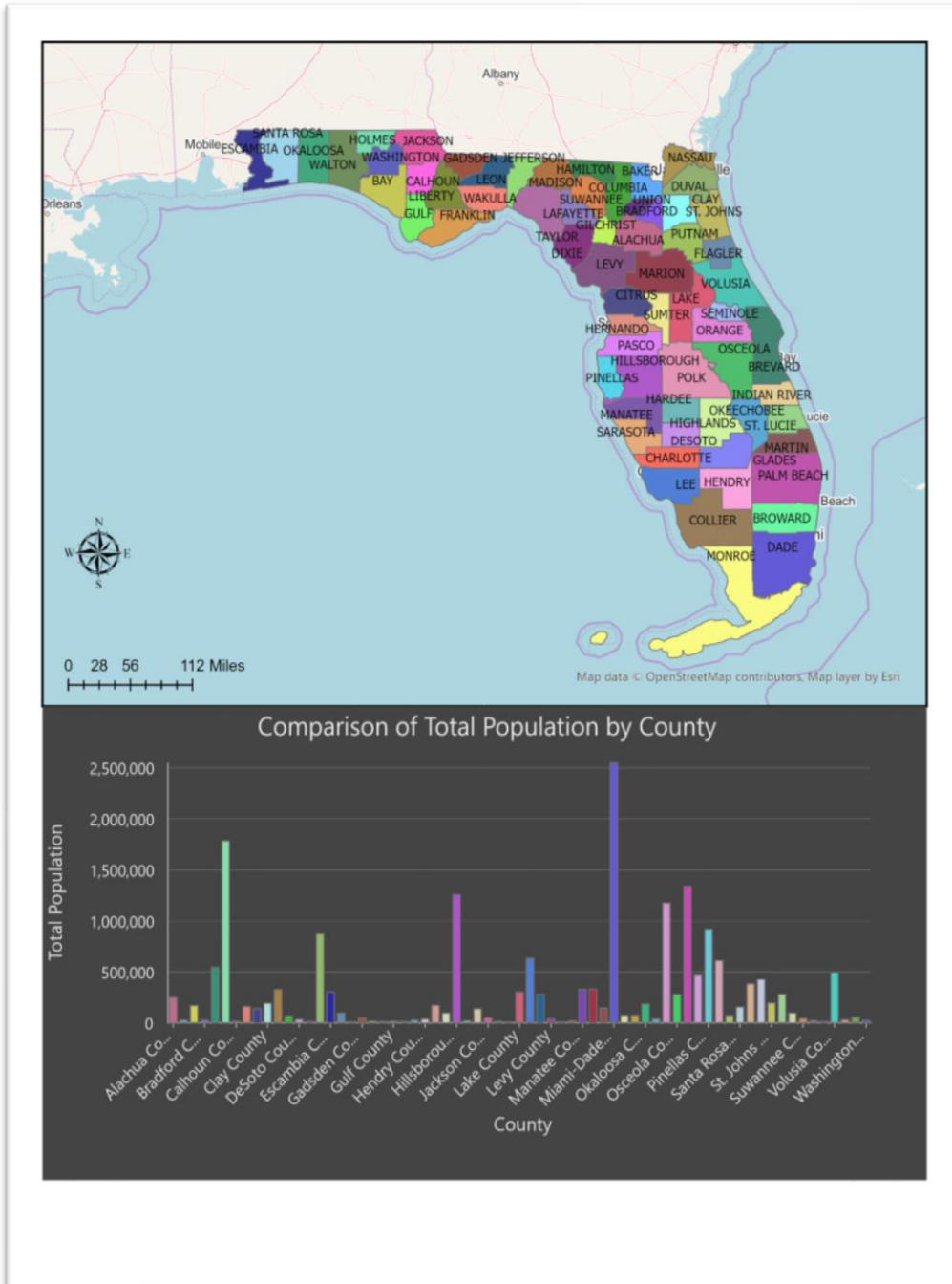
Figure 7: Florida Counties and Total Population per County

3.3　Data Preparation

Data were collected for each phase of this research. The following sections provide
details of the data collection and preparation processes. Four sets of data were used: crash data,
incident data, a street network and historical traffic dataset, and GIS data. A list of the sources of
these data is presented in Figure 8.
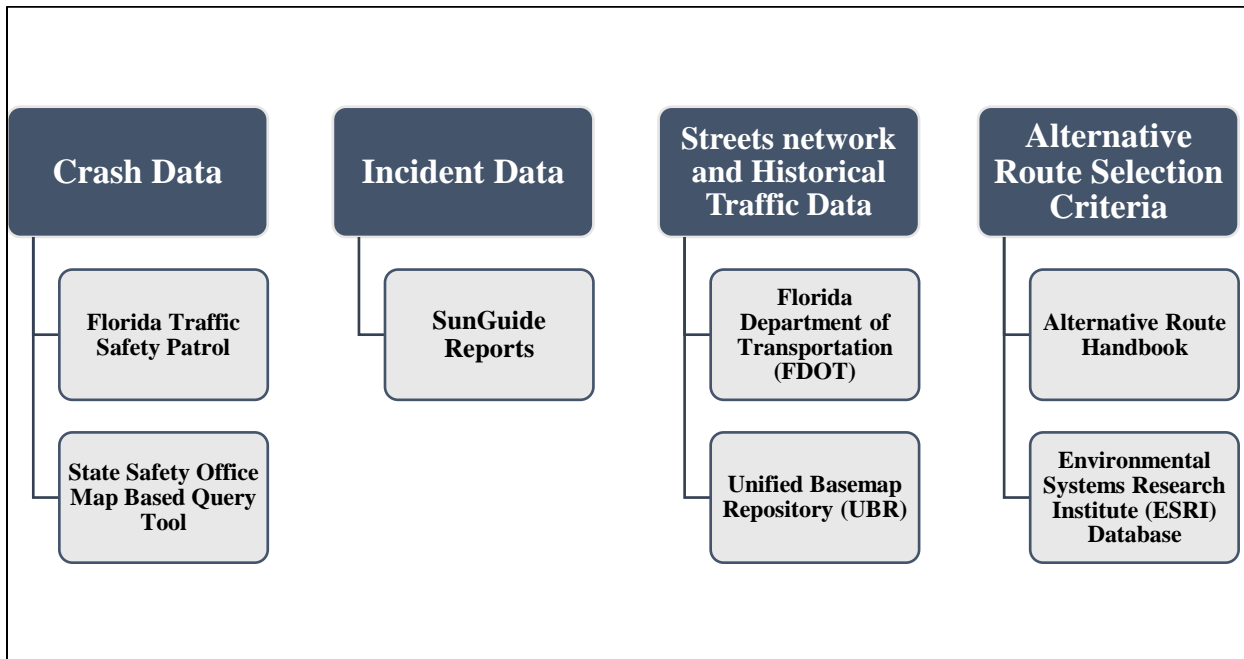
Figure 8: Flowchart of Data Categories and Related Sources

3.3.1　Crash Data

Crash data were collected from the State Safety Office Geographic Information System
(SSOGIS) using the Crash Query Tool web application, which contains descriptions and
information about crashes that occurred from 2012–2020 on Florida roads. SSOGIS is a crash
data system used to report, query, and analyze data from crashes on public roads. It enables users

to view crash details and road information in map and chart format and includes a web-based

map with a query function accessible from the state's Traffic Safety portal. For the current

research, it was necessary to identify crashes that occurred within the selected counties along the

I-75 corridor. The SSOGIS database allows users to specify such parameters when executing

queries.

Crashes were selected by location, filtered by crash characteristics, and then extracted in

the format of GIS shapefiles and their respective databases. Crash data collected include the

occurrence of injuries or fatalities, crash roadway ID, crash date, crash location mile-point, type

of crash, light conditions, road surface condition, time of the day, speed limit, and functional

classification of the roadway on which the crash occurred.

Crash data were collected for a period of four years from 2014 to 2017, for a total of

622,861 crash records. Data were filtered for the selected 20 counties, and a total of 307,774

crash records were used in this analysis. The GIS software used for analysis was ArcGIS Pro 2.5.

The FDOT provides an open data hub that contains GIS maps for the state that can be extracted

in shapefile or XML format. Several maps were obtained from the FDOT open data hub,

including a Florida counties layer that contains a map of Florida's 67 counties and an interstates

layer that maps the interstate system within the state. This layer's table of attribute also provides

the beginning and ending mile-point of the roadway and the roadway ID number. Figure 9

presents a comparison of crash counts by day of the week. Friday has the highest number of

crash records. Figure 10 presents a comparison of crash counts by county, showing that Miami-

Dade County has the highest number of crash records within the study area.
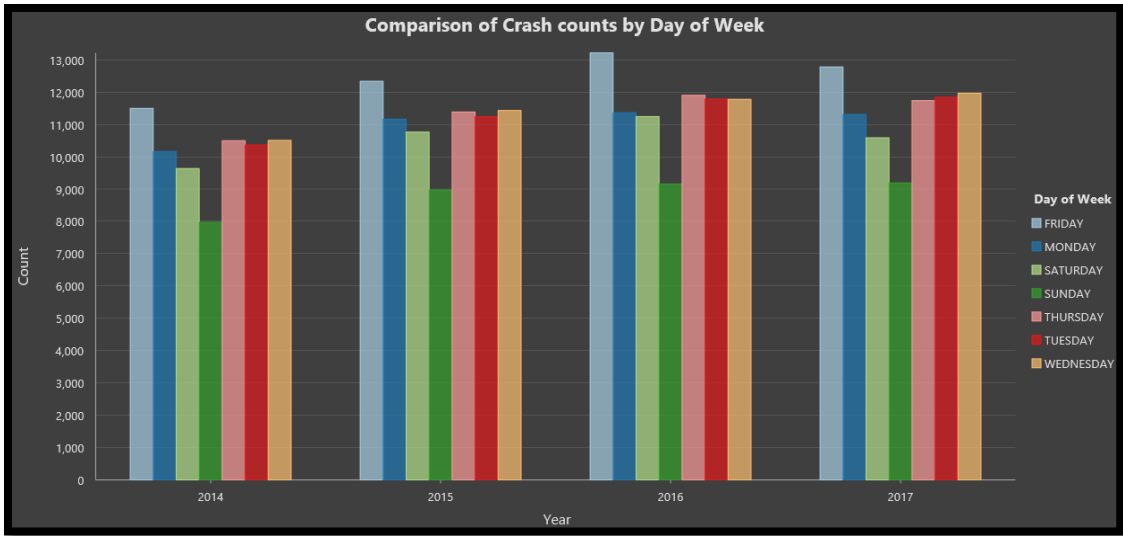
Figure 9: Crash Counts per Day of Week for the Years of 2014 to 2017
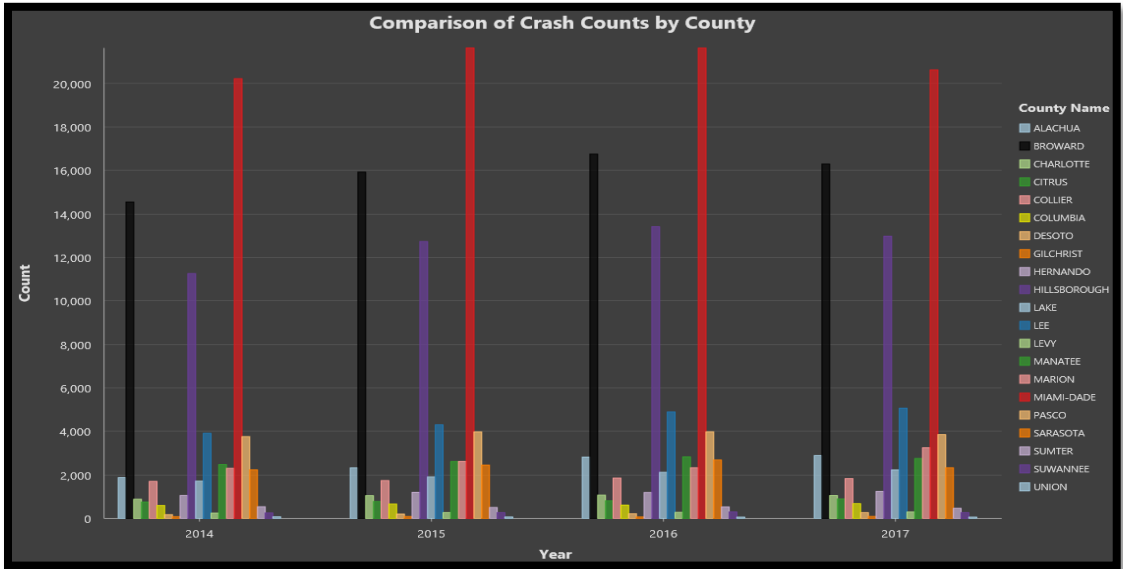
Figure 10: Crash Counts Comparison by County of the Study Area

3.3.2 Incident Data

Traffic incidents are a significant cause of nonrecurrent congestion. To gain a thorough understanding of the effects of an incident on the overall traffic, the incident timeline needs to be determined. Estimating incident duration is crucial for incident management. As a step to

accomplishing this task, previous studies investigated several techniques and models to predict incident clearance time. In general, these models can be classified as probabilistic distribution analysis, linear regression analysis, conditional probability analysis, time-sequential models, and decision tree methods. Based on previous research, Valenti et al. (Valenti, Lelli, & Cucina, 2010) argued that there is no approach considered to be the best approach in all circumstances.

First, it is imperative to define the terminologies of the incident timeline. When an incident occurs, it consists of several phases: namely, the incident detection, verification, response, clearance, and recovery phases. The incident detection phase represents the interval between the incident occurrence and its detection by Traffic management Center (TMC), and the incident verification phase is the amount of time required to confirm incident occurrence. The incident response phase represents the period from incident detection to the arrival of the first responder on the incident scene. The incident clearance phase is the time between the arrival of the first responder and incident clearance. Finally, the recovery phase is the time required for the dissipation of the traffic queue that is formed due to the incident and the return to typical traffic conditions after the scene is cleared.

As indicated in the Florida Statewide Operations Performance Measures and Data Collection report, the FDOT roadway clearance period is described as the period between the first recognition of the incident and the time all major roadways are cleared. The incident duration timeline contains notification, verification, and response times, as well as the open road clearance period. Open roads clearance time is defined as the time period that begins when the first responder arrives at the incident site and ends when all main travel lanes are cleared. Figure 11 depicts the FDOT incident duration timeline that was adopted in this research.
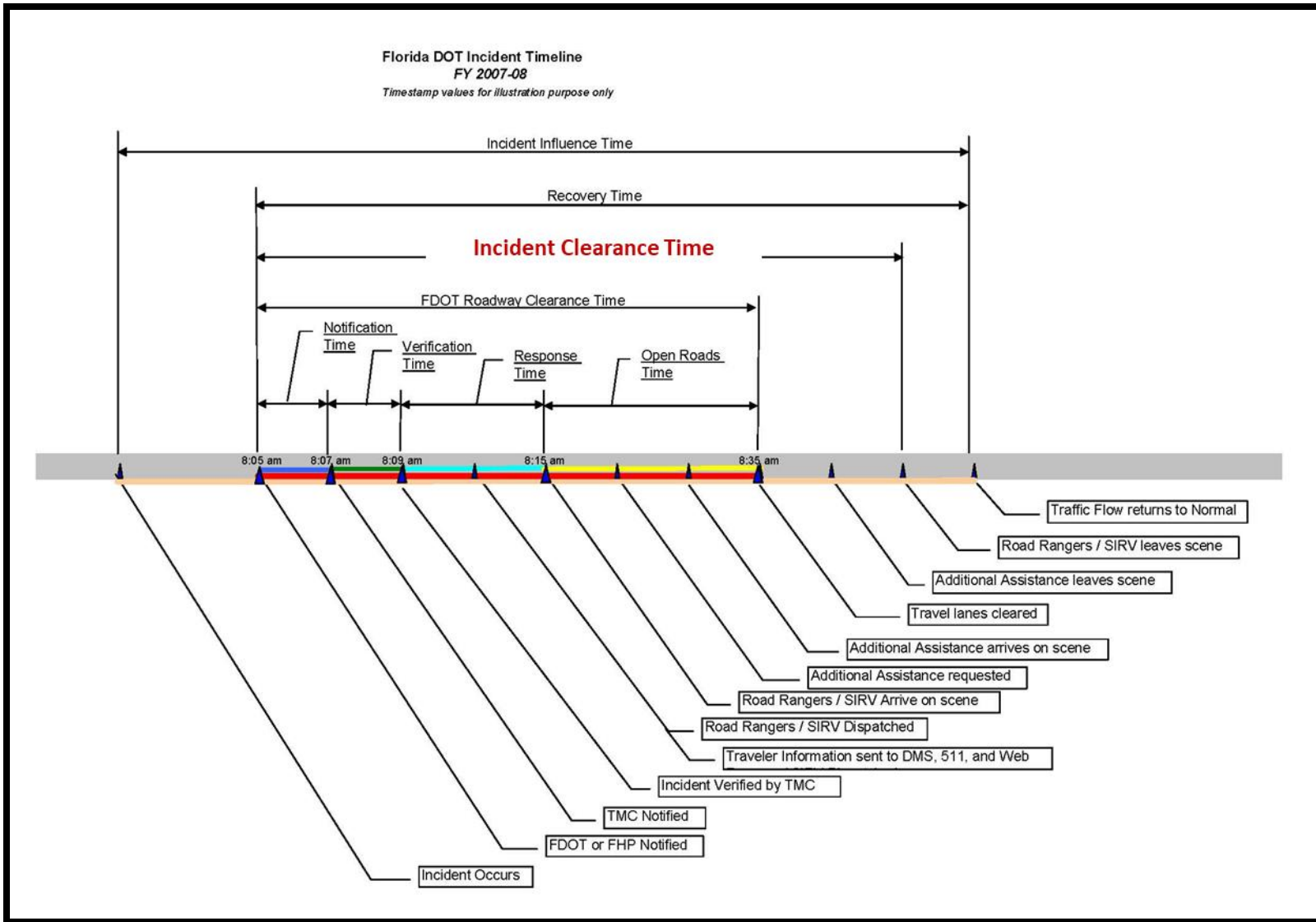
Figure 11: Florida Department of Transportation Incident Timeline

Traffic incident data used in this research were obtained from the SunGuide database. SunGuide is a suite of ITS software that has been developed and deployed by the FDOT to integrate hardware, software, and network applications for Florida roadways and exchange data among agencies. FDOT started with software that had been developed by the states of Texas and Maryland and customized it for the state of Florida into the SunGuide system.

The incident data used in this research were collected from July 1, 2018, to June 30, 2019, for the I-75 corridor. The SunGuide database recorded a total of 3,550 incidents that occurred during this period. The records comprise critical incident information such as incident description and spatial and temporal characteristics. The recorded data includes all types of incidents, such as crashes, roadway debris, disabled vehicles, and fire vehicle involvement. Detailed descriptions of incident data categories follow.

- **Incident Description:** This consists of general features of an incident, including incident type, number of blocked lanes due to the incident, and incident severity.

- **Spatial Characteristics:** The location of the incident is documented by recording the travel route as well as incident point longitude and latitude.

- **Temporal Characteristics:** The incident timeline is recorded, starting with notification time, verification time, and dispatching and response times. Additionally, the roadway clearance time is recorded. Notification time is the time at which the TMC was notified. Dispatching and response time indicate the time for the first responder to arrive at the incident scene. Finally, the clearance time records the time when all lanes of the roadway are clear, and the last responder has left the site.

- **Operational Characteristics:** These fields include information about the notifier agency name and ID.

Additional roadway and traffic characteristics, including the number of lanes, lane width, surface width, toll road status, AADT, truck traffic percentage, median width, median type, speed limits, and functional classification, were collected from FDOT and spatially joined into one table with the incident data. The capacity reduction factor due to traffic incidents was estimated as a function of the total number of lanes and the number of blocked lanes based on the Strategic Highway Research Program table derived from the highway performance monitoring system database maintained by the FHWA.

A detailed description of each incident dataset field is presented in Table 3.

Table 3: Description of Incident Data Fields

Data Field Name	Description
EVENTID	A unique identifier for each incident record
EVENTTYPE	Type of incident (Crash, Disabled vehicle, Debris in the road, Fire vehicle, Wildlife, Police activity, Emergency vehicles, or other)
EVENT_LATITUDE	Latitude of incident location
EVENT_LONGITUDE	Longitude of incident location
SEVERITY	Injury severity level ranging from 1 to 3
WRS_BLOCKAGE_DESC	A description of road blockage caused by the incident, including number of lanes blocked, shoulder closure, and exit/entry ramp closure
FIRSTNOTIFICATION	Time and date on which incident was reported to FDOT or Florida Highway Patrol (FHP)
TMCNOTIFIED	Time and date on which incident was reported to TMC
VERIFICATION	Time and date on which incident was confirmed and verified
FIRSTRESPONDERARRIVAL_DT4	Time of the first responder arrival at the incident site
ROADWAY CLEARANCE	FDOT roadway clearance time is the duration between the first notification time and the time when travel lanes were cleared
LAST_DPV_DEPART_CLSD_DATE	Additional assistance leaves the incident scene
FIRSTRESPONDERDISPATCH	Traveler information sent and Road Rangers dispatched
LASTRESPONDERDEPARTURE	Last Road Ranger/Severe Incident Response Vehicle (SIRV) leaves the incident scene
COUNTY	Name of county in which incident occurred
SHORT_NAME	Name of route on which incident occurred
SYS_LOCATION_DESC	A detailed description of the incident site location
NOTIFIER_AGENCY_ID	The ID of the agency that was first notified of the incident
NOTIFIER_AGENCY_NAME	The name of the agency that was first notified of the incident

The study area for this research consists of 20 counties along the I-75 corridor. Figure 12 displays incident counts by year for these 20 counties. During 2019, Hillsborough County had the highest crash count.
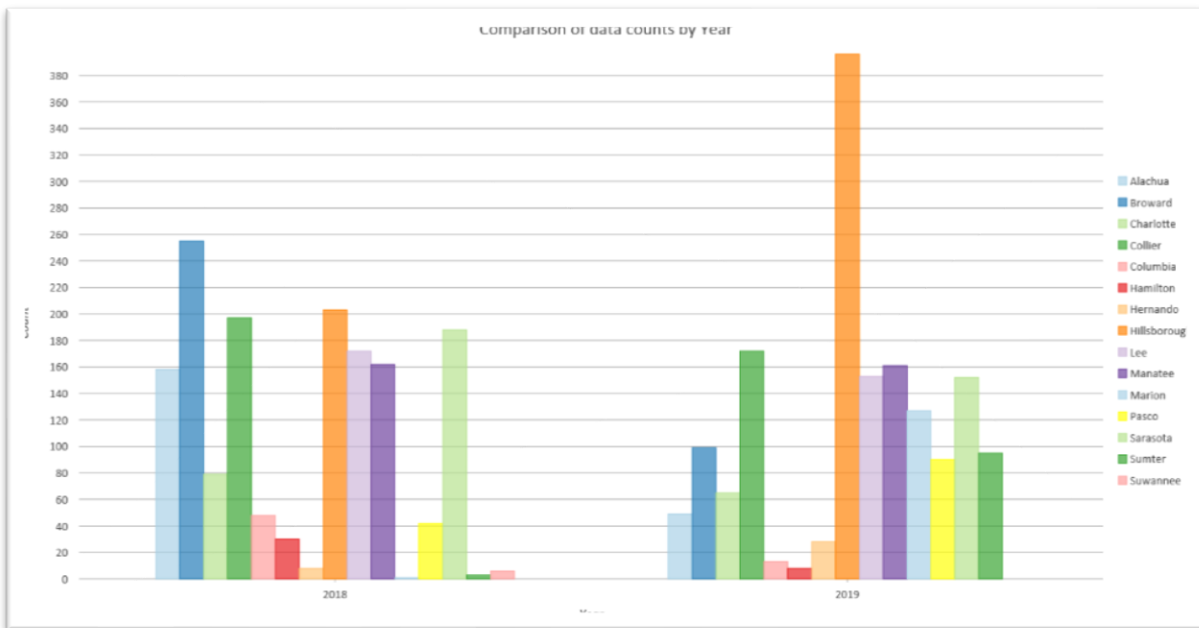
Figure 12: Incident Data Counts Comparison by Year

3.3.3   Network Dataset and Historical Traffic Data

For the third phase of this research, a network analysis was performed. The objective of this phase was to develop an alternative route selection model to determine the route most suitable for truck traffic. Data for this analysis were collected from various sources. First, street and traffic data were collected and processed to build a dynamic routable network dataset that stored road edges and junctions and their attributes for all segments of the road network. Second,

historical traffic profiles were incorporated into road edges. This allowed time-dependent

variables to be assigned to road edges and junctions to reflect actual traffic conditions throughout

the day. Finally, truck alternative route selection criteria were defined to evaluate the network in

terms of suitability for trucks. Figure 13 depicts the network dataset components.
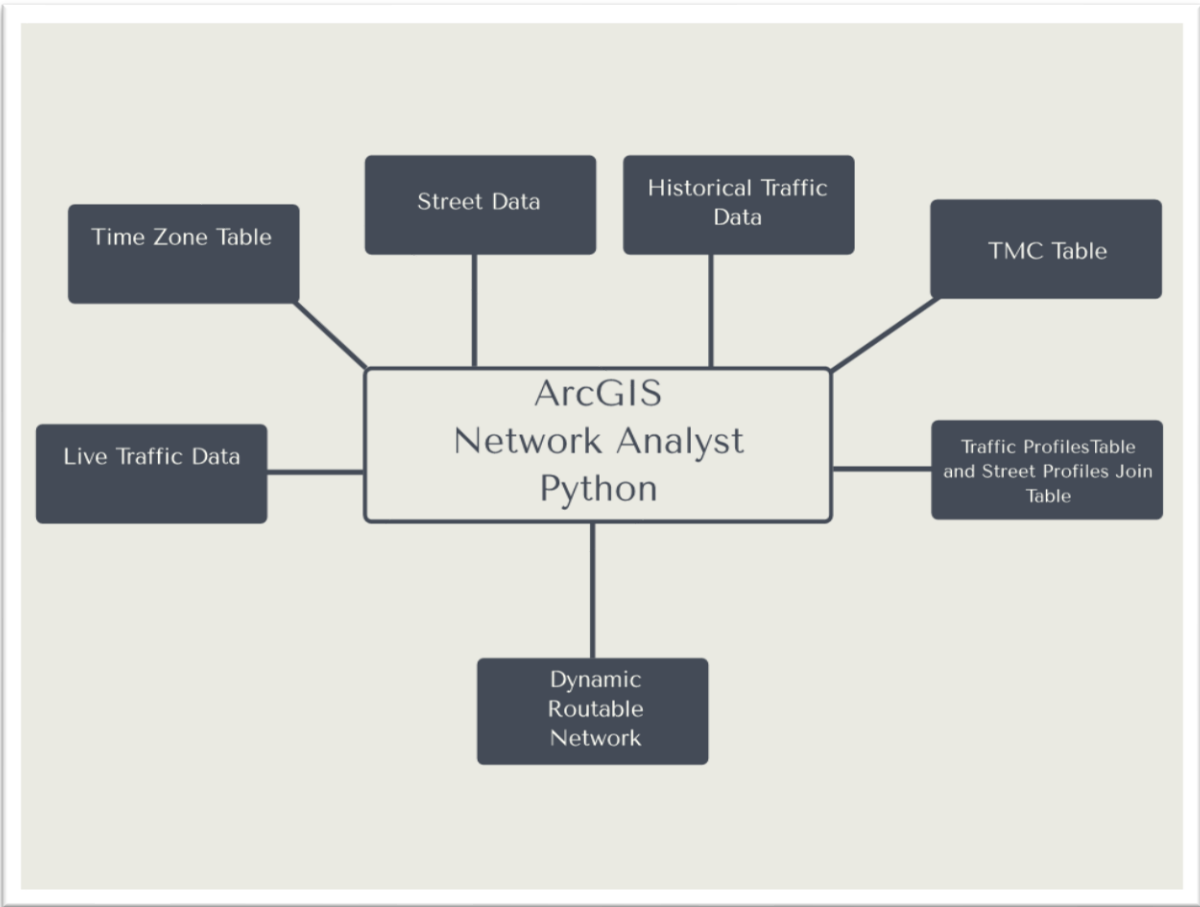
Figure 13: Required Data for Network Analysis

The ArcGIS Network Analyst extension was utilized to design, create, and build a

transportation network dataset. The network dataset is a series of synchronized network

components, including the edges, junctions, and turns of the road network model. Network

databases are well suited for the simulation of transportation networks. They are designed based

on a source feature class, which may include features such as lines, points, one-way restrictions,

and turns.

For this research, a file geodatabase network was created. Streets and turn feature classes

were created in one feature dataset and stored in this file geodatabase. Figure 14 presents the

workflow used to build the network dataset.
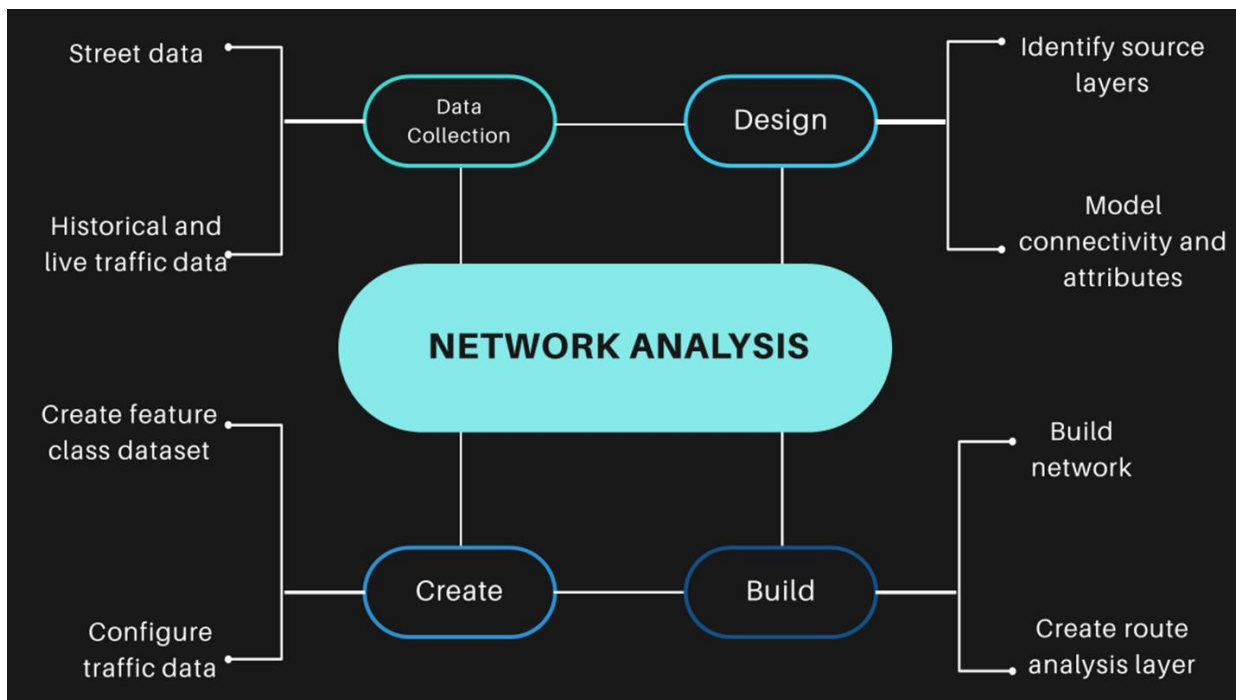
Figure 14: Workflow to Build Network Dataset

This section describes the data sources and explains how the data were collected and

prepared to build a routable network incorporating traffic data. Most of the geographic datasets

used in this analysis were collected from the FDOT's Unified Basemap Repository (UBR)

database. The UBR provides quarterly street and traffic datasets from the network provider

NAVSTREET's street data by HERE Technologies. Additionally, the UBR database contains

data suitable for routing applications with a complete navigable road network. Data were

extracted in the format of a file geodatabase for the GIS platform. The Z-level layer was used to

create roadway connectivity. The quality of the collected data was evaluated, and data were

preprocessed for integration into the Network Analyst extension. The related dataset descriptions

and sources are listed in Table 4.

Table 4: Network Dataset Description and Sources

Data Description		Data Source
Streets Dataset	Street database including street shapefile, one-way restriction, U-turn, prohibited street, toll road, hierarchy, and shape-length	FDOT, Unified Base Repository, HERE
Traffic Dataset	Historical traffic data and live traffic data	FDOT, Unified Base Repository, HERE
School Zones	Private and public school information including school address, zip code, and county	Florida Geographic Data Library
Hospital Locations	Hospital facility information, address, zip code, and county	Florida Geographic Data Library
National Bridge Inventory	Data on more than 600,000 bridges in the US; includes information about design load, vertical clearance, and efficiency ranks	Bureau of Transportation Statistics
Interstate Exits	The dataset contains roadway ID, exit number, county, and district	FDOT Transportation Data and Analytics Office GIS Data

To perform routing analysis, a file geodatabase network was created to support historical

and live traffic data. This research used the ArcGIS Network Analyst extension to incorporate

traffic data in the routing analysis. Properties of the network layer were set to include travel time and impedance attributes.

3.3.4 Criteria for Alternative Route Selection

When an incident occurs and causes road closures, state agencies consult guidelines for determining when to divert traffic to circumvent the congested facility. The Federal Highway Administration *Alternative Route Handbook* (2006) provides a comprehensive guideline on how to execute diversion strategies considering key factors, including incident duration, the number of lanes blocked, the observed traffic condition, and the capacity of the candidate alternative route. Table 5 presents the rerouting policies used by several state agencies.

Table 5: Rerouting Policies by State Agencies (Alternative Route Handbook, 2006)

AGENCY	CRITERIA
North Carolina	• Complete closure of the highway in either direction is anticipated to last 15 minutes or longer.
New Jersey	• Complete closure of highway is anticipated to last more than 90 minutes.
Oregon	• Incident with two or more lanes blocked, or • Incident with one lane blocked and expected to last more than 20 minutes.
New York	• Implemented only when the highway is completely closed.
Florida	• Two or more lanes blocked for at least 2 hours.
ARTIMIS (Ohio/Kentucky)	• Deployed during peak hours when more than two lanes are closed for at least 30 minutes.
Idaho	• An incident taking over 2 hours from detection to anticipated fully restored traffic flow.
Wisconsin	• Incident causes delays that will exceed 30 minutes.

Truck diversion strategies should be based on a collection of specifications to determine the effect of the rerouted traffic. In this research, alternative selection criteria were defined based on four key considerations:

1. Roadway characteristics.

2. Heavy vehicle restrictions.

3. Traffic conditions.

4. Neighborhood impacts.

Data collection was required for each selection criterion. In this study, alternative route selection criteria were defined based on the Federal Highway Administration (FHWA) handbook. These criteria can be defined as truck restrictions used for assessing alternative route candidates. They serve as measures of how effectively a route is being utilized for diversion. Data for selection criteria were collected as variable indicators, processed to create input layers for network analysis, and finally applied to evaluate potential alternative routes to select the optimal route for truck traffic. Generally, the alternative route is the shortest route, but some increase in distance can be allowed to avoid specific road characteristics that are not suitable for trucks. Multiple sets of data were collected for each selection criterion. Data were separated into several feature classes and projected into the same coordinate system for the analysis. Figure 15 presents the selection criteria that were considered in this research.
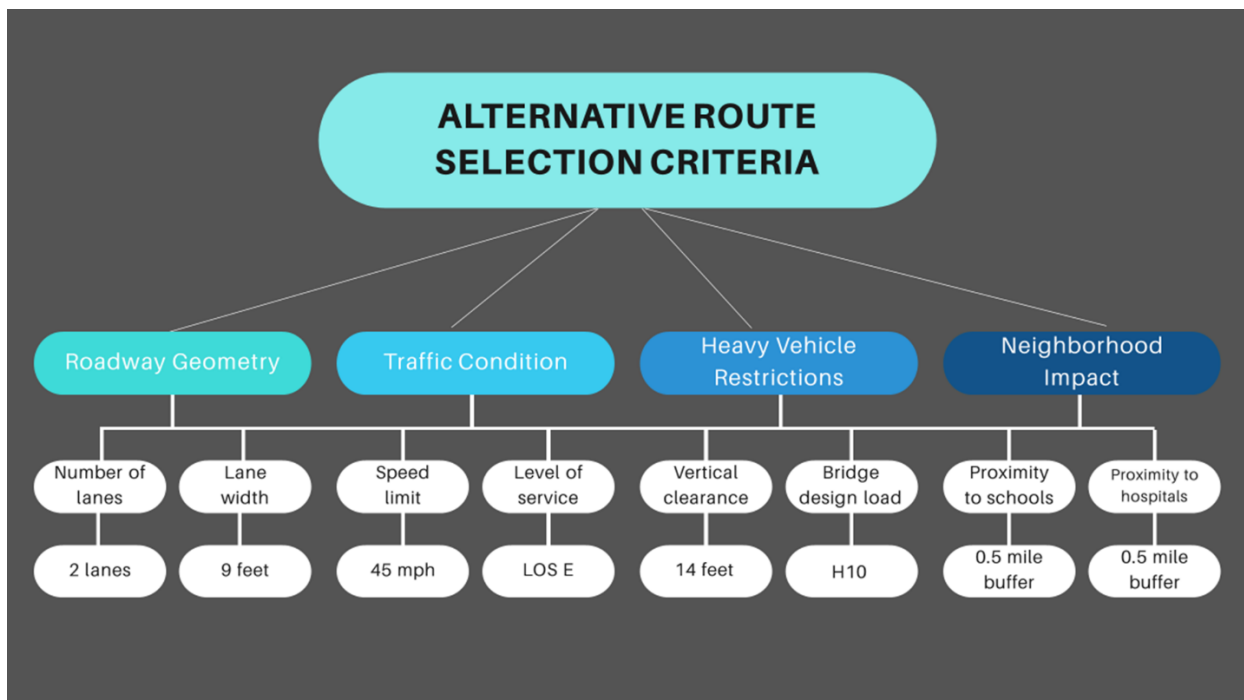
Figure 15: Study Alternative Route Selection Criteria

3.3.4.1 Height and Weight Restrictions

From the National Bridge Inventory database of 600,000 bridges, Florida bridges with low clearance, restriction design loads, and poor performance were selected.

3.3.4.2 Pavement Conditions

It is essential to ensure that the appropriate pavement conditions are available on the selected alternative route. Poor pavement conditions can be hazardous for heavy vehicles, which can cause safety issues. If the pavement condition on the alternative route is already poor, the redirected truck traffic can cause further damage.

3.3.4.3 Geometry and Road Characteristics

It is essential to investigate roadway characteristics and geometry to select an alternative route that can accommodate truck restrictions. Vertical clearance, turn restrictions, and steep roadway grades should be evaluated prior to the diversion operation.

3.3.4.4 Existence of Schools and Hospitals

Roadways near schools and hospitals should be avoided to ensure these facilities remain accessible for public service. The locations of Florida schools and hospitals were collected from the Environmental System Research Institute (ESRI) database for the study area. A new layer was created with this information and incorporated into the network model as a scaled factor barrier. Additionally, parks and public recreational areas should be safely accessible to the public and should also be avoided.

3.3.4.5   The Intensity of Commercial Development

A potential alternative route that is near substantial commercial development should be avoided, as diverted traffic increases traffic demand and therefore affects roadway capacity.

3.3.4.6   Level of Service

When traffic is diverted from the main roadway to an alternative route, the alternative route then carries both its traffic and the rerouted traffic. Therefore, it is essential to evaluate the level of service of the potential alternative route before diverting traffic. In this research, alternative route selection criteria were predefined and implemented in the rerouting model as restoration or scaled costs.

3.3.4.7   Truck Weight and Size Restrictions Data

According to the FHWA's and Florida's weight and height restrictions on heavy vehicles, the maximum width for a truck is 102 inches, and the maximum height is 13 feet, 6 inches. Additionally, the maximum weight limit for a single axle is 22,000 lbs. And for a tandem axle is 34,000 lbs.

3.3.5   Data for Cost-Benefit-Analysis

This study developed diversion decision-support tools to assist transportation personal in making the best diversion decisions. The developed model quantified the resulting benefits by comparing diversion scenarios to scenarios without diversion. This section presents the

procedure followed to collect the data needed to estimate the benefits of traffic diversion during nonrecurrent congestion.

This study used the total travel time along the alternative route, taken from the output of the developed model, to compute the reduction in delay due to the diversion. Moreover, as reducing delays can also decrease fuel consumption, both delay reduction and fuel consumption savings were converted to monetary values using conversion factors obtained from the U.S. Census Bureau.

3.4 Summary

This chapter described the collection and preprocessing of datasets and the identification of alternative route selection criteria used in this research. It also provided details on the various data sources considered and on the study area selected. The primary analysis approaches used for each stage of this study are described in the following chapter.

CHAPTER 4: METHODOLOGY

4.1 <u>Introduction</u>

All data of interest collected and prepared for this study were utilized to develop a framework for evaluating truck diversion strategies. The following sections present the approaches used to achieve the objectives for each stage of the study. This chapter starts with a crash hotspot analysis of the collected data, including a descriptive analysis of the distribution of crashes records over the study area. The statistical regression approach used to assess the impacts of various explanatory variables on incident clearance duration is then described, as is the methodology of the incident clearance prediction model. Finally, the process of the design of the network dataset is presented.

4.2 <u>Crash Hotspot Analysis</u>

It is essential to understand, interpret, and forecast the trends in road safety and then implement appropriate countermeasures to prevent crashes and reduce injury severity. For this purpose, traffic safety indicators, such as fatality risk, the number of crashes with injuries, and the numbers of victims, are regularly collected to monitor the safety trends of specific sites (Bergel-Hayat et al., 2013). Because of the complexity of identifying the causes of crashes, the role of the crash location, recognizing high-crash and low-crash road segments is a challenging problem.

In this section, the first phase of the research methodology is presented. The main objective of this phase was to understand crash patterns and to examine the distribution of crashes utilizing hotspot and spatial statistics analysis. This section presents the methodology

used to conduct a spatiotemporal analysis utilizing a space-time cube, spatial autocorrelation, and emerging hotspot analysis to identify high-crash-rate locations in the study area. Twenty counties in Florida along the I-75 corridor were selected as a case study. The crash analysis was performed utilizing ArcGIS Pro 2.5. Crash data for the years 2014–2017 were investigated to identify statistically significant crash trends over space and time. The structure of the first phase of this research is diagrammed in Figure 16.

First, road segment data were collected and clipped to the study area. Crash data were obtained from the SSOGIS Crash Query Tool web application for the years 2014–2017. Crash data included location, date, and time. Subsequently, crash data points were aggregated using the space-time cube tool. Spatial autocorrelation analysis was then performed to investigate spatial hotspot trends. Finally, emerging hotspot analysis was utilized to classify the hotspots and analyze their spatiotemporal patterns.
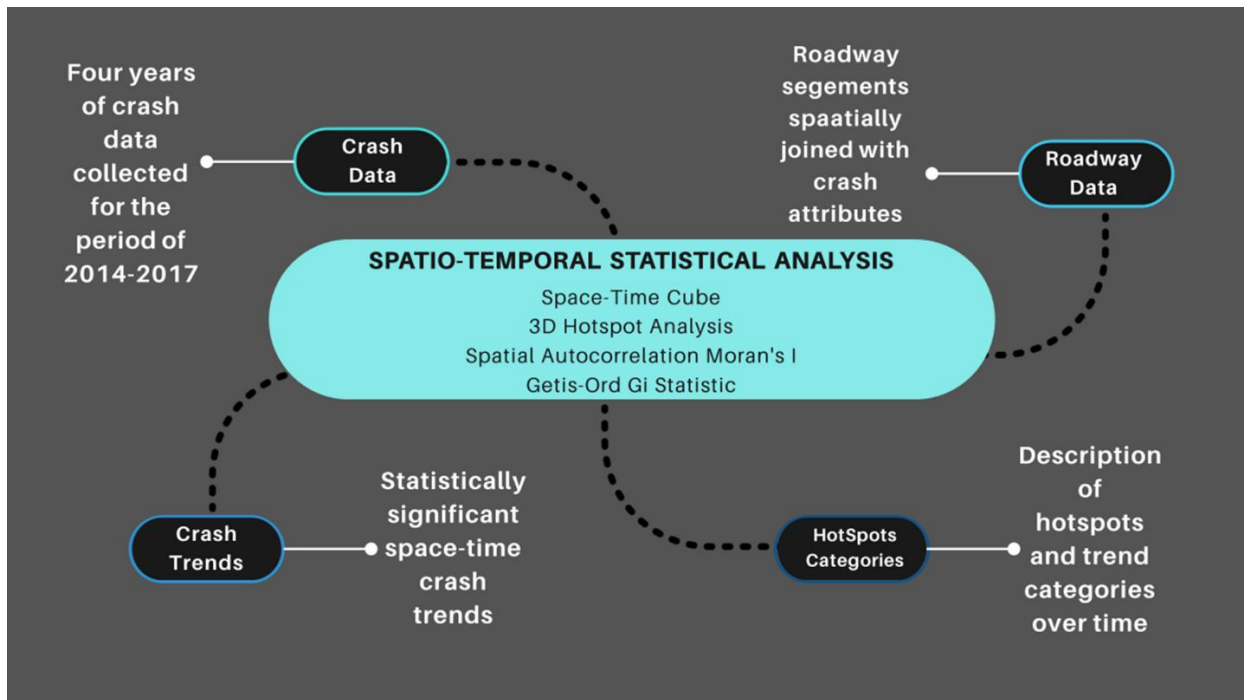
Figure 16: Flowchart of Hotspot Analysis

The aim of the spatiotemporal crash analysis was to analyze the characteristics of crashes and classify hotspot trends over time to identify the location with the highest rate of crashes. Descriptive analysis was performed to investigate the distribution of crash frequencies over the study area. Graphs of these distributions and summaries of observations from these figures are provided in the following sections. Crash data were plotted into ArcMap by using the longitude and latitude of each crash data point. The distribution of four years of crashes over the study area is illustrated in Figure 17.

Crash distribution over study area for year of 2014 to 2017
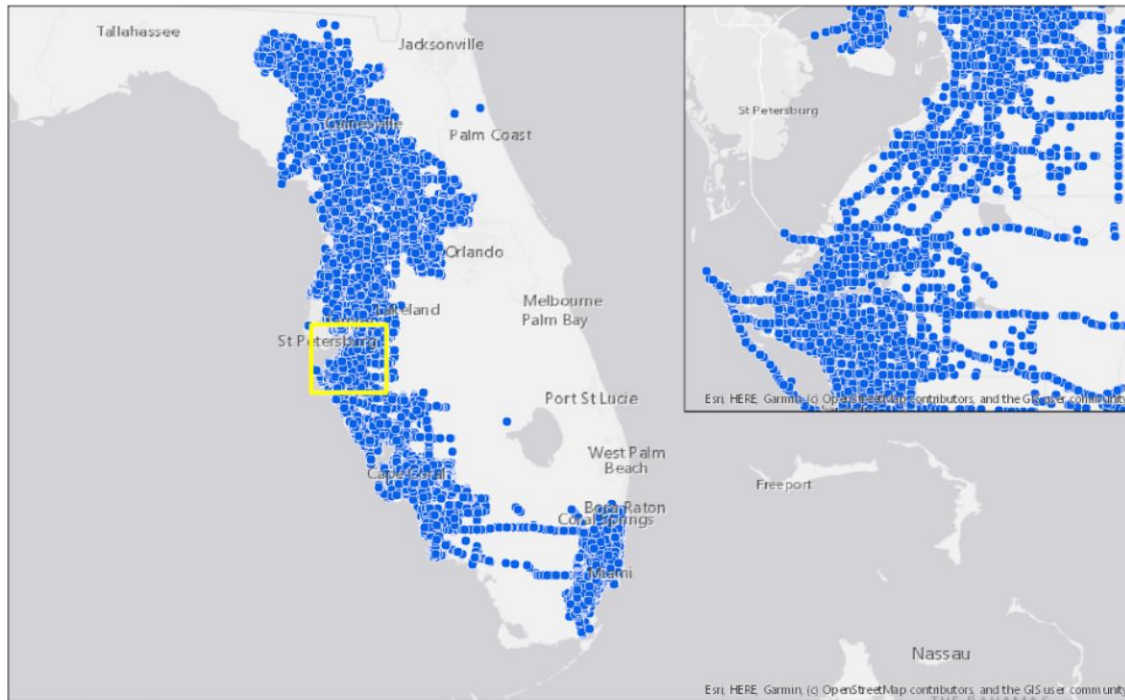
A total of 307,774 crash points for a period of four years, (2014-2017) at the 20 counties along Interstate 75.

Figure 17: Crash Data Distribution Over the Study Area

To investigate the temporal distribution of the crash data, the crash counts were plotted by month for the years 2014 to 2017. Figure 18 presents a monthly crash time clock over the study period.
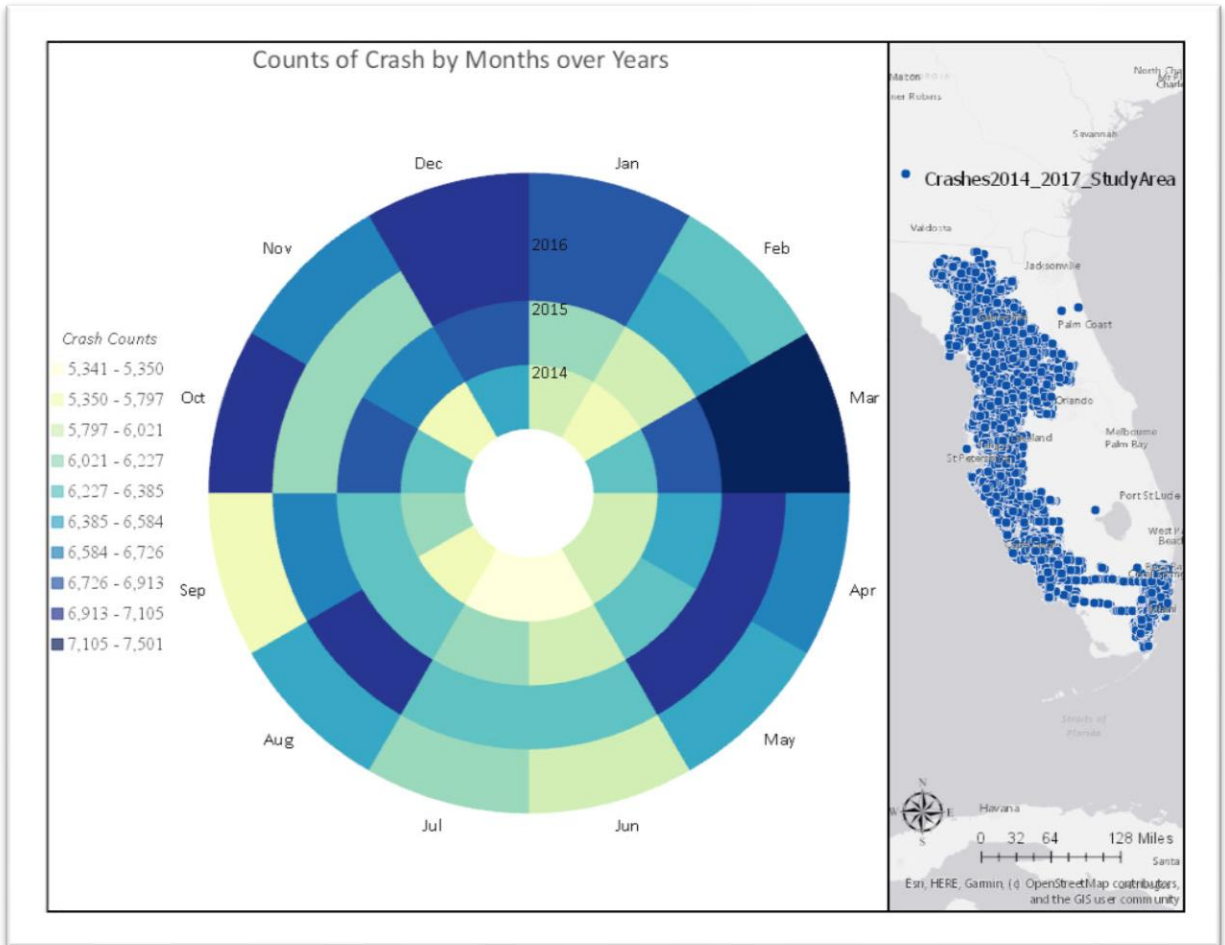
Figure 18: Crash Data by Month for the Years of 2014 to 2017

Figure 19 presents the crash count distribution by year, showing that 2016 had the highest number of crashes.
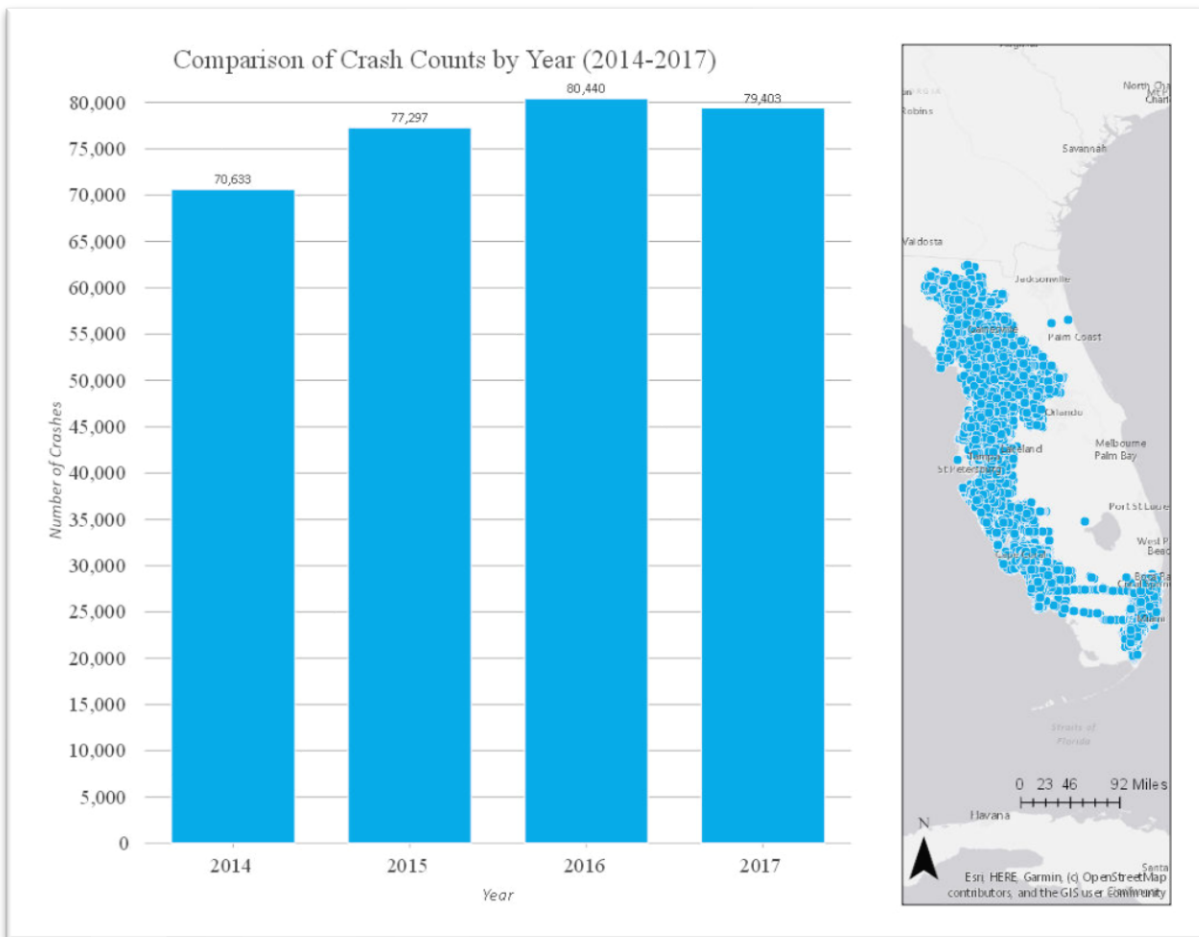
Figure 19: Crash Counts Distribution of the Study Area

4.3   Space-time Cube Analysis

A space-time cube model was utilized on the ArcGIS platform to analyze the temporal characteristics of the crash points along with roadway segments. A space-time cube is a tool that

provides 3D visualization of crash data in spatial and temporal dimensions. The Space-time cube

tool aggregates data points into space-time bins. The timestep interval defines the time period for

each bin. In space-time cube analysis, time is denoted along the z-axis, and the spatial locations

of the crash records are represented using the x-axis and y-axis. Figure 20 depicts the structure

of the space-time cube analysis. A timestep of one month was defined; thus, the z-axis included

48-time steps that represented the 48 months of the study period. In the crash dataset, a field with

type "date" was created in the attribute table. This field was populated based on crash occurrence

date and time and aggregated the data points into 1-month bins by time.
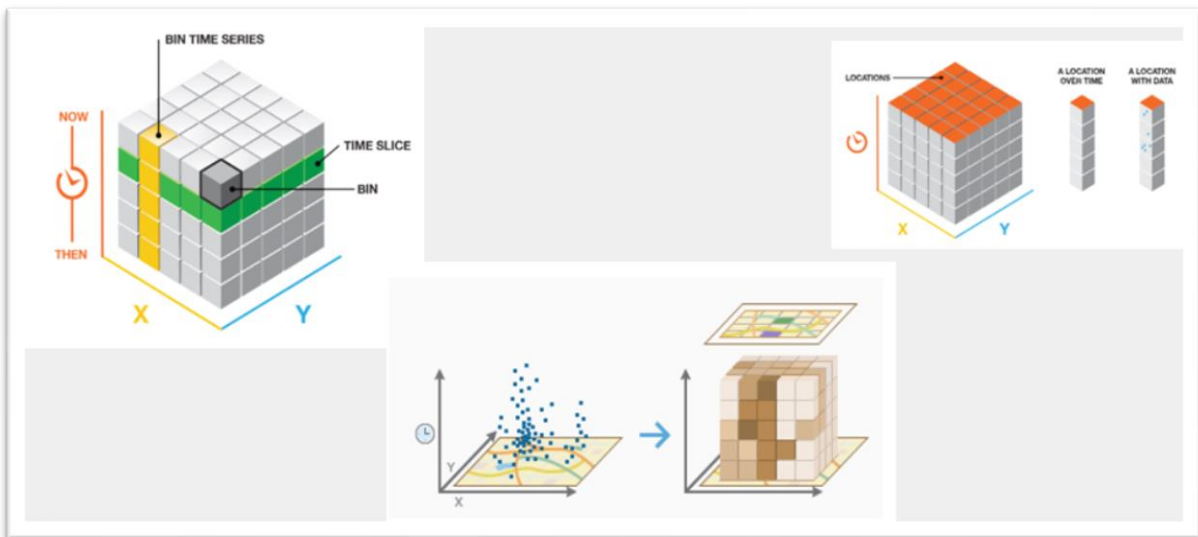
Figure 20: Space-Time Cube Structure (ArcGIS tool reference)

4.4   Global Spatial Autocorrelation Analysis

The previous section described the space-time cube analysis. To further explore the

spatial aggregation characteristics and to identify statistically significant crash locations,

autocorrelation analyses were also conducted. Generally, spatial autocorrelation analysis can be classified as global spatial autocorrelation or local spatial autocorrelation.

The space-time cube analysis identified the spatiotemporal aspects of crash location but did not explore the spatial aggregation characteristics of the statistical significance of the crash distribution. To determine statistically significantly high spatial autocorrelation locations, a spatial autocorrelation analysis was conducted on crash data for the years 2014–2017 in the selected counties using Moran's index (Moran's I). First, the crash attributes were spatially joined with road segments based on their longitude and latitude. Second, a road network was built using the joined crash–road segment attribute. Finally, a spatial weights matrix for the network arcs was generated, and a global Moran's I was computed.

4.5 Emerging Hotspot Analysis

As explained in the previous section, autocorrelation analysis was conducted to identify crash hotspots. This section describes a detailed interpretation and classification of crash hotspots and the analysis of emerging hotspots. After crash data had been aggregated into space-time cube bins, the emerging hotspot analysis tool was used to statistically analyze each bin. Subsequently, crash trends were identified by the Getis-Ord Gi statistic. Hotspots were classified in 17 different categories to present a detailed explanation of hot and cold spots and their locations and changes over time.

4.6 An Incident Clearance Prediction Model

 Incident data were collected for this study to predict the incident clearance time and to identify which variables have the most significant impact on incident duration. The following

sections present the statistical methodology that was used to achieve the objectives for this stage. Incident data for the period 2018–2019 were used for model development. During this time period, 3,550 incidents were managed by the TMC, and incident-related information was recorded in the SunGuide database.

Events with their associated fields in the data log were exported to a spreadsheet to allow further analysis. Multiple regression analysis was used to predict incident clearance duration. Prior to the analysis, a data cleansing process was performed that removed errors, false entries, duplicate records, and records with missing fields to ensure adequate data quality. Filtering and cleaning the incident data left 2,558 of the original 3,550 incidents to be included in the analysis. Descriptive statistics of the incident types are presented in Table 6.

Table 6: Descriptive of the Incident Data by Type

Incident Type	Total Number	Percentage of all incidents
Crash	1,564	38.9%
Disabled vehicle	496	19.4%
Debris on road	196	7.7%
Fire	130	5.1%
Police activity	0	0%
Emergency vehicle	122	4.8%

To predict incident clearance duration, a linear regression model was utilized to identify the significant exploratory factors that impact incident clearance duration.

A multiple linear regression statistical approach was used to predict incident clearance time. Based on normality tests, trials, and errors during model calibration efforts, explanatory variables were modified to assess the effect of each variable on the incident clearance time; all

categorical attributes were transformed into binary representations (i.e., 0 or 1). The Statistical

Package for Social Science (SPSS) software was utilized for model development.

A set of incident, traffic, and road characteristics were examined for possible inclusion as

independent variables in the developed prediction model. The following independent variables

were used:

- Temporal characteristics: weekday/weekend, AM (the periods from 6:00 AM to
  9:00 AM and 9:00 AM to 11:00 AM), midday (the periods from 11:00 AM to
  2:00 PM and 2:00 PM to 4:00 PM), evening (the period from 4:00 PM to 7: 00
  PM), and night (the period from 7:00 PM to 6:00 AM).

- Incident characteristics: incident type, incident location, number of blocked lanes,
  truck percentage, response time, severity. Incident types may have a significant
  impact on incident duration. Disabled vehicles, debris on the road, and crashes
  were considered in this research.

- Road characteristics: median type, median width, functional classification, and
  number of lanes.

- Traffic characteristics: AADT, maximum speed, capacity reduction, and truck
  percentage.

The frequency distribution of incident clearance times in the preprocessed dataset (2,558

incidents) is presented in Figure 21. As shown in the figure, most incidents had a clearance time

of less than 100 minutes. From the initial investigation of incident data, a histogram was plotted;

and as shown in Figure 21, the histogram is skewed to the right. Additionally, incident data

distribution has a mean value of 64 minutes and a standard deviation of 48 minutes.

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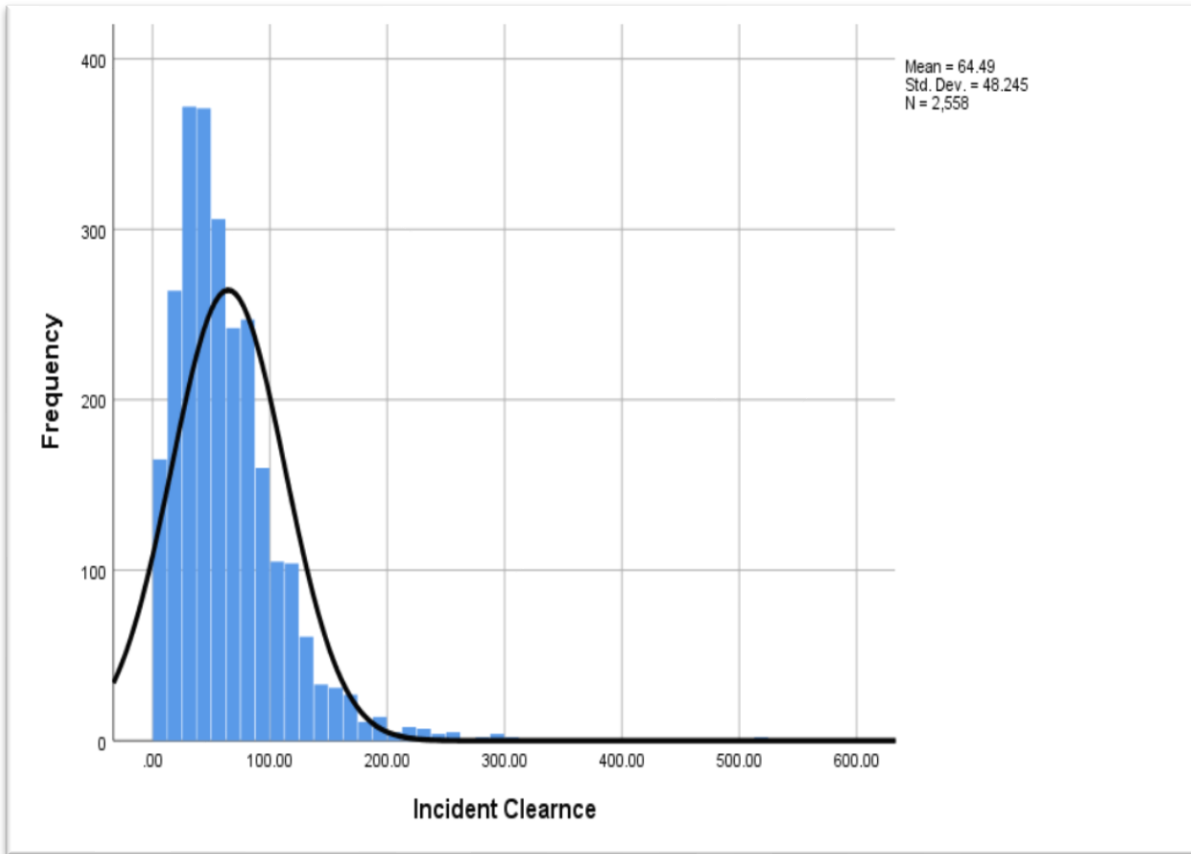
Figure 21: Incident Clearance Time Histogram

4.7   Network Building

This section presents the procedure used to design and create a dynamic network dataset and to develop an alternative route selection tool that can identify optimal routes that accommodate truck traffic. First, street and traffic data were collected and processed, and a dynamic routable network dataset was built to store road edges and junctions and their attributes for all segments of the road network. Second, historical traffic profiles were incorporated into road edges; this allowed time-dependent variables to be assigned to road edges and junctions to

reflect actual traffic conditions throughout the day. Finally, truck alternative route selection criteria were defined to evaluate the network in terms of suitability for tucks.

The network dataset is a roadway network segmented at intersecting roadways. These segments are called edges, and the intersection points are called junctions. The ArcGIS platform and its Network Analyst extension were utilized to design and build a network dataset that incorporates traffic data and facilitates navigation from one edge to another.

The first step in creating a network dataset was to create a file geodatabase to store and manage spatial and nonspatial data. Then, a line feature class and two historical traffic data tables were created and stored in the file geodatabase. The line feature class represents the road segments, while the two historical traffic tables were used to store the change in travel time throughout the day. These tables are a speed-profiles table used to store speed profiles and a street-profiles table used to store the relationships between streets and speed profiles. The times of day were grouped into 15-minute intervals. Each record in the traffic profiles table has a scale factor that is multiplied by free-flow speed for each time slice. Historical traffic data (with 15-minute time slices) and real-time data were incorporated in the network dataset. Time-dependent variables were assigned to road edges and junctions to reflect actual traffic conditions throughout the day. Figure 22 shows network dataset properties and the implemented traffic data elements.
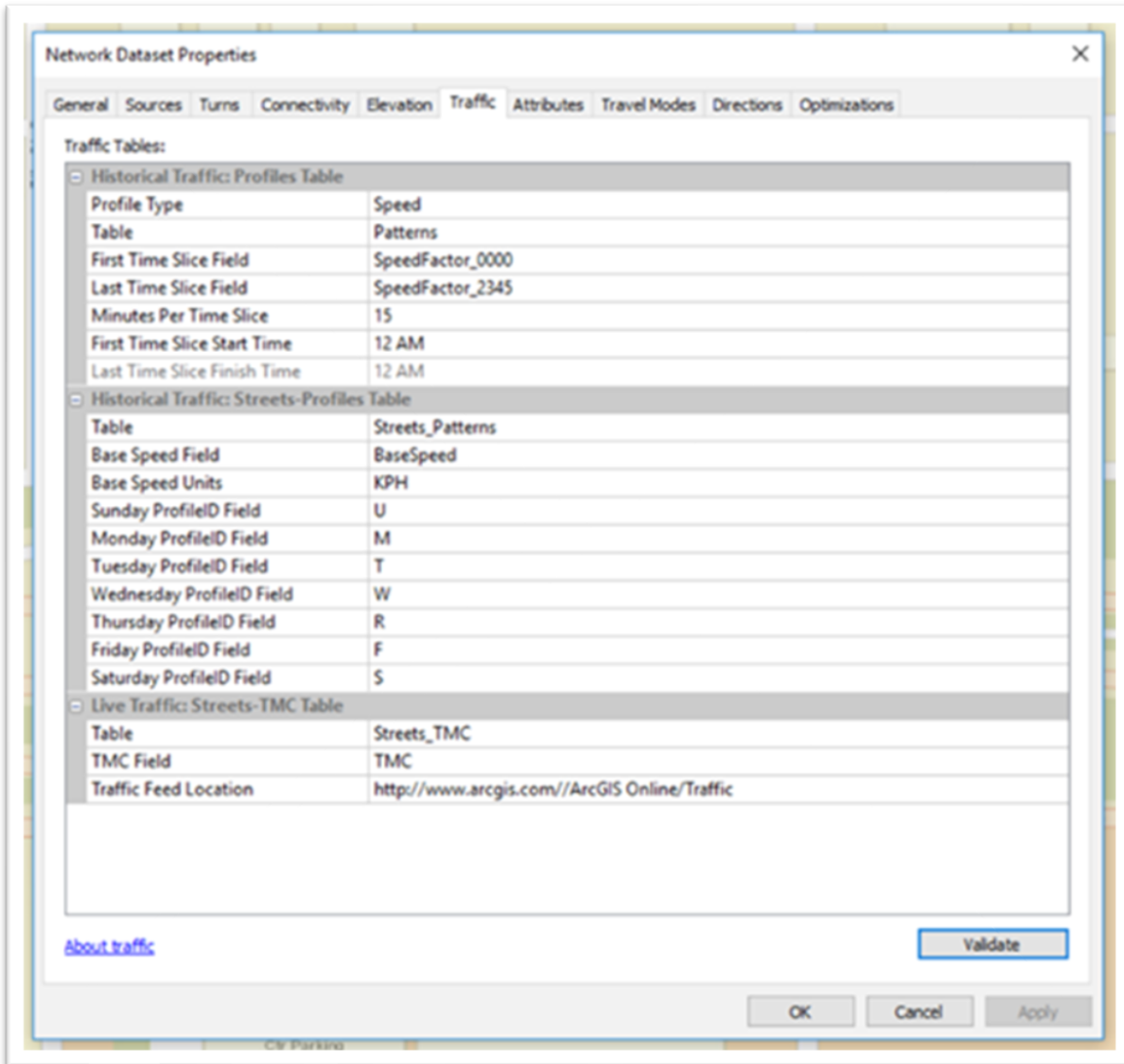
Figure 22: Network Dataset Properties

Finally, a network dataset was built to develop network elements and to assign values to the network attributes. Additionally, connectivity was established with *z*-elevation to simulate overpass and underpass scenarios. After the network was built and traffic data were incorporated, all potential alternative routes were identified and evaluated using alternative route

selection criteria. The selection criteria were defined based on the FHWA's alternate route

handbook. Figure 23 maps the traffic data incorporated into a network dataset.
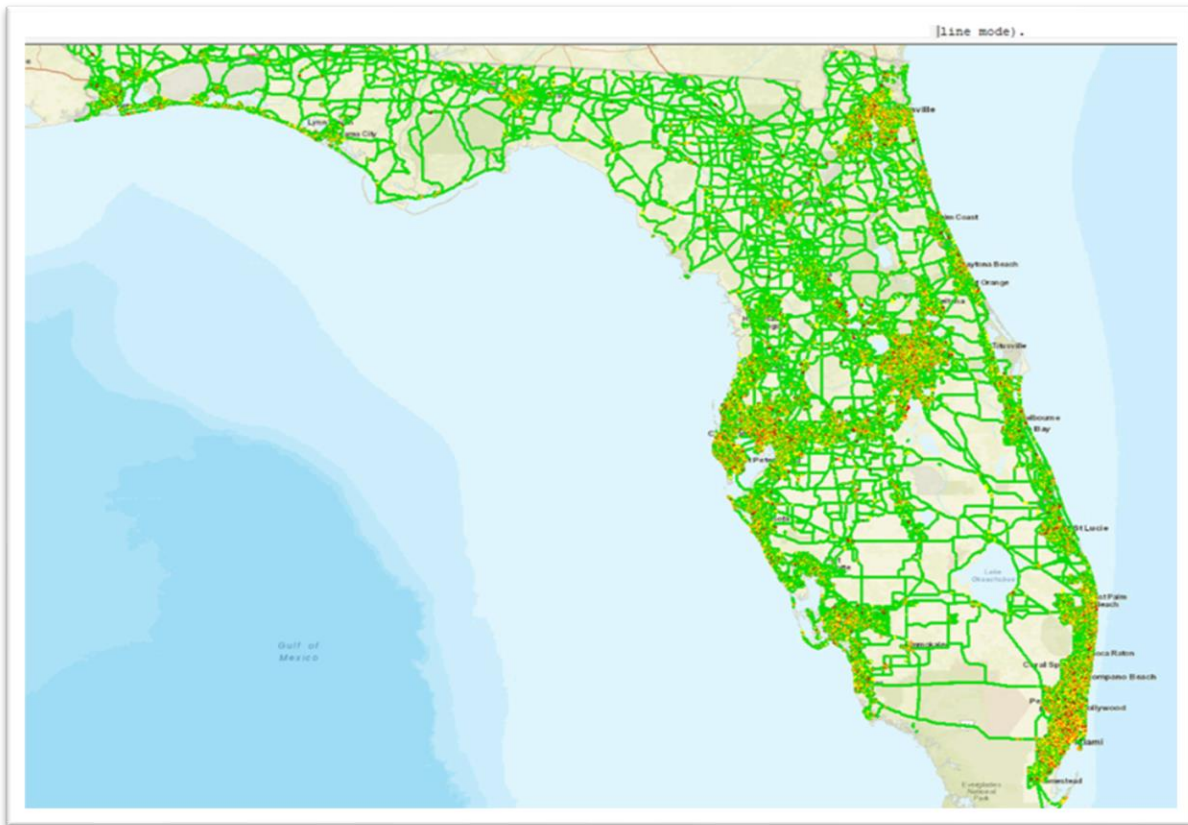
Figure 23: Traffic Data

Routing restrictions and attributes can also be incorporated into the network analysis. Network

attributes, including travel time, restricted turns, posted speeds, and one-way streets, were

assigned to network elements. Figure 24 shows the network dataset properties for the

restrictions.
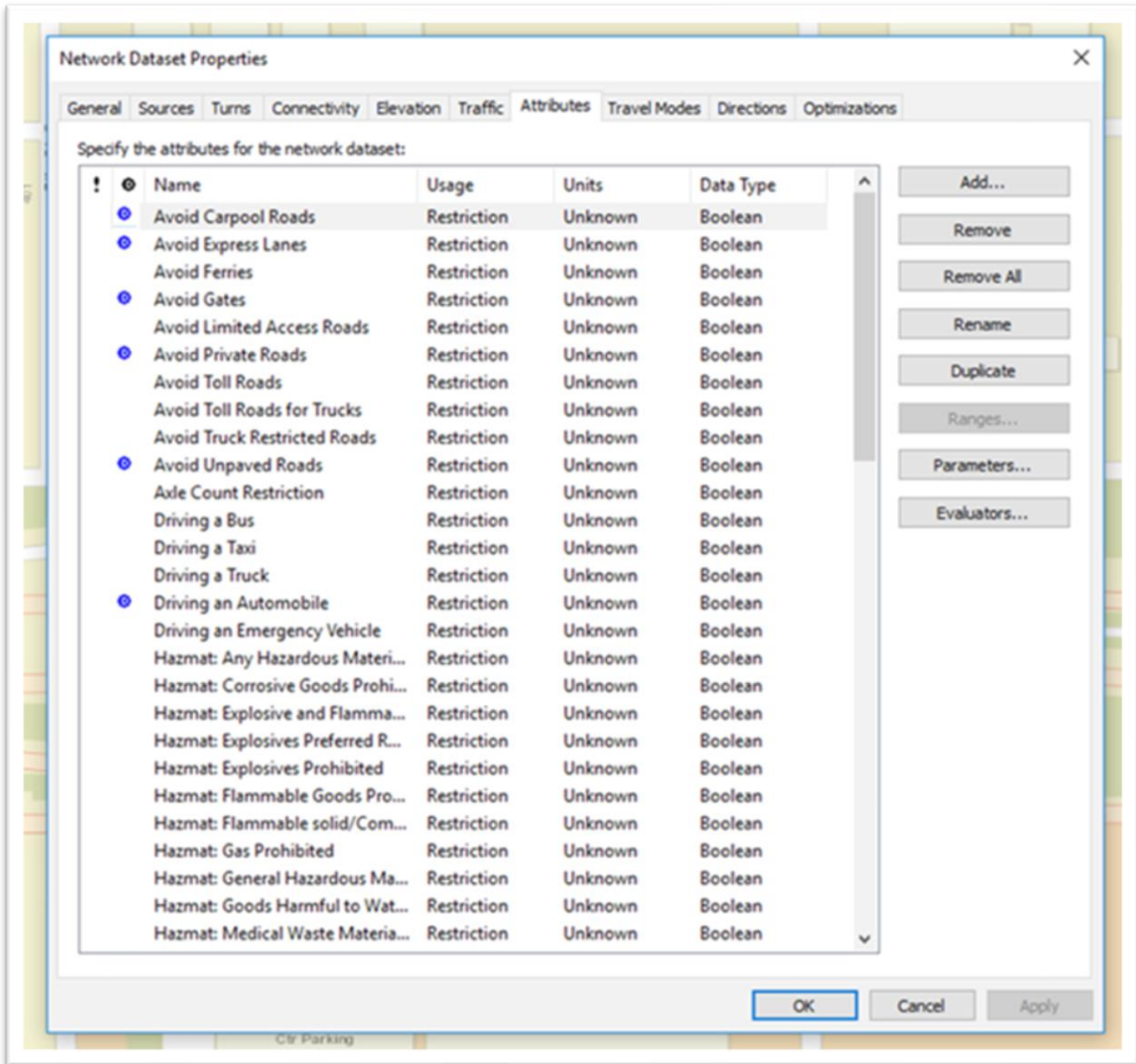
Figure 24: Network Dataset Attributes

Global turn delays are utilized as a type of cost attribute to refine travel time calculations by restricting movements from one section of the road to another. Such delays are often referred to as time constraints. Moreover, heavy vehicle characteristics and restrictions were considered as parametrized attributes. Figure 25 presents details on the global turn delay as a cost attribute.
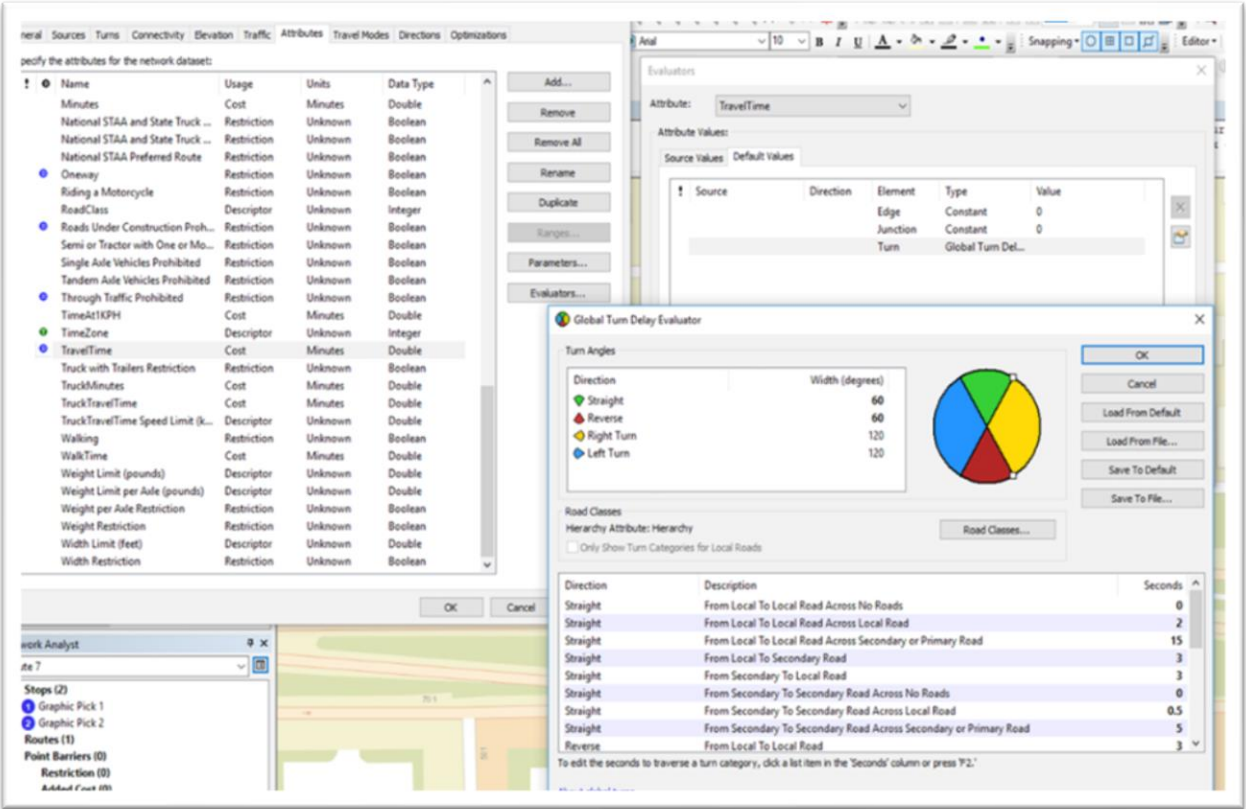
Figure 25: Global Turn Delays

4.8 Alternative Route Selection Criteria

To select an alternative route that can accommodate heavy vehicle characteristics and restrictions, selection criteria were defined. The main characteristics for assessing whether a candidate route is feasible for truck traffic were specified as follows:

1. Roadway geometry, including lane width and number of lanes

2. Roadway conditions, including level of service and speed limit

3. Heavy vehicle restriction, including vertical clearance restrictions and insufficient bride design loads

4. Neighborhood impacts, including proximity to schools and hospitals

After identifying the alternative route criteria, relevant data were collected from various sources. Data were extracted in shapefile format, and additional data processing was done utilizing data management tools in the ArcGIS platform.

This section presents the methodology used for developing requirements for evaluating whether alternative routes are suitable for heavy vehicles. Collected data relevant to alternative route selection considerations were used as restrictions or scaled-cost barriers in the network analysis. Restrictions indicate that the selected road segment is restricted for heavy vehicles and is not feasible for truck traffic diversion. Scaled cost barriers penalize a route by increasing the travel time based on predefined factors.

Barriers raise the cost of transport along edges and junctions of the linked network dataset. Barriers can be classified as points, lines, or polygons, and they can be modeled as preferred or avoided features within the Network Analyst extension to represent temporary changes to the network. When point barriers are added to a roadway segment, travel in the segment is prohibited. Added cost point barriers, however, still allow movement through them but may add costs to that movement. Line barriers are the second type of barrier within ArcGIS. Line barriers can restrict road segments entirely or can multiply travel costs by a given factor. The third type of barrier is the polygon barrier. A scaled cost can be added to roads that pass through a polygon barrier.

4.8.1 Roadway Geometry

Roadway capacity is related to the number of lanes on the roadway. Additionally, lane width is an essential factor for maneuverability. In this study, the threshold for truck diversion was identified as lanes with a width of 9 feet. Roads with lane widths of 9 feet or less were added to the network as restrictions.

4.8.2 Traffic Conditions

To ensure that diversion does not increase congestion on an alternative route, the available level of service on the route was determined and added to the network as a scaled cost. Roads operating near capacity or having a low level of service were assigned a cost factor of 2, which doubles the travel cost

4.8.3 Neighborhood Impacts

It is essential to eliminate truck traffic from suburban areas with high population densities to preserve the health and quality of life of the neighborhood. Areas near schools are overcrowded during morning and afternoon hours, and a heavy vehicle redirected to the vicinity of a school would present a risk to schoolchildren.

Data were collected from the ESRI database and extracted as a shapefile then clipped to the study area. A 0.5-mile buffer was created around school locations, and a polygon barrier was added to network analysis as a scaled cost. Segments that intersect with school polygon barriers were assigned a scaled cost value of 2. Hospital locations data were collected from the ESRI library and extracted as a point shapefile. Data were clipped to the study area, and a 0.5-mile

buffer was created around each hospital location. A polygon barrier was added to the network analysis as a scaled cost barrier.

4.8.4   Heavy Vehicle Restrictions

The National Bridge Inventory data were inspected to identify criteria that could be used as restrictions on the network. Bridges with insufficient design loads (less than H1) were added to the network in a new layer as restrictions to prevent the diversion of truck traffic to these locations. Bridges with vertical clearance less than 14 feet were also added to the network as restrictions.

Bridge inventory data was extracted as a CSV file and converted to a shapefile, and the layer was projected and plotted to ArcGIS. The bridge points were clipped to the study area. Bridges with a design load less than H1 or with low vertical clearance were selected, and a new layer with the selection was created. This feature class was buffered by 0.5 miles. These buffers were added as scaled-cost polygon barriers in Network Analyst.

4.9   Benefit Estimation

The model benefits allowed for the following:

1. Calculations of the travel time with and without diversion.

2. Estimates of the difference in total travel time between two scenarios.

3. A reduction in delays due to truck diversion.

4. Reduced fuel consumption due to the diversion strategy, using conversion factors obtained from the National Highway Traffic Safety Administration's *Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study* (June 2015).

5. Conversion of savings in delay time and fuel consumption to monetary values using conversion factors obtained from Texas A&M Transportation Institute's *Urban Mobility Report*.

4.10 Summary

A research methodology was developed to improve truck travel efficiency and assess the impacts of truck diversion strategies. This chapter described the details of the methodology and the criteria used for the methodology and for data collection. It also described the various data sources used in this research and the primary methods of analysis employed for different phases of the study. The following chapter details the development of a model that uses the analysis approaches described above.

CHAPTER 5: MODEL DEVELOPMENT

5.1   Introduction

As described previously, the I-75 corridor and the 20 counties along this corridor were considered as the study area. One of the main aims of this study is to evaluate the impact of truck diversion on the functioning of this road network. The results of this evaluation contribute to achieving another aim of the study: assessing the ability of alternative route candidates to accommodate truck traffic.

The criteria used for selecting alternative routes have been categorized into four primary keys: roadway geometry, traffic conditions, heavy vehicle restrictions, and neighborhood impacts. To achieve the aim of this study, incident clearance time must be predicted, and the resulting estimated delay time integrated into a diversion initiation model to compare travel time on the main route with travel time on the candidate alternative route. Additionally, a truck traffic diversion strategy must be evaluated using predefined alternative route selection criteria to assist in selecting the optimal diversion route.

5.2   Crash Hotspots Analysis

Traffic crashes are a significant public safety concern and are one of the leading causes of death around the world (World Health Organization, 2015). For this reason, traffic safety indicators, such as fatality risk, the number of crashes with injuries, and the number of victims, are regularly collected to monitor the safety trends of specific sites (Bergel-Hayat et al., 2013). Identifying high-crash-rate road segments provides safety professionals with insight into crash patterns to improve road safety management. Due to the increasing number of crashes and

insufficient financial resources, it is imperative to identify priorities for future investments in road safety to ensure more efficient resource distribution. Identifying crash-prone segments can help decision-makers to prioritize financial resources and to plan the proper actions to improve the problematic segments.

This study presents a methodology for prioritizing and classifying roadway segments by employing a comprehensive 3D hotspot analysis based on crash data, including crash severity and crash spatial and temporal characteristics. Evaluation and classification of road networks based on safety performance and crash rates can be used to identify the most critical segments in terms of crash severity and crash type.

A macroscopic spatial analysis was conducted using traffic crashes to identify statistically significant crash trends and locations on the I-75 corridor from 2014–2017. The proposed model was incorporated into the diversion decision-making tool to more efficiently support the planning and improvement of road safety.

The hotspot crash analysis investigated crash trends over time and space. The findings are symbolized by 17 distinct categories defining the statistical importance of hot or cold spots and the pattern of locations over time. Crash patterns were identified in the study area between 2014 and 2017.

Hotspot analysis was performed, and results revealed a high z-score and a low p-value with positive Moran's I value. As shown in Figure 26, a z-score of 52.9 and low p-values are indications of cluster distribution of the crash-prone locations and the spatial autocorrelation between them.
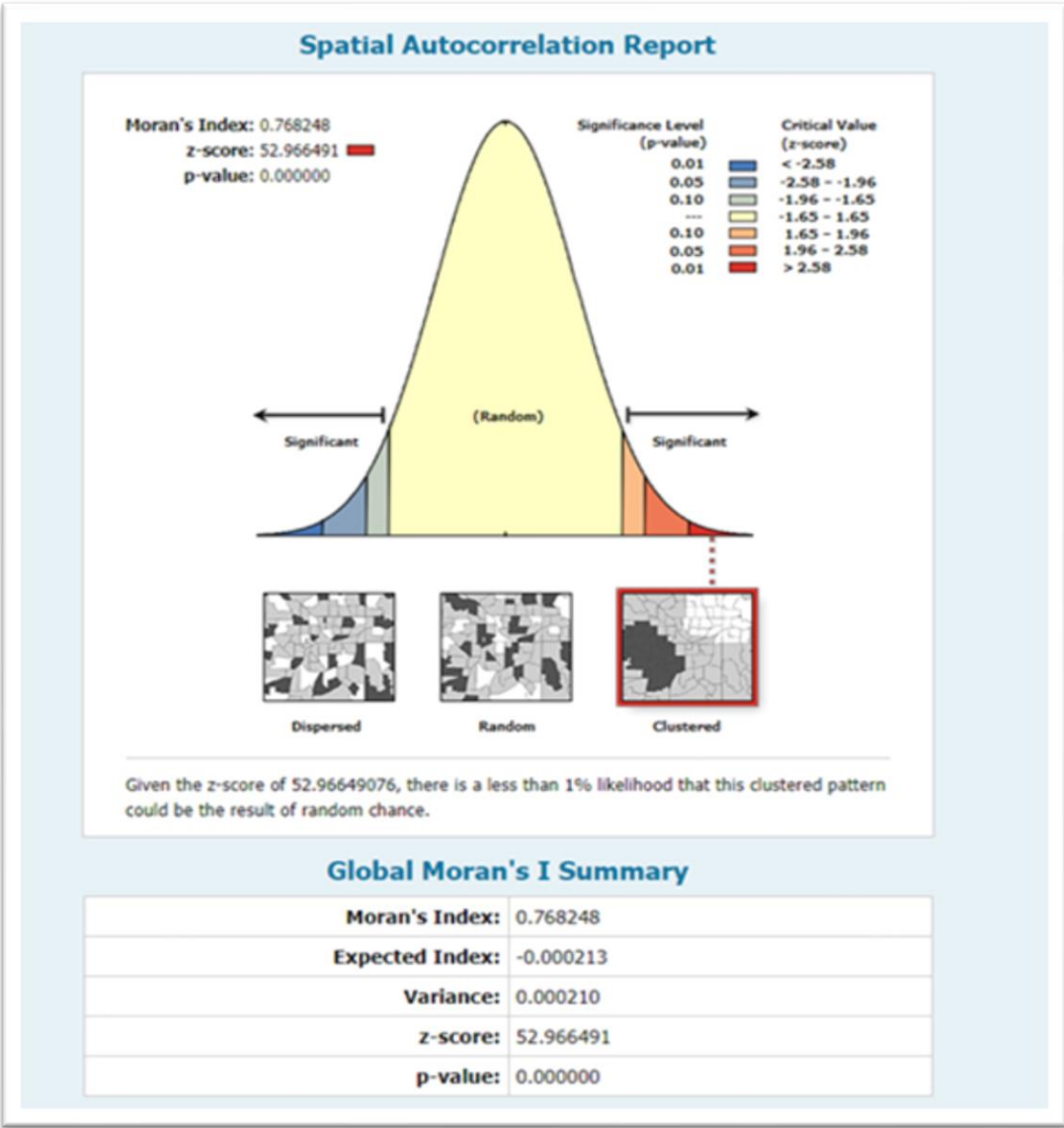
Figure 26: Global Moran's I Summary Report

The emerging hotspot analysis revealed that four types of hotspots—consecutive hotspots, intensifying hotspots, sporadic hotspots, and for the years 2014–2017, new hotspots— are statistically distributed at various locations in the study area. Figure 27 shows seven new hotspot locations. These locations need more attention, and more traffic management needs to be

applied in line with the particular temporal and spatial patterns of these hotspots. In conclusion, the results determined the locations where different types of hotspots are concentrated.
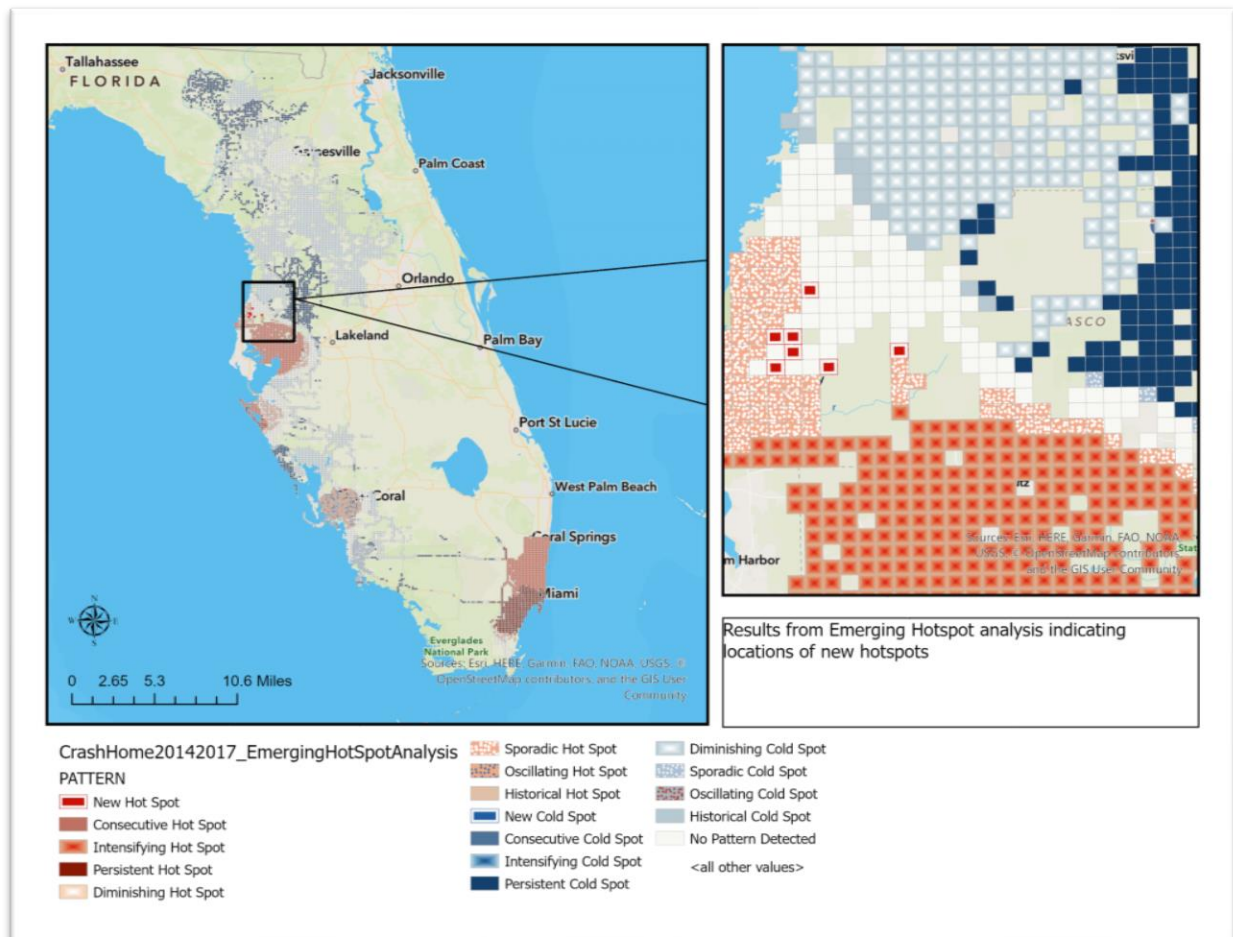
Figure 27: Emerging Hotspot Analysis

In this research, Space-Time Cube analysis was performed to identify the statistically significant locations of the crashes between the years 2014 and 2017. As shown in Figure 28, the bright red hexagons represent new hotspots that are statistically significant high crash rates value during the last months of 2017.
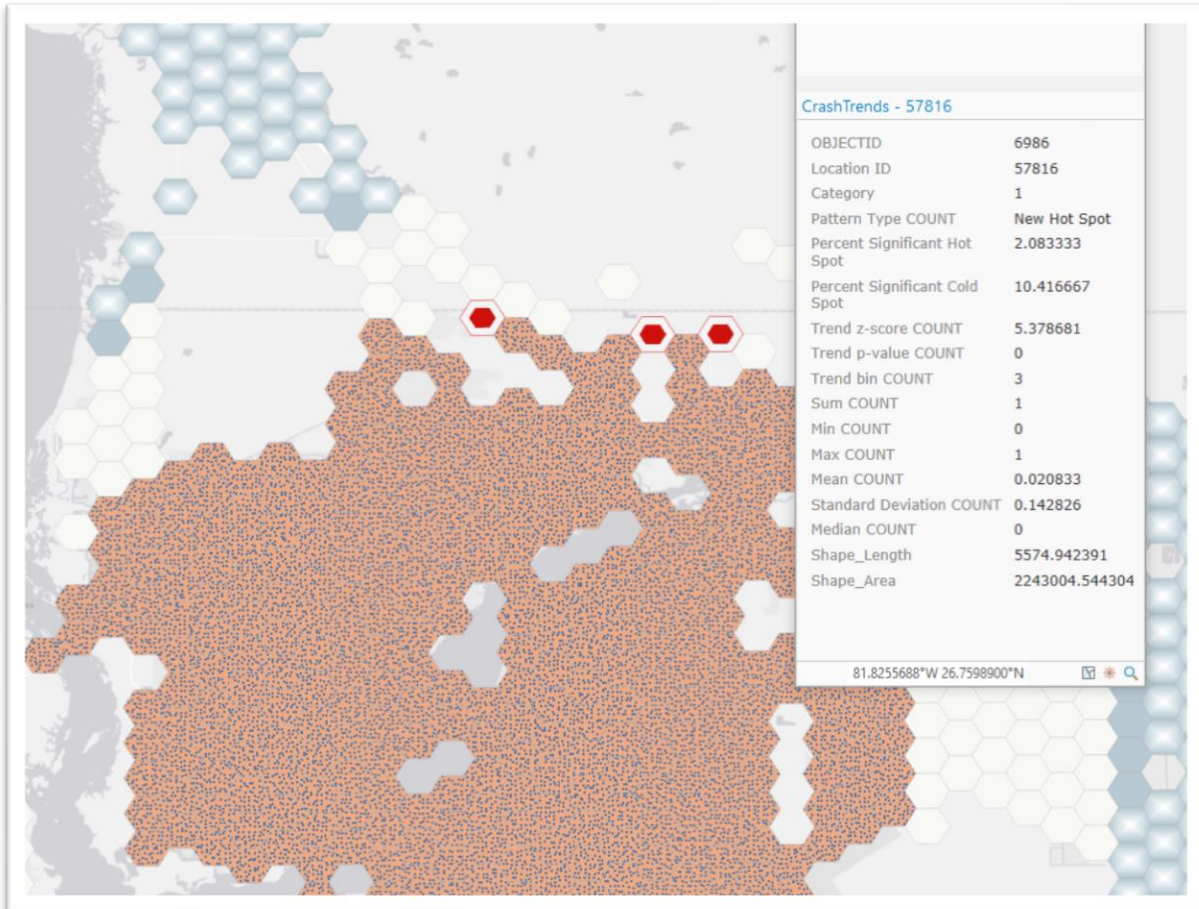
Figure 28: Emerging Hotspot Analysis, New Hotspot Locations

Additionally, the crash trends were investigated and visualized in three dimensions to present crash Spatio-temporal patterns over the study area during the years of 2014 to 2017. As shown in Figure 29, hexagons in 3D shown as columns of slanted bins. Each bin represents one month time period. The top of the column represents the most recent time. The red bins are statistically significant crash clusters with high crash rates, while the blue bins are statistically significant clusters of low crash rates.
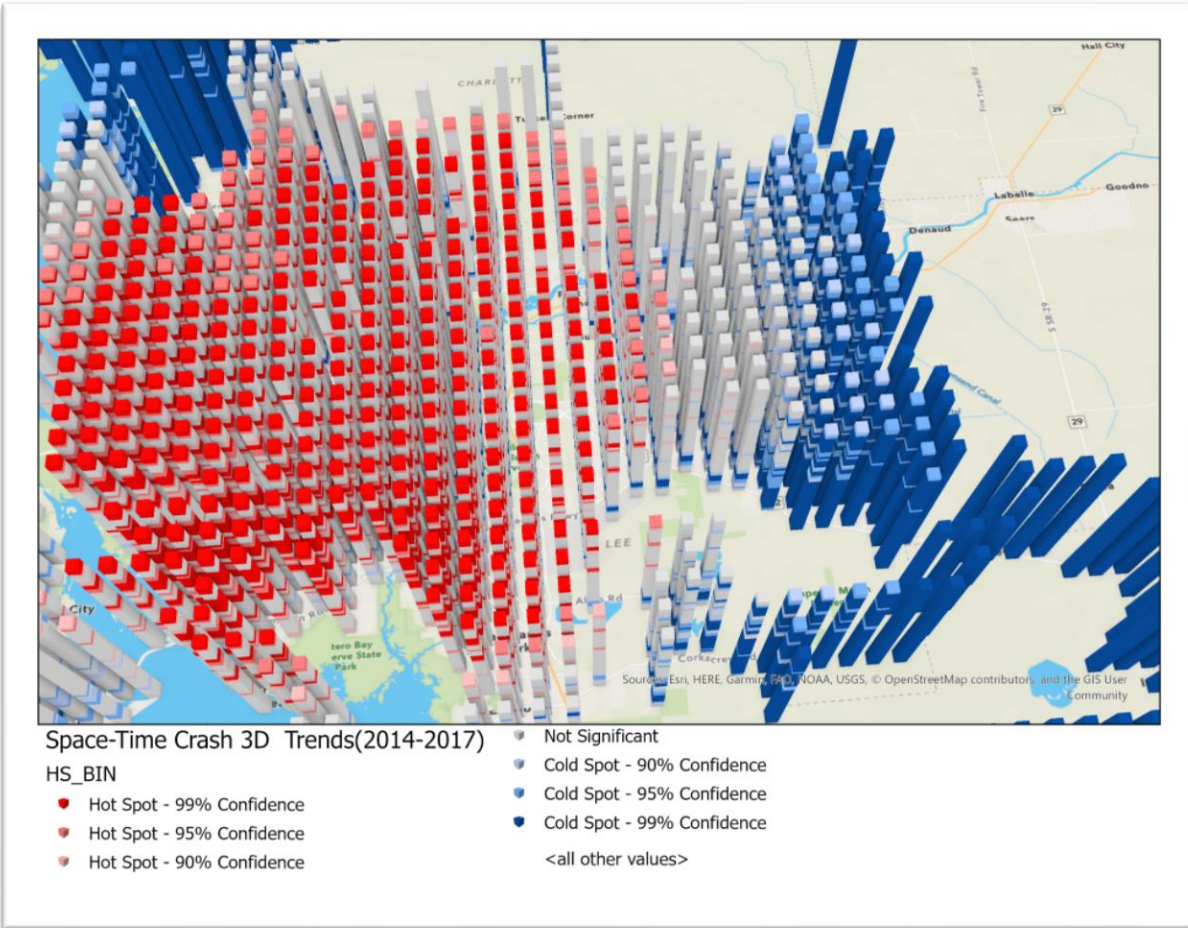
Figure 29: Space-Time Crash Trends 3D Analysis

5.3   Incident Clearance Prediction Model Development

To validate the linear regression model, data were tested to determine whether they met

the regression model assumptions. Several approaches could be used to investigate the

assumptions of linear regression, such as collinearity and normality. In this research, the criteria

used were skewness of the histogram, normal probability plots, variance, and scatterplots

between the dependent variable and independent variables.

Scatterplots were constructed between the dependent and the explanatory variables to test the linearity assumption. To evaluate the normality assumption, histogram skewness was measured. To evaluate multicollinearity between independent variables, the correlation coefficient and variance inflation factor (VIF) was determined by applying multiple linear regressions. Tolerance values less than 0.3 and a VIF greater than 10 indicate a multicollinearity problem. The dependent variable (incident duration, or *dur5*) was transformed using the log function for improved symmetry and stable variance with the purpose of improving normality. Figure 30 presents the histogram of the transformed variable
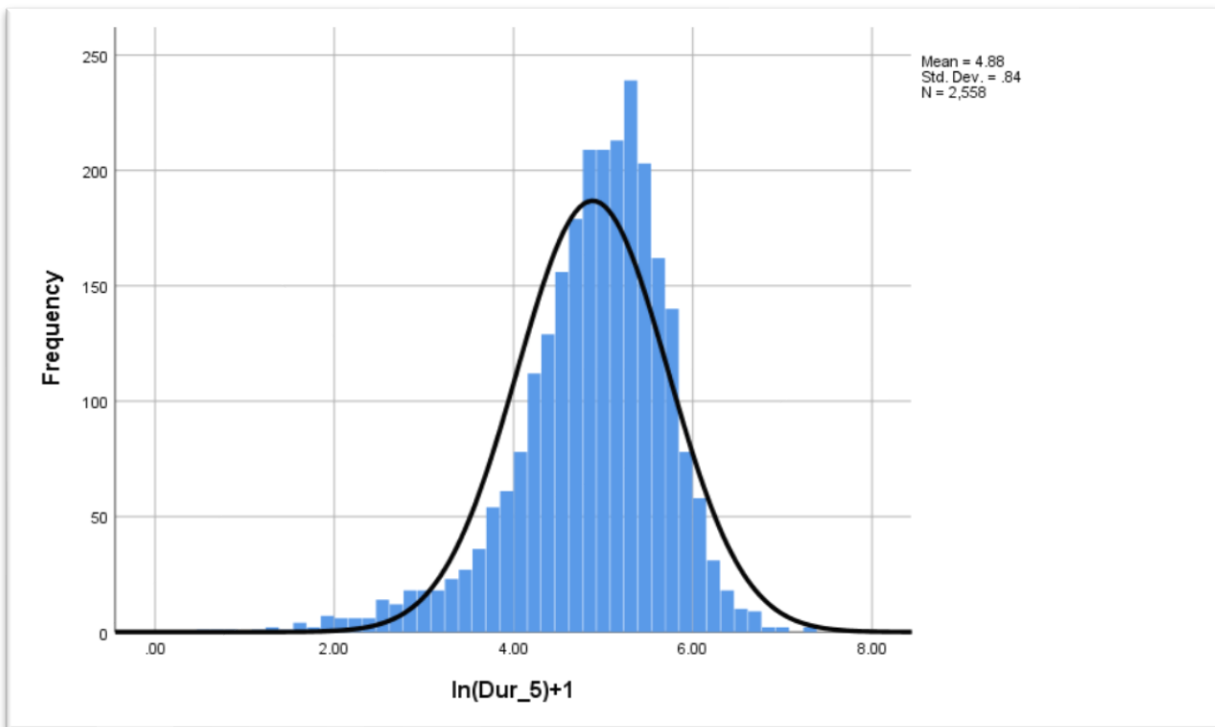
Figure 30: Log Transformation of Incident Clearance Time

To demonstrate how independent variables, relate to each other and to evaluate the strength of correlations among these variables, the relationships between all pairs of variables were plotted. The overall pattern of these relationships appears regular and shows typical trends.

This section presents the development of the incident clearance duration prediction model. Prediction of incident clearance time is essential in the management of nonrecurrent congestion due to incidents on freeways. A statistical model was developed to predict incident clearance duration. Findings from this model were implemented in the incident management process to reduce the impact of congestion on the network. To improve the operational efficiency of urban freeways and to minimize the impact of congestion, several strategies were implemented. To make these strategies operate efficiently, the prediction of incident clearance duration is necessary. In chapter 3, a description of incident data and an overview of the study area were presented. In this section, the development of the incident clearance prediction model is presented, followed by a discussion of how the results of this model are integrated with a diversion decision algorithm.

In this study, regression analysis was used to develop a model for predicting incident clearance duration as a function of relevant variables. The goal is to develop a prediction model that can easily be used by a practitioner in incident management. The multiple regression analysis options of SPSS software were utilized in developing this prediction model

The first step was to regress the dependent variable (incident clearance duration) with all the independent variables to examine the effect of each variable. Determining which variables are significant at $\alpha = 0.05$ was the second step. The third step was to regress the dependent variable individually with all possible combinations of independent variables to select the best

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functional form. Next, each two-factor interaction term was introduced. The final step was to employ the stepwise procedure one more time using the variables resulting from the previous three steps. The outcomes of these steps are detailed below.

The model summary output shown in Table 8 revealed that the model could predict 31.4% of the incident clearance duration using the selected independent variables. The t statistics of the independent variables used in the model, the overall F statistics, and the standard error imply that the model is an adequate predictor. The VIF and the condition index (CI) are often used to measure collinearity in a multiple regression analysis. The larger the value of the VIF or CI for any variable, the more troublesome is the variable. From the literature, a CI value of 30 or more reflects moderate to severe collinearity.

Table 7: Statistics Model Summary

Model Summaryᵇ										
Mode l	R	R Squar e	Adjuste d R Square	Std. Error of the Estimat e	Change Statistics					Durbin - Watso n
					R Square Chang e	F Chang e	df 1	df2	Sig. F Chang e	
1	.560 a	.314	.300	.70325	.314	22.026	52	250 5	.000	.565
a. Predictors: (Constant), AADT*TruckPerc/1000000, Incident Severity, November, Median Type, Sunday, Other, Three lanes blocked, Incident Verification, Fire, Lane width, Wildlife, 2:00 PM-4:00 PM, Dur_4, Left lane blocked, August, Two lanes blocked, February, Wednesday, Debris on the road, October, 9:00 AM-11:00 AM, Emergency Vehicle, September, Tuesday, Response, July, 12:00 AM-6:00 AM, Entry Ramp, January, 7:00 PM-12:00 AM, AADT/10000, Saturday, Disabled Vehicle, May, 6:00 Am-9:00 AM, March, Monday, an Exit ramp, Shoulder closed, June, Center lane blocked, 11:00 AM-2:00 PM, Thursday, Toll Road, April, Urban, Right lane blocked, Number of lanes, MedWid_40, One lane blocked, Crash, Capacity Reduction										
b. Dependent Variable: ln(Dur_5)+1										

Table 8: ANOVA Table

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	566.448	52	10.893	22.026	.000[b]
	Residual	1238.879	2505	.495		
	Total	1805.327	2557			
a. Dependent Variable: ln(Dur_5)+1						
b. Predictors: (Constant), AADT*TruckPerc/1000000, Incident Severity, November, Median Type, Sunday, Other, Three lanes blocked, Incident Verification, Fire, Lane width, Wildlife, 2:00 PM-4:00 PM, Dur_4, Left lane blocked, August, Two lanes blocked, February, Wednesday, Debris on the road, October, 9:00 AM-11:00 AM, Emergency Vehicle, September, Tuesday, Response, July, 12:00 AM-6:00 AM, Entry Ramp, January, 7:00 PM-12:00 AM, AADT/10000, Saturday, Disabled Vehicle, May, 6:00 Am-9:00 AM, March, Monday, Exit ramp, Shoulder closed, June, Center lane blocked, 11:00 AM-2:00 PM, Thursday, Toll Road, April, Urban, Right lane blocked, Number of lanes, MedWid_40, One lane blocked, Crash, Capacity Reduction						

To assess the model fitness of data, Pearson residuals were plotted against the predicted value of log*dur5*, as shown in Figure 31. The residual plot figure shows a normal P-P plot. As shown in Figure 31, the points generally follow the normal line with no substantial deviations; this indicates that the residuals are normally distributed.
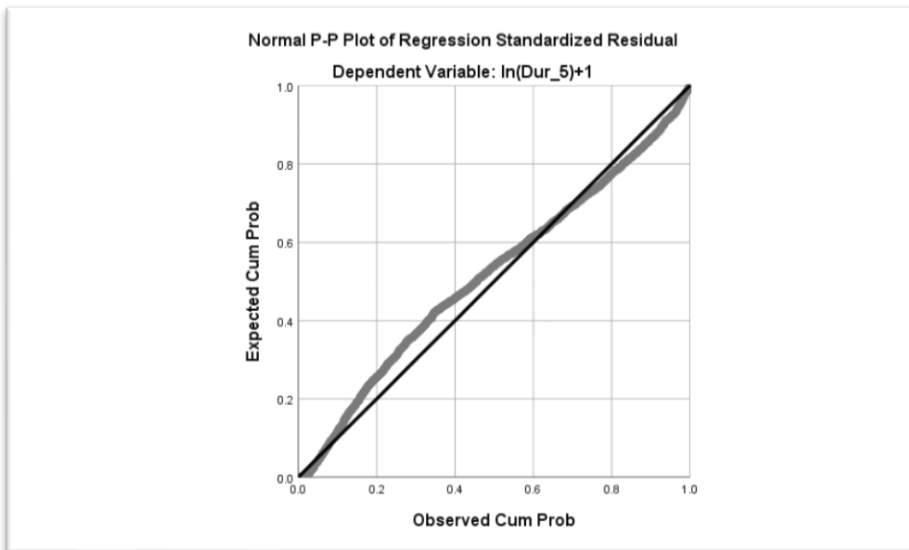
Figure 31: Normal P-P Plot of Regression

Moreover, regression analysis results revealed that not all the independent variables were statistically significant in explaining the variation in incident clearance duration. Among them, the main effect of, and, were not significant to affect incident duration (dur5). However, incident verification time, response time, and shoulder closed were significant in explaining the variation in incident clearance duration (dur5). Shoulder closure presented the highest significance representing an increase of clearance time. Additionally, verification time and response time showed statistical significance to increase the incident clearance time.

In summary, this section provided a descriptive analysis of the distribution of incident clearance duration dur5 by several independent variables. Explanatory variables were explored for their effects on incident clearance duration. The criteria that were used in this study to test the assumption of linear regression were skewness of histogram, normal probability plots, variance, and scatterplots between the dependent variable and independent variables. Accordingly, the dependent variable dur5 was transformed using the log function for improved symmetry and improved Normality. In order to evaluate the model, Pearson residuals were plotted against the predicted value of the incident clearance duration (logDur_5)

5.4   Sensitivity Analysis

The statistical approach in this study was used to predict incident clearance time is Multiple Linear Regression. Multiple linear regression attempts to model the relationship between two or more independent or explanatory variables and a dependent variable by fitting a linear equation to observed data. Based on the normality tests, trials, and errors during the model calibration efforts, explanatory variables were modified to assess the effect of each variable on

the incident clearance; all categorical attributes were transformed into binary representations (i.e., 0 or 1). The Statistical Package for Social Science (SPSS) software was utilized for model development.

A set of the incident, traffic, and road characteristics were examined for possible inclusion as independent variables in the developed prediction model. Several approaches could be used to investigate the assumptions of linear regression, such as collinearity and normality. In this research, the criteria that were used to validate these assumptions were skewness of the histogram, normal probability plots, variance, and scatterplots between the dependent variable and independent variables.

Scatter plots were performed between the dependent and the explanatory variables to test the linearity assumption. In order to evaluate the normality assumption, the value of Histogram skewness was identified. In evaluating multicollinearity between independent variables, an inspection of the correlation coefficient and Variance Inflation Factor (VIF) was performed by applying multiple linear regressions.

Values of tolerance less than 0.3 and VIF greater than 10 indicate the problem of multicollinearity. The dependent variable (Incident duration dur5) was transformed using the log function for improved symmetry and stable variance with the purpose of improving normality. The incident duration was transformed into its natural log and included in the model as the dependent variable. The model summary output revealed that the model could predict 31.4 % of the incident clearance duration using the selected independent variables.

Sensitivity analysis was used to indicate which parameters have more influence on the prediction of the dependent variable. Therefore, Sensitivity Analysis was performed by varying

the input parameters one by one while keeping the other inputs fixed at the baseline and monitor changes in the output.

Regression analysis was utilized for sensitivity analysis. The importance of inputs was indicated by the changes in R squared with the change of each input in the regression model. Sensitivity analysis steps of this study are as follows:

- First, the base scenario output was defined. The base scenario includes all the independent variable in the prediction model, and all the input are kept constant.

- Then, the value of the output after removing one of the input parameters while keeping other inputs constant was calculated.

- The percentage change in the output was obtained by comparing the model accuracy of each scenario with the base scenario.

Incident data were divided into six categories; Incident type, road closure, time of day, month, day of the week, road characteristics. Table 11 shows the parameters included in each category.

Table 9: Incident Data Categories for Sensitivity Analysis

Data Category	Incident type	Time of Day	Month	Road Closure	Day of Week	Road Characteristics
Parameter	Crash	12:00AM-6:00AM	January	Right lane blocked	Sunday	Lane Width
	Disabled Vehicle	6:00Am-9:00AM	February	Center lane blocked	Monday	Number of Lanes
	Debris on road	9:00AM-11:00AM	March	Left lane blocked	Tuesday	Median Type
	Fire	11:00AM-2:00PM	April	Shoulder closed	Wednesday	Median Width
	Wildlife	2:00PM-4:00PM	May	Exit ramp	Thursday	Functional Classification
	Police Activity	4:00 PM-7:00 PM	June	Entry Ramp	Friday	Speed Limit
	Emergency Vehicle	7:00PM-12:00AM	July	Ramp Shoulder	Saturday	AADT
	Other		August	One lane blocked		Truck Percentage
			September	Two lanes blocked		
			October	Three lanes blocked		
			November			
			December			

By removing one of the input parameters while keeping other inputs constant, model accuracy was calculated and compared with the model accuracy of the base scenario. As shown in Table 12, six scenarios were performed, and model accuracy was compared to the base scenario.

Table 10: Results of Sensitivity Analysis Scenarios

Variables	Model Accuracy
Road Characteristics	3.6%
Road Closure	8.0%
Incident Type	11.5%
Time of Day	1.3%
Day of Week	0.6%
Month	1.0%

The results of the six scenarios were plotted. As shown in Figure 32, the incident type has a significant impact on model accuracy, followed by road closure parameters.
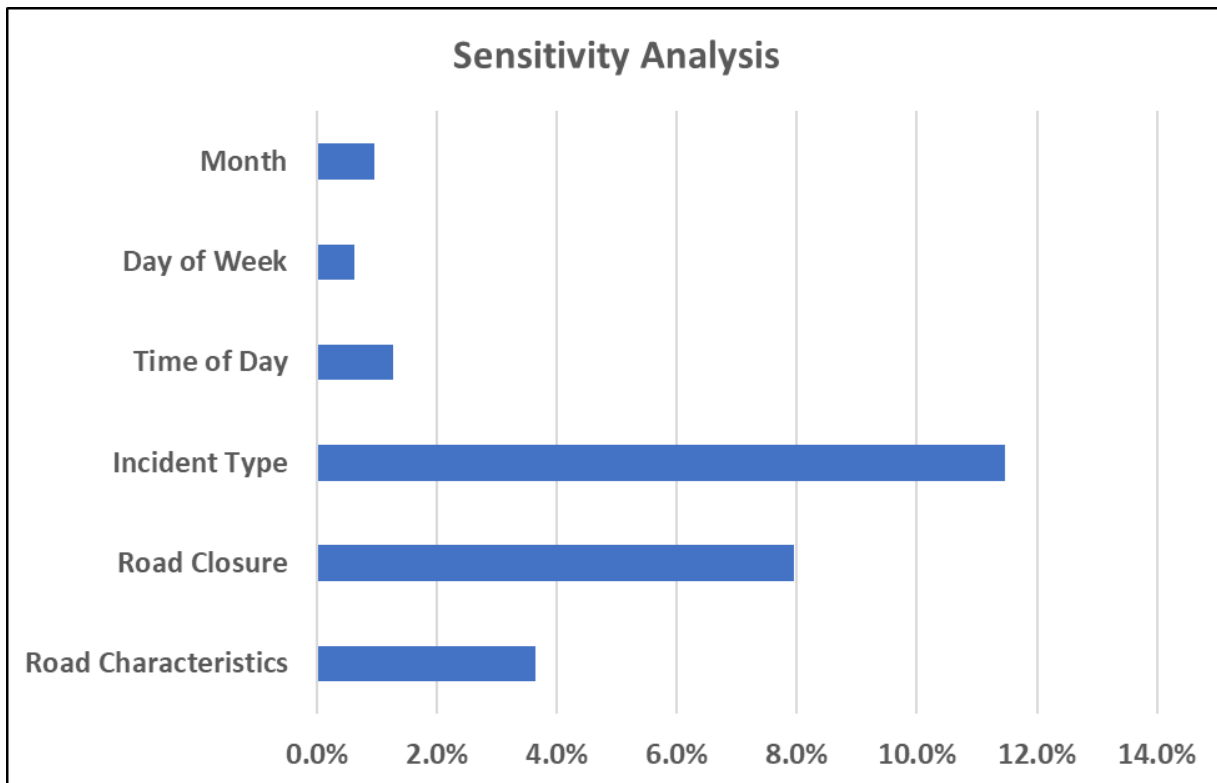
Figure 32: Impact of Input Parameters on Model Accuracy

5.5   Diversion Model

A network analysis model of I-75 in Florida was developed. The developed model finds all potential alternative routes throughout the study area, taking into consideration heavy vehicle restrictions and the impacts of traffic diversion on neighborhood and traffic conditions. Predefined alternative route selection criteria were incorporated in the network dataset. Based on the criteria for lane width, capacity, and vertical clearance, those routes with features that made

them unacceptable as alternate routes were excluded from consideration. A penalty factor (scaled cost) was also applied to roads within a defined distance of schools or hospitals.

The main objective of this research was to develop a framework to evaluate the impact on the overall road network operation of truck diversion strategies to mitigate nonrecurrent congestion due to incidents. As explained previously, a network analysis dataset was designed and created, and the ArcGIS platform was utilized with it to develop alternative routes that consider truck restrictions such as vertical clearance limitations, road characteristics, and traffic conditions. The entire corridor of I-75 was analyzed using this approach.

The next process was to establish criteria that made it possible to test alternative routes in terms of appropriateness for trucks. A threshold was identified for each criterion. Alternative route selection criteria were added to the network as restrictions or scaling factors to assign penalties to each segment that intersected a specified criterion. Additionally, estimated travel time, restrictions, and barriers such as low-clearance bridges and school zones were considered.

The algorithm was designed to find the shortest path, excluding scalable costs and constraints; this would be the base scenario. Another scenario was also considered that added cost factors and restriction barriers. This scenario simulates the truck diversion route. The Network Analyst extension produces turn-by-turn instructions for each simulation scenario to define alternative routes to avoid high-risk interstate closures.

The criteria used to evaluate potential truck routes are summarized as follows:

1. Neighborhood impact
2. Traffic conditions
3. Roadway geometries

4. Heavy vehicle restrictions

5. Cost

Neighborhood impacts consider the properties of nearby land use along the proposed truck path. Truck intrusions into residential areas and near other critical facilities, such as schools or parks, are not desirable. Truck restrictions can be introduced to prevent truck drivers from driving on roads near these land uses.

Also, road conditions selection criteria consider both the level of traffic congestion along the proposed road route and its capacity. Roads carrying traffic volumes approaching capacity are less attractive as potential truck routes, as traffic congestion would have a detrimental effect on freight movements.

Different case studies were developed to evaluate the potential alternative route and validate the proposed model. These scenarios were compared with the base scenario, which is travel on the main route during incident conditions.

CHAPTER 6: RESULTS AND DISCUSSION

6.1   Introduction

Traffic diversion strategies can be utilized as congestion mitigation strategies by diverting truck traffic to an alternative route. The alternative route then carries both the diverted traffic and its regular traffic load. Therefore, the selection of alternative truck route should consider the safety and efficiency of the overall network system. Although traffic diversion strategies are implemented in many regions, there has been only limited study of the criteria used in deciding on optimal truck traffic diversion routes.

The criteria for selecting alternative truck routes should be carefully defined to consider truck characteristics so that only optimal routes that can efficiently accommodate truck traffic are selected. Limited work has been done evaluating the economic, social, and environmental impacts of truck traffic diversion on the performance of the selected alternative routes.

This chapter details three case studies to demonstrate the efficiency of the developed truck routing framework during incident-induced congestion on a segment of I-75 in Florida. The proposed framework first performed a space-time cube hotspot analysis to identify statistically significant hotspots and classify hotspot trends over space and time to identify high-crash segments. Additionally, a statistical regression model was applied to identify the explanatory variables that influence incident clearance duration. Finally, a regression model was developed to estimate incident clearance duration times in the I-75 corridor.

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6.2   Case Study

The proposed truck rerouting framework was applied to three case studies using suitable

alternative route selection criteria. The selected truck routes helped to reduce delays and satisfy

truck maneuverability restrictions while maintaining satisfactory road conditions on the selected

route. The scenario sites were determined by investigating high-crash trends and statistically

analyzing incident clearance results. A stretch of I-75 was identified as a study site for applying

the developed framework for each case.

The first case study was of an incident on I-75 Northbound, beyond mile marker 258, that

occurred on September 3, 2018. The incident type was a crash with severity level 3, which is

defined as causing an incapacitating injury. The incident blocked two out of three lanes. Incident

information was collected from the FDOT SunGuide report. The roadway characteristics and

simulation variables used in the model and the details of the incident characteristics are listed in

Table 13. Additionally, Figure 33 shows the incident location of the first case study.

Table 11: Details Information for Case Study 1

Category	Data details
Date and time	2018/09/03 13:15:17
Location	I-75 Northbound, Beyond MM 258
Severity	3
Number of blocked lanes	2 Right Lanes (of 3 Lanes) Blocked
First responder arrival time	2018/09/03 13:23:09
Incident clearance duration (minutes)	52.7
County	Hillsborough
Notifier Agency	TBRCC
Incident type	Crash
maximum speed	70
AADT	151500
Truck %	6.50%

Figure 33: Incident Location- Case Study 1

A second case study selected for model application simulated an incident that occurred on I-75 Northbound on December 25, 2018. The incident type was a crash with severity level 2, which is defined as a possible injury. The incident caused the blockage of the exit ramp as well

as the left lane. Incident information was again collected from the FDOT SunGuide report. The
roadway characteristics and simulation variables used in the model and the details of the incident
characteristics are given in Table 14. Additionally, Figure 34 shows the incident location of the
second case study.

Table 12: Detailed Information Related to Case Study 2

Category	Data details
Date and time	2018/12/25 02:00:33
Location	I-75 Northbound, Ramp to Big Bend Rd
Severity	2
Number of blocked lanes	Exit Ramp Left Lane Blocked
First responder arrival time	2018/12/25 02:08:06
Incident clearance duration (minutes)	92.4
County	Hillsborough
Notifier Agency	FHP
Incident type	Crash
maximum speed	70
AADT	89000
Truck %	10.50%
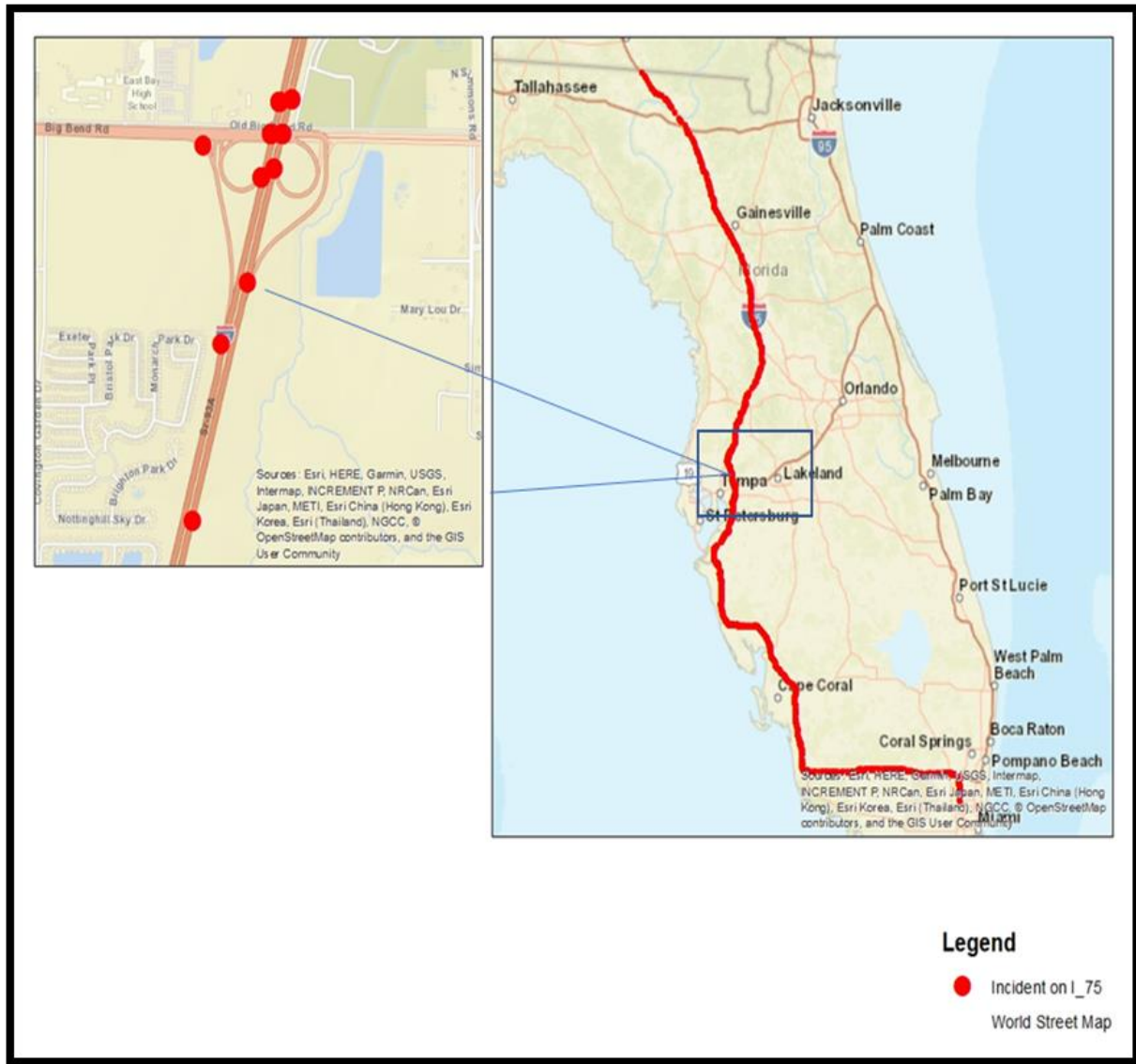
Figure 34: Incident Location- Case Study 2

The third case study assessed an incident that occurred on July 07, 2018 and closed all lanes on I-75 Northbound at mile marker 91. Incident information was collected from the FDOT SunGuide report. The roadway characteristics and simulation variables used in the model and the details of the incident characteristics are shown in Table 15. Additionally, Figure 35 maps the incident location of the third case study.

Table 13: Detailed Information Related to Case Study 3

Category	Data details
Date and time	2018/07/011 15:00:27
Location	I-75 Northbound, At Mile Marker 91
Severity	3
Number of blocked lanes	Road closed
First responder arrival time	2018/11/15 04:23:15
Incident clearance duration (minutes)	65.68
County	Collier
Notifier Agency	FHP
Incident type	Vehicle fire
maximum speed	70
AADT	41500
Truck %	11.20%
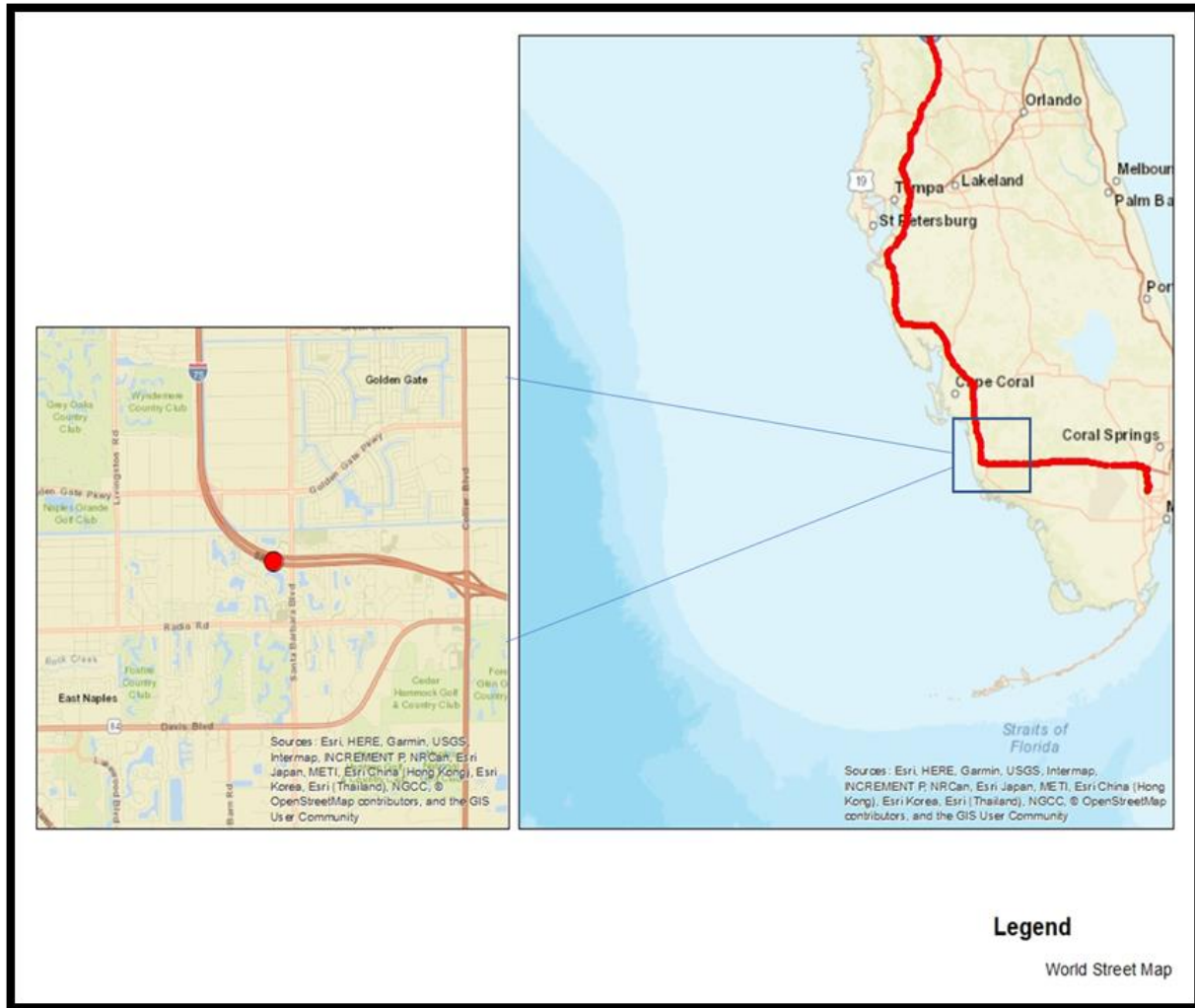
Figure 35: Incident Location-Case Study 3

The three case studies were simulated using the developed algorithm. The appropriate height restriction was identified as follows: descriptor attributes specified the height limit for each road, and a restriction attribute stored the vehicle height parameter. Following this, a script evaluator was created, so that selection of a street was prohibited when the actual vehicle height exceeded the maximum vertical clearance. By applying height restrictions, the developed model diverted trucks to avoid low vertical clearances. Additionally, a scaled factor was used as a polygon barrier to avoid school zones.

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When constraints and scaling factors were applied to the network, the resulting algorithm was used to classify two sets of alternate routes. To compare travel times and estimate benefits from the model application, two simulation scenarios were performed for each case study: a base scenario and an optimized alternative route scenario. The base scenario route was estimated without consideration of the limitations and the scaled factors, resulting in the shortest path between origin and destination. The optimized route scenario was estimated with consideration of scaled costs and limitations; this route provided an optimized diversion path for trucks. Additionally, turn-by-turn directions were generated for each route scenario.

The results of the three case studies are presented below. As shown in Figures 36 to 41, for each case study, two routes were generated with driving directions.

Case Study 1

Figure 36: Case Study 1, Base Scenario Route on I-75

Figure 37: Truck Alternative Route to Bypass the Congested Segment Case Study 1
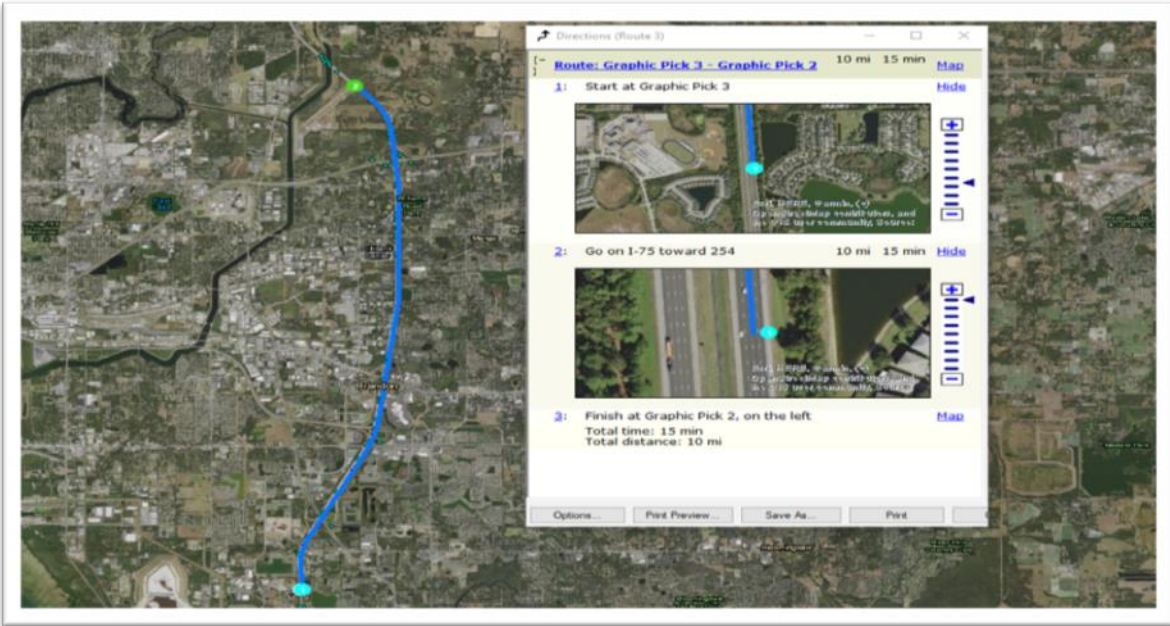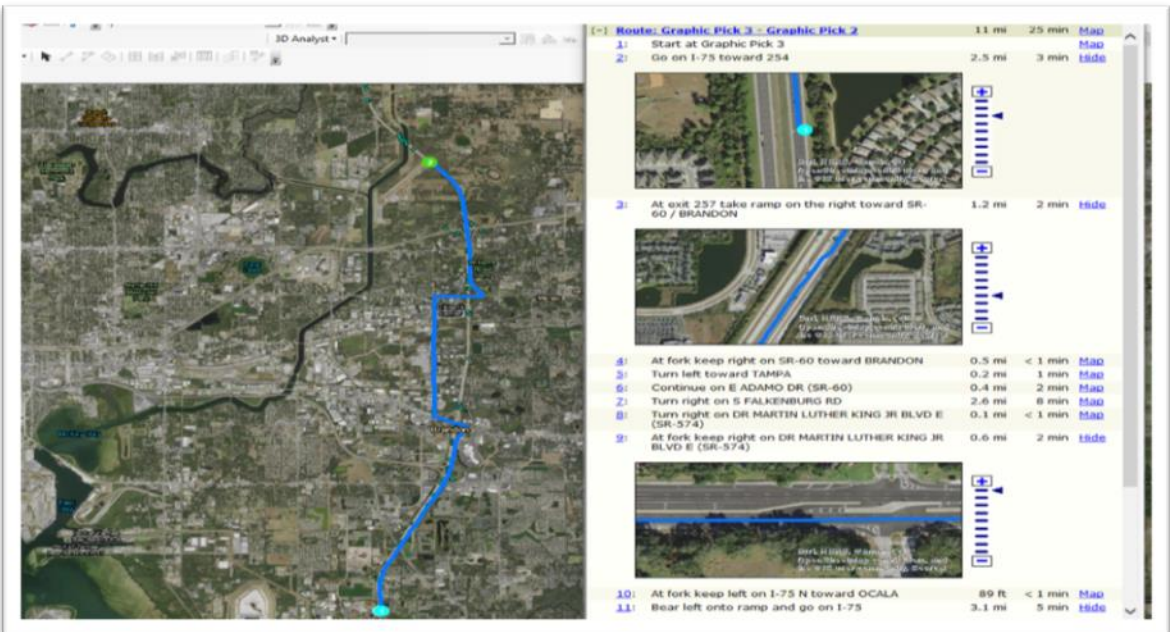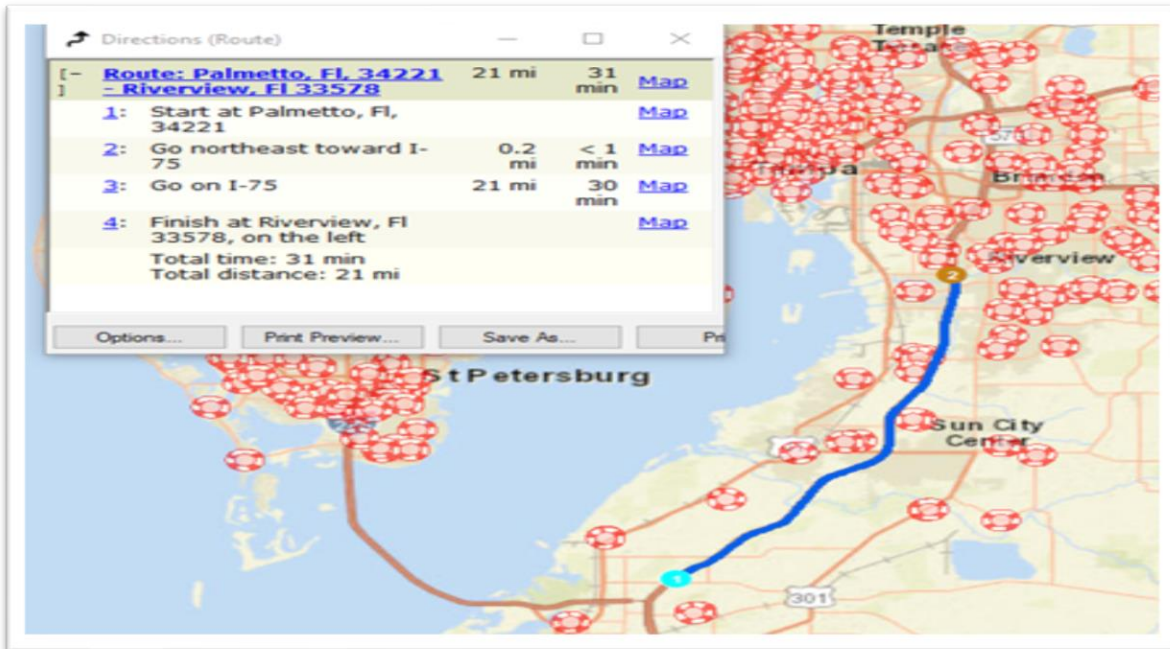
Case Study 2

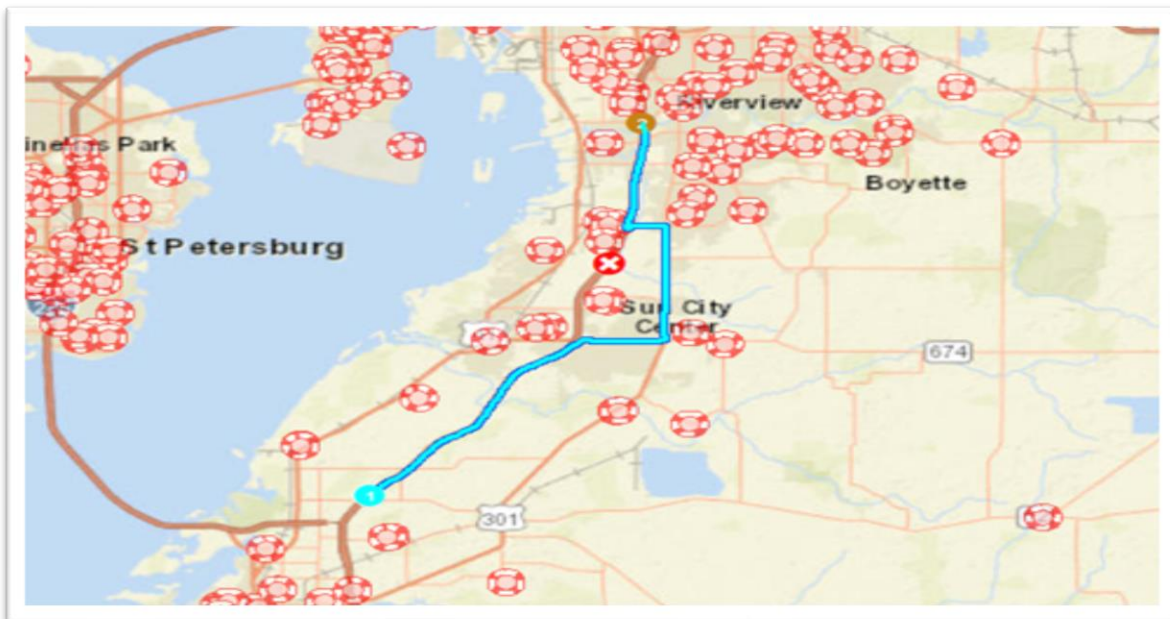Figure 38: Case Study 2, Base Scenario Route on I-75

Figure 39: Truck Alternative Route to Bypass the Congested Segment Case Study 2
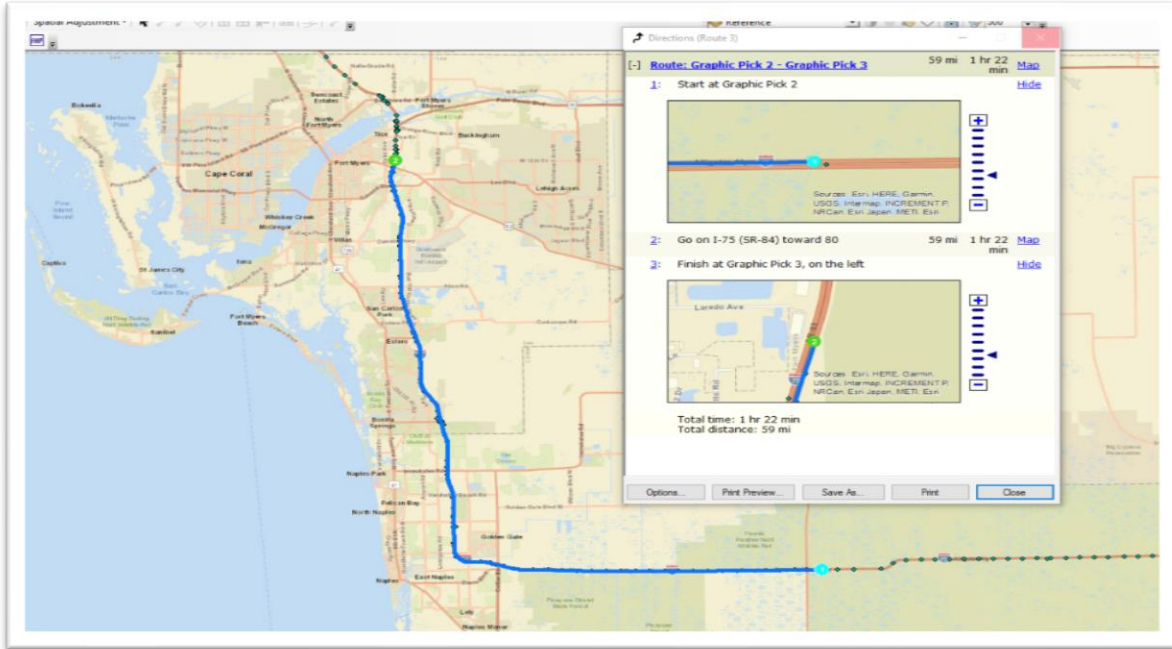
Case Study 3

Figure 40: Case Study 3, Base Scenario Route on I-75
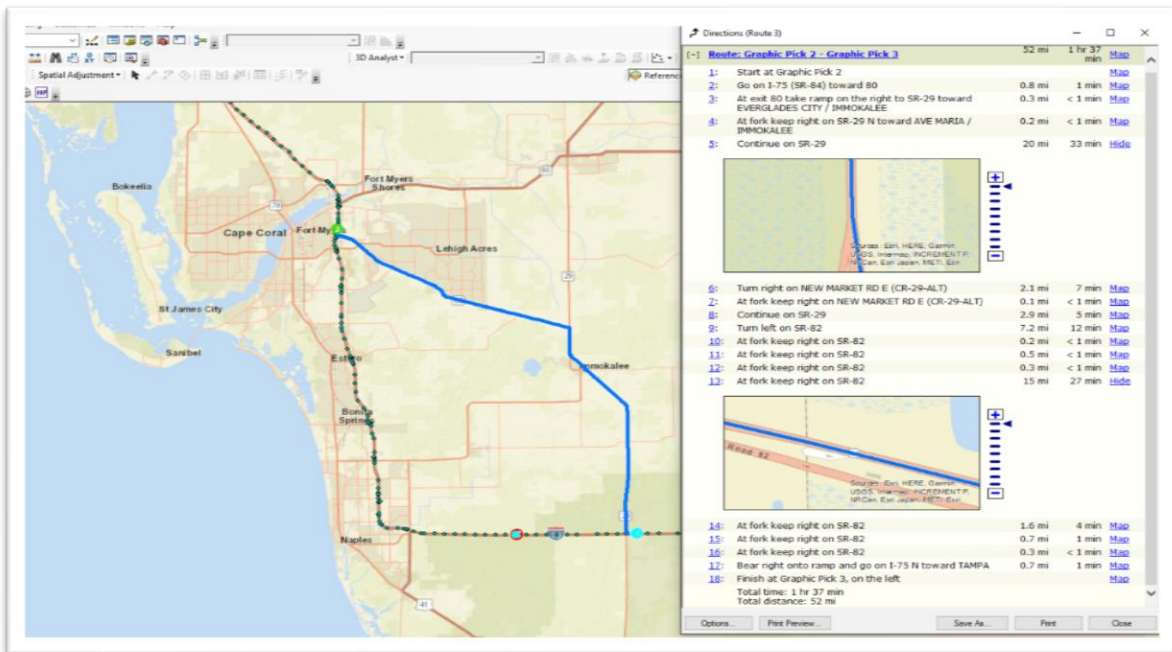
Figure 41: Truck Alternative Route to Bypass the Congested Segment Case Study 3

6.3   Benefit Estimation:

The primary purpose of incorporating diversion strategies is to alleviate congestion and the potential delay caused by an unforeseen interruption of the road. Therefore, it is essential to quantify the advantages resulting from diversion strategies as a basis for comparing operational costs. This section explains how the benefits of diversion strategies were quantified to validate the proposed diversion decision-making framework. Moreover, it demonstrates whether the diversion strategy implemented is genuinely advantageous for the overall network.

To explore how the advantages of diversion strategies can vary depending on the traffic situation and incident impacts, three case studies were chosen for incorporating diversion strategies based on this diversion-decision framework.

The model benefits were estimated with the following procedure:

1. Calculation of the travel time on the shortest route (without diversion) and the travel time on the optimized truck route (with diversion).

2. Estimation of the difference in total travel time between the two scenarios.

3. Calculation of the reduction in delays due to the implementation of the diversion operation.

4. Quantification of the reduction in fuel consumption due to the implementation of the diversion strategy, using conversion factors obtained from the National Highway Traffic Safety Administration *Commercial Medium- and Heavy-Duty Truck Fuel Efficiency Technology Study* (June 2015). The following conversion factors were used in this step:

   a. For idle, a value of 6.515 miles per gallon

b. For stop and go, a value of 3.78 miles per gallon

c. For the alternative route, a value of 5.13 miles per gallon (The World Harmonized Vehicle Cycle) (WHVC)

5. Conversion of the savings from reduced delays and fuel consumption to monetary value using the following values:

a. Truck VOT = $96/hour

b. Price of diesel = $2.55/gallon

Table 14 presents a summary of benefit estimation from the three case studies.

Table 14: A Summary of Benefit Estimation of Three Case Studies

	Case Study 1		Case Study 2		Case Study 3	
	Base Route	Alternative Route	Base Route	Alternative Route	Base Route	Alternative Route
Travel Time (minutes)	16	26	31	49	82	97
Route Length (miles)	9.7	11	21	25	59	52
Incident Duration/additional time (minutes)	52.75	10	92.4	18	65.7	15
AADT	151,500	38,000	89,000	15,400	41,500	3,100
I-75 Diverted one-way AADT Trucks	4,924		4,673		2,531	
Speed limit (mph)	70	45	70	55	70	60
Delay Reduction (minute)	42.75		74.4		50.7	
Delay Cost $	$17,315	$3,283	$28,783	$ 5,607	$11,088	$ 2,531
Delay Saving $	$ 14,033		$23,176		$ 8,556	
Total Fuel Consumption	$ 1,147	$ 485	$4,229	$ 1,973	$7,663	$ 4,401
Fuel Saving $	$ 662		$ 2,256		$ 3,263	
Total	$ 14,695		$ 25,432		$ 11,819	
Median	$ 14,695					
Total for a year per Corridor	$ 52,165,570					

6.4   Summary

This chapter presented an overview of three case studies that were used to demonstrate the application of the proposed diversion decision framework. For each case study, two scenarios were designed and simulated: a base scenario with no diversion and an optimized scenario with a diversion strategy. The resulting benefits were estimated, and the two scenarios were compared to validate the developed framework.

CHAPTER 7: CONCLUSION AND FUTURE RECOMMENDATION

7.1   Summary and Findings

In this research, the main objective was to develop a diversion decision-making framework for selecting alternative truck routes to circumvent congested highway segments. To achieve this objective, data were collected, prepared, and utilized to design and build a dynamic routable network dataset for the state of Florida. Additionally, the ArcGIS platform was utilized to generate an alternative route that accommodates truck characteristics and constraints. Predefined alternative route selection criteria were developed, taking into consideration road conditions, truck weight and height restrictions, and neighborhood impact. Truck diversion strategies are fundamental as an approach to congestion mitigation. A previous comprehensive analysis has been undertaken to understand various congestion mitigation strategies. Overall, the findings of this study shed considerable light on the impact of truck diversion on the performance of a road network. The systematic approach used in this study included alternative route selection criteria, such as truck characteristics of weight and size, to ensure that the alternative route could accommodate the diverted truck traffic

7.2   Conclusion

The purpose of this research was to develop a truck routing framework to improve the process of selecting alternative truck routes and to measure the effectiveness of rerouting approaches on travel time and to determine the resulting effects on the economy and the environment. The study shows that truck rerouting strategies for relieving traffic congestion have substantial economic and environmental impacts. The framework methodology developed in this

study can be used to measure these impacts on any segment of limited access highway with an alternative route. The use of an efficient traffic diversion strategy during incident-induced congestion provides safety and mobility benefits to highway users. The application of appropriate diversion criteria utilizing truck VOT analysis, fuel consumption aspects, safety studies, and environmental impact analysis can lead to the selection of alternative routes that reduce travel time, meet the restrictions for truck operations, and sustain an acceptable level of service on the alternative route. This framework provides a decision-support tool for decision-makers and traffic management centers that can enable them to cope more efficiently and effectively with nonrecurrent congestion on highway networks.

7.3   Model Scalability

The methodology described in this study can be applied to roadway networks in other locations in order to facilitate diversion decisions. The presented framework can also be used as a basis for making more efficient rerouting decisions while maintaining operational safety.

While this study was conducted into the Interstate 75 in Florida, the developed framework can be generalized to all of the Florida interstate corridors. By following the same procedure developed in this study, Decision makers would be able to:

- Predicting incident clearance duration at the study area of interest.
- Building a dynamic routable network
- Implementing alternative route selection criteria into the network to select the optimal route that suitable to divert truck traffic

- Quantifying the benefits resulting from diverting truck traffic to the selected alternative route

The effects of incident data for other highways would be different depending on different road characteristics, different traffic conditions; therefore, a different incident timeline could be predicted. However, the developed framework could be applied to other regions in the U.S. interstates.

7.4   Recommendation for Future Research

The rapid growth of truck traffic has raised safety and operational concerns. Truck diversion strategies have been executed throughout the U.S. to diminish the impact of incident-induced congestion. The execution of optimized truck rerouting strategies can improve the operational efficiency of freeways and enhance traffic safety in these facilities.

Although trucks need to support trade and business productivity, their movements do not have to lead to a deterioration in the quality of life or public safety. The impact of freight on the transportation system is further exacerbated by the fact that trucks occupy a greater proportion of the road capacity and thus trigger more severe problems, particularly traffic congestion, delays, secondary incidents, air pollution, fuel consumption, and pavement damage.

This study reviewed research related to traffic management and truck rerouting to identify and analyze truck traffic rerouting strategies meant to avoid nonrecurrent congestion. This section presents an overview of the limitations in the development and deployment of diversion strategies, such as a lack of comprehensive evaluation of the impact of truck drivers' behavior on route preference. These limitations suggest a direction for future research to advance the congestion management process and create more efficient traffic flows. Given the limitations noted above, together with the investment gap in infrastructure expansion in the U.S., there is a need to embrace alternative strategies to detect, manage, and efficiently mitigate traffic congestion.

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