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# Effects of Traffic Incidents on Adjacent Facilities and Alternative Re-Routing Strategies

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# EFFECTS OF TRAFFIC INCIDENTS ON ADJACENT FACILITIES AND ALTERNATIVE RE-ROUTING STRATEGIES

By

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## DEDICATION

*...to my oldest relative and namesake: my grandfather, Ali Karaer.*

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First, I wish to thank all my family members and friends for their endless support and trust, despite living on the other side of the world. They all made me who I am, and it is an honor to see their belief in me as well as their pride. Through it all, Dr. Thobias Sando, my supervisor and committee chair, has been a tremendous resource and mentor for the part of my life I spent here in the US. I thank him for his enthusiasm for the subject matter and for tireless support. A special thanks also go to one of my committee members, Dr. Murat Tiryakioglu, who set an example by his leadership, expertise, understanding, patience, and punctuality, all of which molded me into the engineer and researcher I am. I also would like to show my gratitude to another committee member, Dr. Cigdem Akan, who spent time reviewing my draft material and offering their creative ideas and guidance throughout my thesis preparation.

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## LIST OF ACRONYMS

| | |
|---|---|
| ANOVA | Analysis of Variance |
| AD | Anderson Darling |
| ATIS | Advanced Traveler Information System |
| C | Crash |
| CCD | Central Composite Design |
| COM | Component Object Model |
| DOT | Department of Transportation |
| DoR | Debris on Roadway |
| DV | Disabled Vehicle |
| FDOT | Florida Department of Transportation |
| FHWA | Federal Highway Administration |
| FTA | Federal Transit Administration |
| HCM | Highway Capacity Manual |
| HSP | Historical Speed Profile |
| ICM | Integrated Corridor Management |
| ITS | Intelligent Transportation Systems |
| LOS | Level of Service |
| PD | Progression Delay |
| PTV | Planug Transport Verkehr (German) |
| TRB | Transportation Research Board |
| U.S. | United Sates |
| USDOT | United States Department of Transportation |
| VAP | Vehicle Actuated Programing |
| VISSIM | Verkehr In Städten – SIMulationsmodell (German) |

## ABSTRACT

This study presents an analysis of detour operations as a concept of congestion management. Since a large portion of traffic delay emanates from traffic incidents, the goal of the study was to alleviate incident-induced impacts on freeways by diverting congested traffic on to adjacent roadway facilities. To balance the demand between freeway and arterial systems, optimization was required through Integrated Corridor Management (ICM). This thesis examines the justification and optimization of dynamic traffic routing strategies.

Previous studies have justified detour operations based solely on traffic simulation results. This study quantifies the impacts from freeway incidents on a parallel arterial roadway using a data-driven signal processing technique, with operating speeds adopted as a performance measure. Results show that rerouting traffic to an adjacent arterial road, due to a freeway incident, can mitigate the mobility of the corridor with a probability of up to 88% depending on the type of incident and occurrence time. Results also indicate that diverting traffic during off-peak hours, especially for minor incidents, provides minimal mobility benefits.

A secondary focus of this study explored the optimum dynamic traffic diversion, to an adjacent arterial roadway, from incident-induced freeway congestion to better utilize the freeway's available corridor capacity. VISSIM, a microsimulation tool, was employed to simulate a freeway incident and measure the performance of detour operations. A $2^3$ full factorial central composite design was used to establish a relationship between the performance of the detour operation and three control factors: incident duration, diversion rate, and demand level. The resulting regression equation predicts the corridor delay with over 83% accuracy. The findings of this study can potentially serve as a building block in the understanding and development of future ICM systems and incident management plans.

Keywords: Detour, Integrated Corridor Management, Signal Processing, Incident Modeling, VISSIM, Dynamic Assignment, Respond Surface, Central Composite Design

# CHAPTER 1: INTRODUCTION

## Background

Traffic delays can significantly undermine the reliability and mobility of the United States (U.S.) highway system. Non-recurrent traffic congestion, due to unpredicted events such as adverse weather conditions or accidents, cause traffic delays on critical transportation corridors. To address the congestion issue, the U.S .Department of Transportation (USDOT) adopted a research initiative, the Integrated Corridor Management (ICM) Initiative, to more effectively move people and goods through metropolitan corridors by using Intelligent Transportation Systems (ITS) with innovative and multi-modal strategies. With ICM, the management and operation of the corridor is treated as a system rather than as an independent transportation facility (e.g. freeway, express lane, arterial road, bus route) (Federal Transit Administration (FTA), 2016).

Freeways generally are limited access facilities with a higher capacity and posted speed compared to arterial roadways. Consequently, an incident may result in a substantial reduction in the Level of Service (LOS) of the freeway. The degree of LOS reduction depends on the current demand and the stochastic nature of the incident such as lane blockage, tow adequacy or dwell time. Nevertheless, there is a tendency among drivers to shift to the adjacent arterial roadways to avoid the stop-and-go driving conditions of congested freeways. Arterial network systems also carry a significant amount of traffic and often operate over capacity, especially during peak hours. Moreover, diverting traffic from a congested freeway to the arterial roadway network may further increase travel delays on both facilities. This thesis focuses on dynamic detour operations and quantifies the impacts of incidents given various demand levels.

## Study Objectives

The analysis of detour operations often involves investigating historical traffic data, archived traffic incidents, and traffic simulation studies. Therefore, researchers have become

increasingly more interested in dynamic traffic routing and ICM that results in the potential better use of available corridor capacity. This study focused on two primary goals:

1) To quantify the impacts of recorded freeway incidents on adjacent facilities with a comparison of the incident-induced operations and prevailing conditions.
2) To optimize the diversion operations by defining the effects of variable diversion rates on different traffic demand levels using a well-calibrated simulation model and an experimental central composite design.

### Potential Study Benefits

According to a guide on detour operations published by the Federal Highway Administration (FHWA), the *Alternate Route Handbook*, incident duration and roadway blockage, observed traffic conditions, the time of the day, the day of the week, as well as background traffic of the alternate route are the critical factors for effective traffic diversion (Federal Highway Administration (FHWA), 2006). Typically, most state agencies only use incident duration and lane blockage to decide on whether to implement a detour operation (Y. Liu, Kim, & Chang, 2013). At present, no guide for detour operations involving the highway system in Jacksonville, Florida has been developed. This thesis presents a detour operation analysis, considering all critical factors, for the northbound of I-95 and US 1 (Philips Highway) corridors in Jacksonville, Florida that may assist in the future development of detour operations guidelines.

### Thesis organization

This thesis is organized into four chapters. Chapter One provides the general overview of the research problem, objectives of the research, and potential contributions of the study in the academic and industrial aspects. The next two chapters of the thesis include two research papers submitted to transportation journals for publication consideration. Hence, Chapters Two

and Three are stand-alone papers that address the primary and secondary objectives of the thesis, respectfully. Chapter Four discusses the conclusion of each study goal.

# CHAPTER 2: PAPER 1

## Quantifying the Impacts of Freeway Incidents on Adjacent Facilities: Jacksonville Case Study

Paper 1 was submitted to the *Journal of Transportation Engineering Part A: Systems* for publication consideration on March 13, 2018.

### Introduction

Traffic congestion is a growing issue in many metropolitan areas. While the total delay in the United States (U.S.) was 6.9 billion hours in 2014, it is expected to grow to 8.3 billion hours by 2020 (Schrank., Eisele., Lomax., & Bak., 2015). A considerable portion of the delay emanates from incidents, which are estimated to account for about 25% of total congestion in the U.S. (U.S. DOT, 2017b). When incidents occur on freeways, it is common for drivers to divert to adjacent arterial roadways to avoid bottlenecks and stop-and-go conditions, and then return to the freeway downstream of the incident. With the deployment of digital message signs that alert drivers of traffic conditions ahead, radio feeds that broadcast incident locations, and smartphone applications that provide real-time alerts to drivers based on a selected route, drivers are better able to choose the best route. Although commuters may prefer using freeways rather than surface streets, incident related closures of a lane(s) and the reduction in level of service of the freeway may divert some drivers to the adjacent arterial roadways to avoid the incident and resulting traffic congestion.

Different transportation facilities such as freeways and arterial roadways have different operational characteristics. Freeways are typically non-signalized limited access facilities with interchanges at cross streets. Arterial corridors are not limited access facilities and generally contain multiple intersections, many of which may be signalized. Therefore, individual network operations along major arterial corridors need to be coordinated. Integrated Corridor

Management (ICM) refers the coordination between discrete operational systems of adjacent roadway facilities (U.S. DOT, 2017a). The goal of ICM systems is the effective usage of available capacity on the surrounding network. Today, many urban freeways and arterial roads employ detection devices that collect real-time traffic data. By comparing the historical traffic data of adjacent facilities during normal traffic conditions with the data gathered during an incident, the performance of ICM and the effects other factors have on the system, such as time of day, day of the week, and severity of the incident, can be estimated. Therefore, there is a need to establish modeling approaches to evaluate the impacts of freeway incidents on adjacent corridor traffic operations.

**Background**

Several studies have quantified the effects of incidents on different aspects such as travel time, capacity reduction, and secondary crashes. Tavassoli Hojati et al. (2016), for example, focused on the effects of traffic incidents on travel time reliability, a central performance measure of traffic operations. The study estimated the impacts of freeway incidents on travel time using the Tobit Model. Findings concluded that incident duration and lane blockage are two key factors that affect freeway performance. However, the study was not corridor-wide and did not analyze the effects of freeway incidents on adjacent roadway facilities.

Another study by Smith et al. (2003) focused on the reduction in freeway capacity due to incidents. The study found that the impact of incidents on capacity is related to the amount of lane blockage, i.e., 63% capacity reduction for one of three lanes blocked, and 77% reduction for two of three lanes blocked. Similar to Tavassoli Hojati et al. (2016), the study was also limited in scale and not corridor-wide. The Highway Capacity Manuel (HCM) also addresses the capacity issue in Chapter 11, “Freeway Reliability Analysis” (TRB, 2016a). Exhibit 11-23

in the HCM illustrates capacity reduction due to incidents based on the number of lanes and nature of the incident (TRB, 2016a).

Chimba and Kutela (2014) also studied the effects of freeway incidents with a focus on secondary crashes – generally considered to be caused by primary incidents. Findings indicate that most secondary crashes emerge within 20 min after the primary incident occurs, and typically at a distance of 0.5 miles upstream. In addition, the posted speed limit, congested segments, percentage of heavy vehicles, and peak hour volume increase the likelihood of secondary crash occurrence. Similar to the aforementioned research, the study was not corridor-wide in scale and did not consider the impacts of freeway incidents on the adjacent arterial network.

Existing literature on incident-induced traffic rerouting focused on the decision mechanism of diversion by investigating driver response to diversion strategies. The effects of rerouting were measured using simulation-based incident modeling with impacts estimated via traffic simulations.

*Decision Mechanism of Traffic Rerouting*

Earlier studies (Al-Deek & Kanafani, 1993; Kanafani & Al-Deek, 1991) focused on Advanced Traveler Information Systems (ATIS) during off-peak travel conditions, and the idealized assumption that every driver had absolute information about traffic conditions ahead. However, in reality, only a small fraction of travelers are typically aware of an incident and anticipated impacts (Sisiopiku et al., 2007).

Several studies employed surveys to examine the effects of digital message signs. Peeta et al. (2000), for instance, found that the more detailed information about the incident, such as location, delay estimation, best detour alternative etc., the more willing drivers were to divert their route. In contrast, Xuan and Kanafani (2014), concluded that visible message signs with incident information had no significant effect on convincing drivers to reroute. However, the

study also found, based on empirical data, that apparent congestion was an important factor in influencing a drivers' decision to change their route.

*Diversion Strategies*

All previous studies on incident-related diversion strategies used traffic simulation, and none used a data-driven approach. Various microscopic simulation models such as CORSIM, VISSIM, AIMSUN, Paramics, SimTraffic, and VISTA have been used to analyze the impacts of diversion strategies on adjacent facilities resulting from an incident. For instance, Zhou (2008) employed CORSIM to simulate a diversion strategy from the freeway to the adjacent arterial facility due to an incident, and used SimTraffic to re-coordinate signal timings at intersections along the arterial roadway to account for the diverted traffic volume. By comparing the 25% diversion rate with the 5% diversion rate, the study found that delay on the freeway reduced by 76.8%, while delay along the arterial roadway increased by 48%. However, the results showed that with the 25% diversion rate, total delay of the network was 21% lower than with the traffic conditions resulting from the 5% diversion rate.

Koorey et al. (2015) used PARAMICS with special signal coordination to model an incident diversion strategy on a roadway network in Auckland, New Zealand. They found that an incident on the motorway increased the travel time on both the motorway and the diversion roadway by 35% and 81%, relatively. In another study, VISSIM with its COM interface was adopted to divert the incident-induced traffic from the freeway to the adjacent arterial facility in Seattle, WA (X. Liu, Zhang, Kwan, Wang, & Kemper, 2013). To determine the optimum diversion rate, the study created weighted delay parameters by treating the delay and throughput values of the freeway and surrounding arterial network as a performance measure. The study found the 4% diversion rate to be the optimum portion of diversion delay. Compared to free flow conditions, the freeway and the arterial roadway had a 123 s and 56 s delay, respectively.

## Study Objectives

The objectives of this study were twofold. First, the study used a data-driven approach to analyze the effects of freeway incidents on parallel arterial roadways. Thus, the study aimed to develop a new methodology that will help in quantifying the effect of incidents. Since the influences of incidents differ in spatial and temporal dimensions, the chosen method had to be time-dependent and responsive to the deterioration due to the incident. The second objective of this study was to determine the relationship between performance deterioration of the freeway and the parallel arterial roadway due to incidents by considering the type of incident and occurrence time. The findings of this study can potentially serve as a building block in the understanding and development of future ICM systems and incident management efforts.

## Methodology

### *Study Area*

The northbound I-95 corridor, located in Jacksonville, Florida, was selected as the freeway facility on which to observe incident occurrence. Philips Highway (US 1), an arterial roadway parallel to the I-95 corridor, was identified as the adjacent facility to which traffic would be diverted when unexpected capacity reduction along the I-95 corridor occurred. The I-95 study section has a posted speed limit of 65 mph. Compared to the freeway, US 1 has lower speed limit (45 mph) based on the roadway characteristics and also serves as a memorial highway (Kocatepe, Ozguven, Vanli, & Moses, 2017). Illustrated in Figure 2-1(a), the study area consists of a 19.8 km (12.3 mi) segment along I-95, and a 19.2 km (11.9 mi) segment along US 1, parallel to I-95. Both facilities were divided into six segments based on the location of traffic monitoring devices and roadway connections between the two facilities. Dividing the corridor into six parts helped to ease data collection efforts and observation processes, as well as determining the effects of incidents. Specifically, in the presence of an incident on any freeway segment, motorists can shift to the parallel arterial road (US 1) at the beginning of the

segment and return to the freeway at the end of the segment via connector roadways. The effects of the incident along each corridor can then be estimated using historical data from the related segment.

*Speed data*

Speed data were mined from BlueTOAD software produced by TraffiCast International, Inc. and comprised of many devices that can detect vehicles that have bluetooth devices. One of the paired devices detects ‘vehicle 1’ and records the time (*T1*). When a second paired device detects ‘vehicle 1’, the time is again recorded (*T2*). Equation 2-1 is used to calculate travel time (*TT*), and Equation 2-2 is used to compute vehicle speed (*V*) by using the known distance ($L$) between the devices.

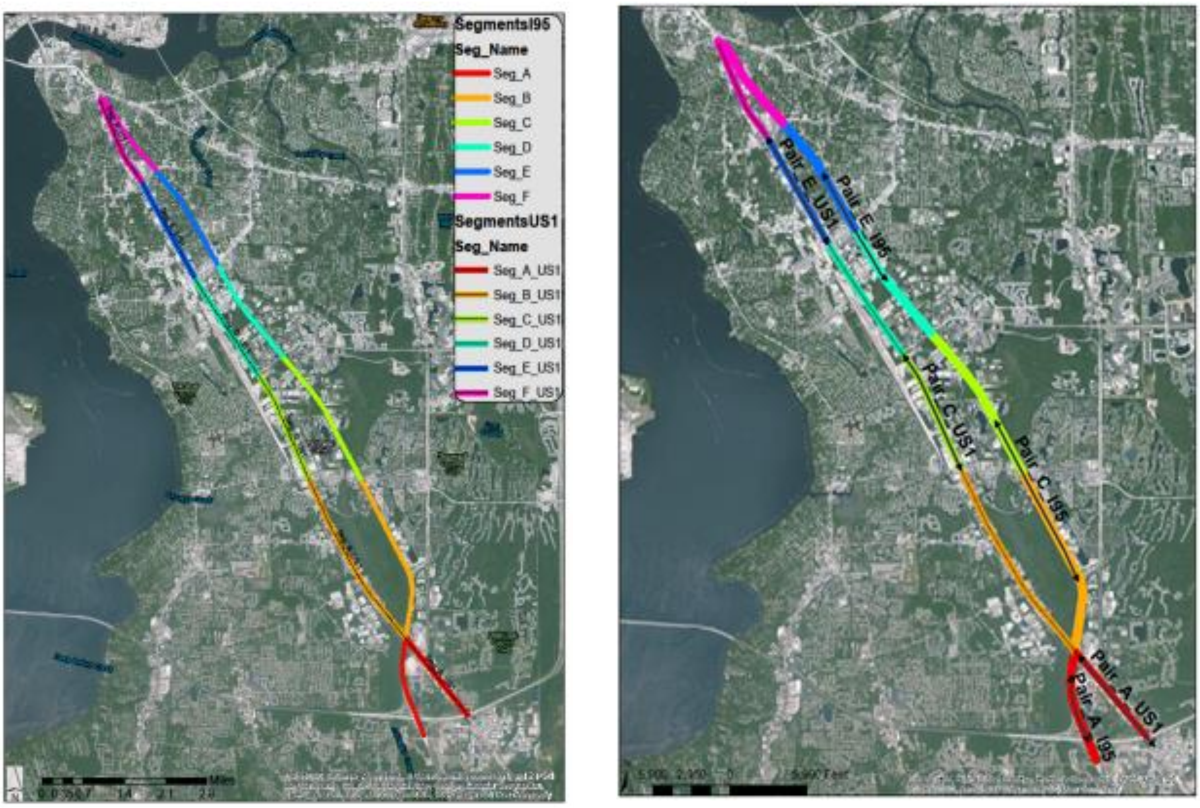
$$T2 - T1 = TT \qquad (2\text{-}1)$$

$$L/TT = V \qquad (2\text{-}2)$$

Since not every vehicle has a bluetooth device, the software does not provide count information. However, the travel time and the speed are calculated for every detected vehicle in a predefined time interval. Averages of these measures were calculated in 15 min intervals for the years of 2015 and 2016. This software and the paired devices provide time, day, date, and averages of travel time and speed for this study.

Each segment of I-95 and US 1 has its own pair. Although this software includes a number of options to choose pairs, the consecutive devices are chosen to dedicate the pair to the segment in this study. While US 1 paired devices are located to cover all the US 1 segments, I-95 paired devices are not, which is why I-95 paired devices scan at least upstream of the segments. A similar approach is implied in other studies (e.g. Christoforou et al. 2012). Figure 2-1(b) indicates the pairs of Segments A, C, and E along each study facility.

Since the paired devices must be turned off for maintenance, some speed data was missing during the study period (2015 and 2016). However, to compare the effects of incidents on I-95 and US 1, data had to be available for both of the parallel segments. Therefore, data with missing time intervals were eliminated from the data set to obtain matched speed data for each segment.




(a) (b)

**Figure 0-1:** Study area
(a) Segments (b) Bluetooth pairs

*Incident Data*

Incident data were extracted from the SUNGUIDE software of Florida Department of Transportation (FDOT) for the years of 2015 and 2016. The data include incident date, time, and location, as well as the type and severity of the incident. After filtering by study area, a total of 2,607 recorded incidents were used for analysis.

Incidents were categorized by type, occurring time, and day-of-the-week to analyze the effects of incident under different conditions. Traffic behavior varies during different conditions, such as day-of-the-week or temporal effects such as weather (Chung, 2012; Hojati et al., 2016; Park, Messer, & Urbanik, 1998). This paper focuses on only weekday incidents. The type of incidents considered for analysis was comprised of crashes (C), disabled vehicles (DV), and debris on the roadway (DoR). Although the time of occurrence can be categorized as AM Peak (06:00-10:00), Midday (10:00 – 15:30), PM Peak (15:30 – 18:30), and Night (18:30 – 06:00), they were classified as 'peak' for AM and PM Peak hours and 'off-Peak' for Midday and Night hours in this study. Detailed categorization with several variables such as lane blockage or seasons of the year is presented as a story map in (<https://arcg.is/1uvC4G>).

*Quantification of the Incident Impacts*

This part of the study presents a methodology for quantifying the effects of incidents inspired by signal processing, a branch of electrical engineering that models and analyzes data representations of physical events (IEEE Signal Procesing Society, 2017).

It should be noted that congestion delay consists of recurrent and non-recurrent delay. Recurrent delay is expected by most drivers as it appears with similar patterns depending on the day-of-the week. Hence, it can be estimated with historical data. Non-recurrent delay, on the other hand, stems from abrupt events such as incidents. Since it has distinctive effects, non-recurrent delay can be identified through the comparison of actual and historical speed profiles.

To obtain the historical speed profiles (HSPs), speed data from each parallel segment were separated by day-of-the week. Then, for each week day (Monday to Friday), averages of speeds in fifteen-minute intervals during the day were calculated for the years 2015 and 2016. For each segment, five different daily speed profiles were created for days of the week consisting 96 data points (15 minutes during a day), as well as the 95% confidence interval for

each data point. Figure 2-2 illustrates the HSP of Segment D for Wednesdays. Each HSP represents prevailing conditions and data points, with expected speeds indexed as $S_{exp}$.

Incident data and speed data were then collaborated. R studio was employed with a customized code that compares the actual speed at the time of the incident with the $S_{exp}$ value of its own segment, day, and time. If the speed is outside of the 95% interval in that particular time interval, the speeds of following time intervals are recorded until it goes back into the 95% confident interval of the HSP. Meanwhile, speeds are also recorded during incident impact duration, defined as the time when the incident occurrence began until the traffic flow characteristics return to normal conditions as demonstrated by Haule et al. (2018). These recorded speeds represent incident conditions and are denoted by $S_i$. Examples of $S_i$ and $S_{exp}$ values are illustrated in Figures 2-3 and 2-4 for I-95 and US 1, respectively.

The next step required creating the signals for I-95 and US 1. In this regard, Normalized speeds ($S_N$) were computed from the $S_i$ and $S_{exp}$ values for each incident to represent the signals on I-95 and US 1 (Equation 2-3). It can be interpreted as a unitless deterioration rate due to the incident.

$$\frac{S_i}{S_{exp}} = S_N \quad \text{, where:} \tag{2-3}$$

$S_N$: *Normalized speed*

$S_i$: *Speed during incident*

$S_{exp}$: *Expected speed during incident*

When the signals are plotted on a timeline that covers 2015 and 2016, they go lower than one with the presence of an incident, and for non-incident times, signals are accepted as one. The area due to reduction in signals on I-95 and US 1 were then calculated and defined as propagation delay (PD) to use as a performance measure of the effects of incidents. Figure 2-5

demonstrates the determination of the PD values. It should be noted that PD refers to the area calculated by multiplying the deterioration rate and incident impact duration to compare the effect of an incident on the adjacent facilities.

Finally, the relationship between PD values on I-95 and US 1 was examined using an impact ratio. This ratio was acquired by dividing the I-95 PD values by the US 1 PD values, as shown in Equation 2-4. If the resulting impact factor is greater than one, the incident caused a greater impact on the speed profile of I-95 compared to US 1. If it is lower than one, the incident affected operational characteristics of US 1 more than I-95. This is most likely due to the high diversion rate. The statistical analysis process is outlined in the flow chart shown in Figure 2-6.

$$\frac{PD_{I-95}}{PD_{US-1}} = F_{II} \qquad \text{2-4}$$

$F_{II}$: $Incident\ impact\ factor.$

$PD_{I-95}$: $The\ area\ of\ I - 95\ normalized\ speed\ reduction\ due\ to\ the\ incident.$

$PD_{US-1}$: $The\ area\ of\ US\ 1\ normalized\ speed\ reduction\ due\ to\ the\ incident.$

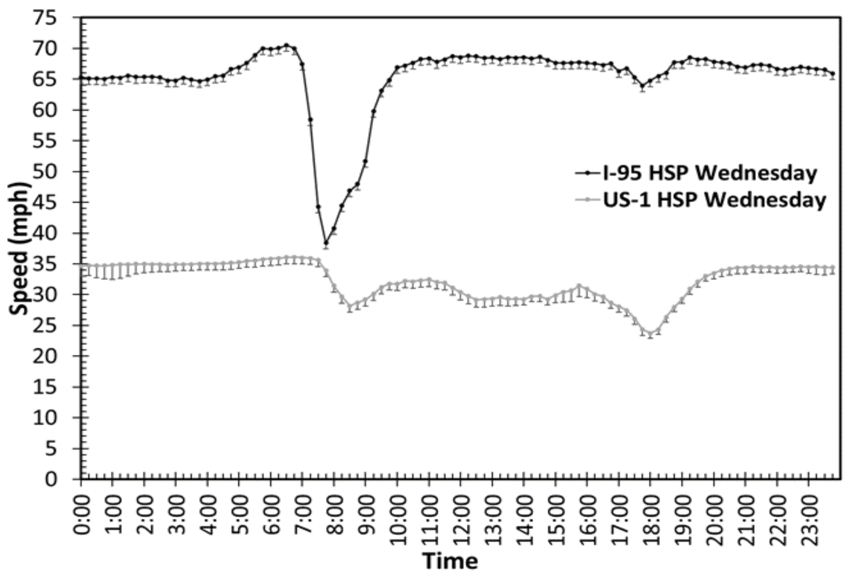



**Figure 2-2:** Historical speed profile for Segment D on Wednesdays

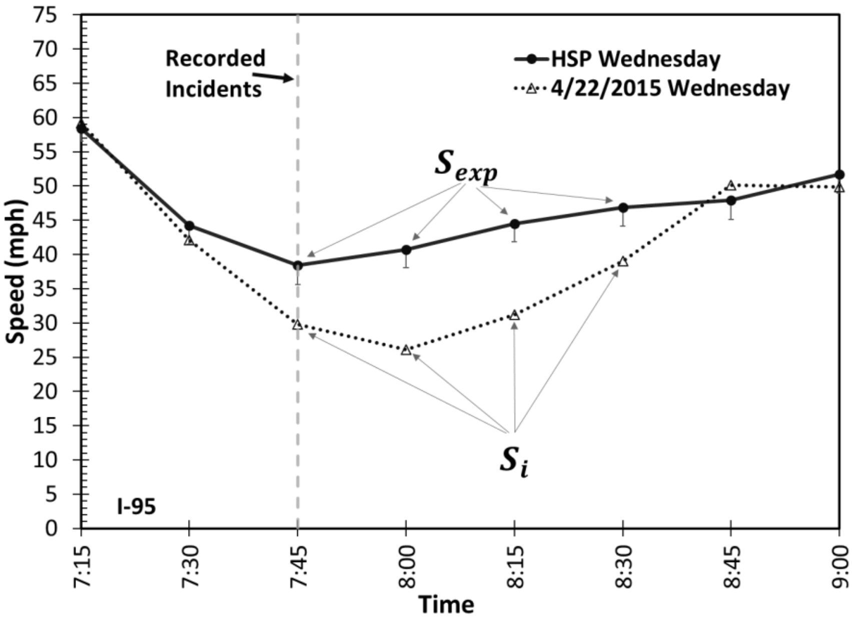



**Figure 2-3:** Determination $S_i$ values for I-95

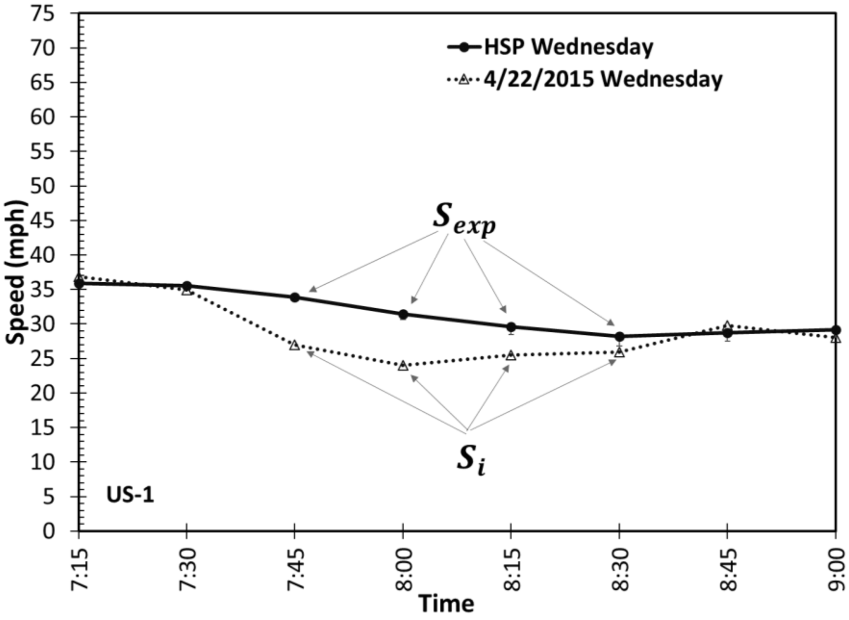



**Figure 0-4:** Determination Si values for US 1

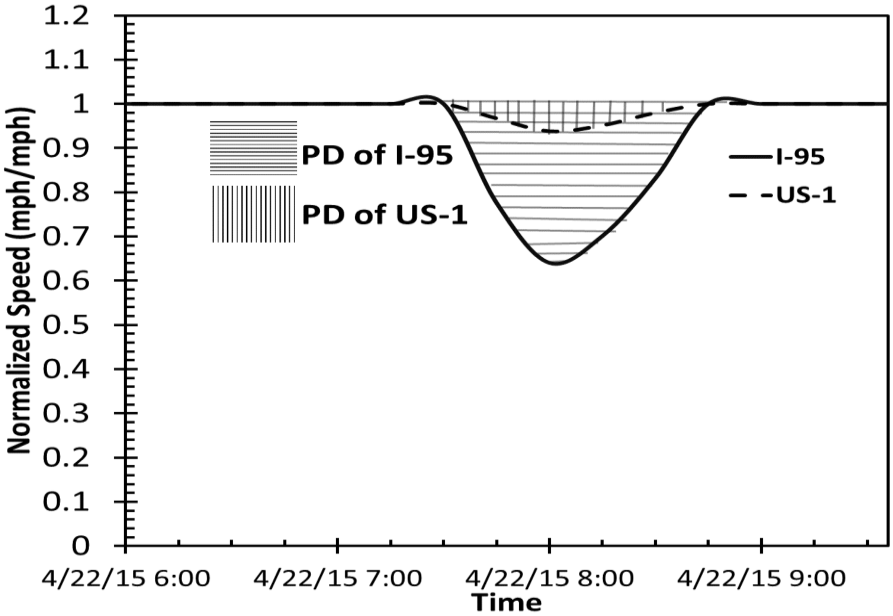



**Figure 0-5:** Progression delays

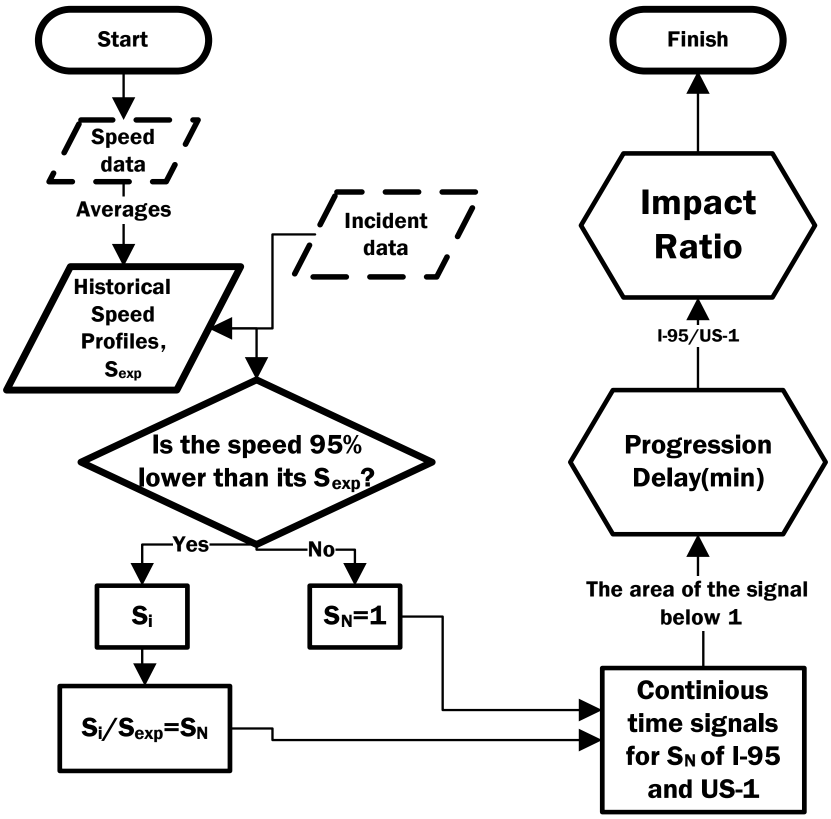



**Figure 0-6:** Flow chart of analysis procedure

**Results**

This section presents the findings from the incident impact factor analysis. Of the 2,607 incidents recorded during the study period, it was initially anticipated that all of the incidents would correspond with the speed data collected. However, after further inspection, only 73 incidents had corresponding speed data for both I-95 and US 1 to compare the effects. Therefore, the sample size used in the analyses consisted of 73 incidents (Table 2-1). Impact factors were computed using the method explained in the previous section, and then categorized into incident types and occurrence time discussed in *Incident Data* section. The first step of the analysis involved finding the distribution that the impact factors follow by using the Anderson-Darling (AD) goodness-of-fit test statistic listed in Equation 2-5.

$$A^2 = -n - \frac{1}{n}\sum_{i=1}^{n}[(2i-1)(lnP_i + \ln(1 - P_{n+1-i})] \quad (2\text{-}5)$$

The AD test was selected due to its sensitivity to the tails of the distribution. The lower the value of $A^2$, the higher the confidence that impact factors follow the underlying distribution (Tiryakioğlu & Hudak, 2007). Since the sum of AD test scores for lognormal distribution is lower than the sum of AD test scores for normal distribution (Table 2-1), it can be assumed that the impact factors for different incident categories follow the lognormal distribution. Lognormal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. Equation 2-6 shows the lognormal function where $0 < x < \infty$.

$$f(x) = \frac{1}{xw\sqrt{2\pi}} exp\left[-\frac{(\ln(x) - \phi)^2}{2w^2}\right] \quad (2\text{-}6)$$

If $W$ has a normal distribution with the mean of $\phi$ and the variance of $w^2$; then $x = \exp(W)$ is a lognormal random variable with a probability density function. Also, $\phi$ and $w$ refer to respective location and scale parameters of the function (Table 2-1).

**Table 0-1**: Sample size, AD test scores, and descriptive statistic

| | Peak | | | | | off-Peak | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Size | $A^2$ norm | $A^2$ log norm | Loc. ($\phi$) | Scale (w) | Size | $A^2$ norm | $A^2$ log norm | Loc. ($\phi$) | Scale (w) |
| C | 34 | 3.07 | 0.25 | 0.86 | 0.71 | 9 | 0.27 | 0.32 | -0.05 | 0.98 |
| DV | 15 | 0.60 | 0.57 | 0.54 | 0.70 | 8 | 1.25 | 0.51 | -0.58 | 0.59 |
| DoR | 3 | 0.39 | 0.43 | -0.10 | 0.61 | 4 | 0.46 | 1.38 | -0.14 | 1.02 |

From this point to forward, the discussion will be on the results from the lognormal distribution. Figure 2-7 shows the distribution of incident types for peak and off-peak times where the $F_{II}$ is equal to one. This value is used to distinguish the effects of incidents, and a value greater than one indicates greater deterioration on I-95 operational characteristics. Table 2-2 indicates the 95% confident levels of $F_{II}$ values and the maximum likelihood points (Mode) assigned to the peak points shown in Figure 2-7. Table 2-2 also shows that US 1 is affected by freeway incidents as much as I-95, i.e. P($F_{II} \leq 1$), for different types of incidents.

When compared to I-95, during off-peak hours, all three incident types resulted in greater capacity deterioration on US 1 (Figure 2-7). Yet, the disabled vehicle (DV) type had the highest probability (83.49%) to cause a greater deterioration in capacity on US-1 than on I-95 (Table 2-2). It is possible that the freeway recovers the effects of incidents faster without the recurrent congestion, while the unexpected diversions cause the arterial roadway (US 1) to easily exceed capacity.

During peak hours, the deterioration in capacity on I-95 due to the effects of vehicle-induced incident types C and DV is significantly adverse compared to DoR type incidents. Additionally, motorists diverting onto US-1 to avoid a crash or disabled vehicle on I-95 during peak hours, have a probability of 88.48% and 78.26%, respectively, of experiencing better driving conditions. However, driving conditions are not significantly affected by time-of-the-day for DoR type incidents. This suggests that incident types that require additional response

vehicles, such as first responders or towing vehicles, increase capacity deterioration on I-95, compared to DoR type incidents.

**Table 0-2**: Confidence interval limits of $F_{II}$ with maximum likelihood value and probability of adverse deterioration on US 1.

| | Peak | | | | off-Peak | | | |
|---|---|---|---|---|---|---|---|---|
| | Lower 95% | F(1) | Mode | Upper 95% | Lower 95% | F(1) | Mode | Upper 95% |
| C | 0.581 | 11.52% | 1.381 | 9.556 | 0.141 | 51.92% | 0.370 | 6.470 |
| DV | 0.439 | 21.84% | 1.082 | 6.741 | 0.177 | 83.69% | 0.388 | 1.777 |
| DoR | 0.271 | 56.61% | 0.632 | 6.329 | 0.119 | 55.63% | 0.304 | 3.011 |

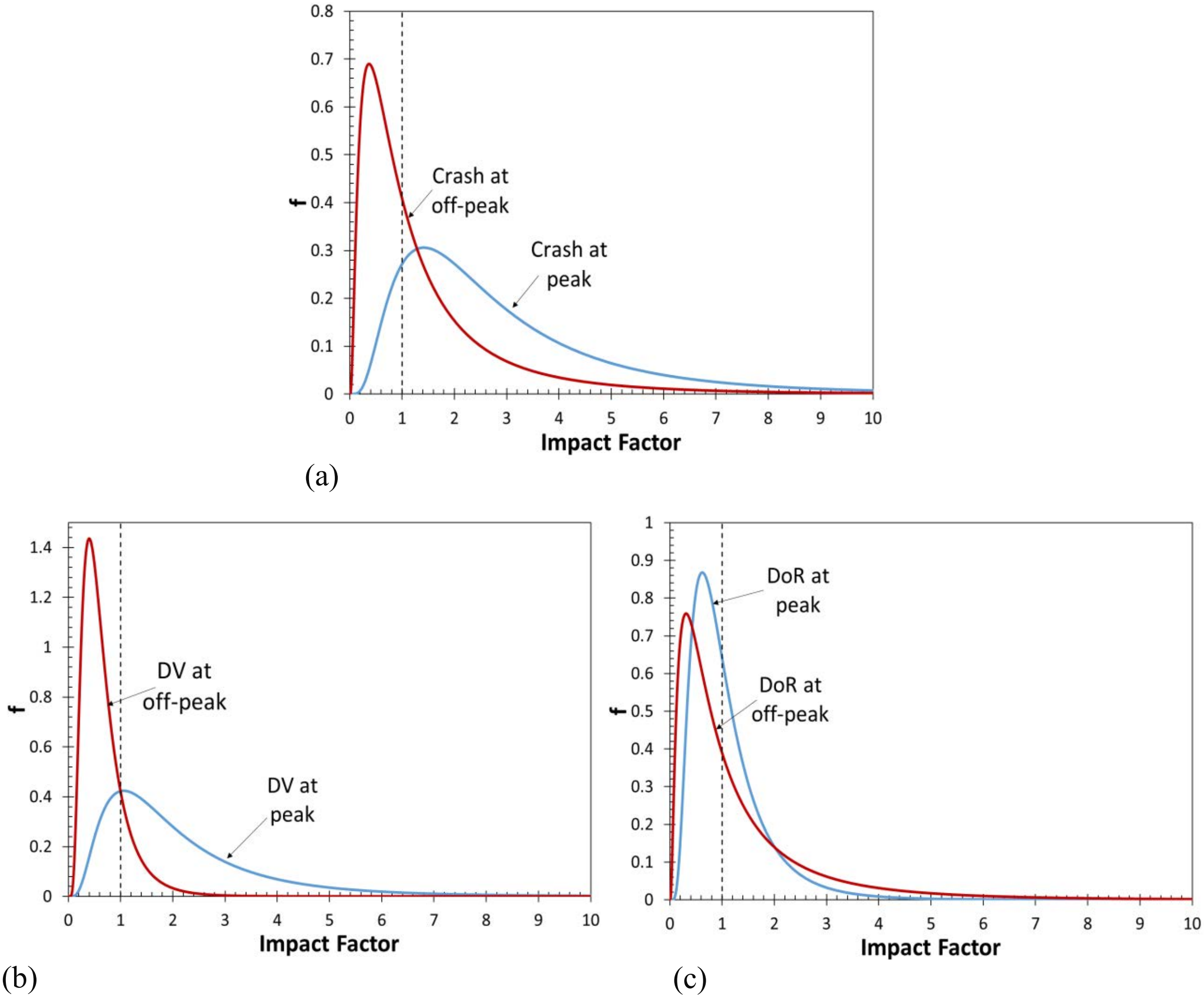



**Figure 0-7:** Probability density functions of incident types
(a) Crash (b) Disabled Vehicle, and (c) Debris on Roadway

As shown in Figure 2-7, vehicle-induced incident types C and DV have similar distribution shapes. The maximum likelihood points for peak and off-peak hours are also closely aligned (see Table 2-2). Therefore, it can be concluded that during peak hours, the effects of a C or DV incident can be 9.56 times higher on I-95 compared to US 1.

**Conclusions and Recommendations**

The goal of this study was to determine the effects of freeway incidents on a transportation corridor consisting of a freeway and adjacent arterial roadway. A portion of I-95 in Jacksonville, Florida was selected as the study freeway. US 1, a parallel facility to I-95, was identified as the adjacent arterial roadway for the corridor. To determine the effects of traffic incidents along the corridor, a comprehensive evaluation was conducted using a new methodology based on signal processing. Speed data were used to calculate speed averages for fifteen-minute intervals, and prevailing (no-incident) and incident circumstances were compared. Speed profiles for I-95 and US 1 were considered as related signals, and examined using the signal processing approach to compare the effects of incidents with variable factors such as type of incident, time-of-the-day, and day-of-the-week. Results indicate that despite the disadvantages of adjacent arterial roadways, such as signalized intersections and lower posted speeds, drivers tend to use these roadways to avoid congestion in on the freeway when an incident occurs. This situation decreases travel speeds on the adjacent arterial highways. Findings from this study indicate that during peak hours, recovery from the effects of vehicle-induced incidents takes longer on the freeway (I-95, for this case). This finding explains why drivers rerouting from the freeway to the arterial roadway (US 1, in this case) due to crash or disabled vehicle type incident have a probability of 88.48% and 78.26%, respectively, of experiencing better driving conditions. Additionally, results indicate a 48% probability of lower capacity deterioration on the arterial roadway during off-peak hours.

The effects of recurrent congestion was eliminated from the analyses by calculating the expected speeds for each 15-minute interval in each day of the week on each segment in the corridor. A total of 5,760 expected speeds were calculated from the observed speeds during for the 2015-2016 study period. Incident detection was based on the distribution of the observed speeds on that particular 15 minute interval. However, it was observed that expected speeds varied in some 15-minute intervals; thus, not all of 5,760 expected speeds came from a normal distribution. This variation meant that some incidents had been missed when compiling the dataset used for analyses; thus, resulting in a smaller sample size. Further research efforts may explore the issue of the elimination of recurrent congestion data by considering bimodal or multimodal speed distributions.

Future research may consider expanding this research to include volume data in addition to the speed profiles used in this study. Since this study focused on the northbound travel direction, additional research may consider analyzing both travel directions (southbound and northbound) along the study corridor. Other factors such as weather and work zones should also be considered for future research. Despite the limitations of this study, findings can be used by traffic agencies and incident management centers to better understand and develop future ICM systems and incident management plans.

## CHAPTER 3: PAPER 2

### Alleviation of Non-Recurrent Freeway Congestion with Detour Operations: Jacksonville Case Study

Paper 2 was submitted to the *Transportation Research Part C: Emerging Technologies* for publication consideration on April 13, 2018.

### Introduction

Traffic delay is a troubling and inefficient aspect of transportation facilities. In 2014, total traffic delay in the United States (U.S.) was 6.9 billion hours, and expected to grow to 8.3 billion hours by 2020 (Schrank. et al., 2015). Traffic delay stems from recurrent and non-recurrent congestion. While recurrent congestion repeatedly occurs with similar impacts, non-recurrent congestion originates from an unexpected event such as an incident or adverse weather condition. According to the U.S. Department of Transportation (U.S. DOT) (2017), 25% of total traffic delay in the U.S. emanates from traffic accidents.

When incidents occur on freeways, it is common for drivers to divert to adjacent arterial roadways to avoid bottlenecks and stop-and-go conditions, and then return to the freeway downstream of the incident. Drivers today are better informed of traffic conditions. With the deployment of digital message signs that alert drivers of traffic conditions ahead, radio feeds that broadcast incident locations, and smartphone applications that provide real-time alerts to drivers based on a selected route, drivers are better able to choose the best route. Consequently, this diversion of traffic from non-recurrent congestion on freeways affects the operational and safety performance of the adjacent arterial roadways.

To alleviate the impacts of freeway incidents and improve the traffic conditions on the entire system, operational systems of discrete facilities within a corridor need to be coordinated. This concept of traffic management is referred as Integrated Corridor Management (ICM), and

was introduced as an intermodal research initiative by the U.S. DOT (U.S. DOT, 2015). The primary goal of ICM is better utilization of the available capacity on a traffic corridor, thus decreasing incident-induced traffic delay. Traffic simulation tools can be useful tool for evaluating the efficiency of traffic diversion strategies and the performance of ICM systems.

### Study Objectives

The objectives of this study were twofold. First, the effects of freeway incidents on operational characteristics of both the arterial roadway and the freeway were evaluated for increasing demand and diversion rate. Therefore, two performance measures were used: travel time and queue length. The second goal of the study was to estimate corridor delay and define the significance of the factors: incident duration, diversion rate, and demand level. For this objective, an experiment was designed, and response surface methodology was employed. The findings of this study can potentially serve as a building block in the understanding and development of future ICM systems and incident management plans.

### Background

Various microscopic simulation models such as CORSIM, VISSIM AIMSUN, Paramics, SimTraffic and VISTA, have been used to analyze the impacts of incidents on traffic conditions. For instance, CORSIM was employed to evaluate the impacts of incidents with traffic signal re-coordination and dynamic re-routing in Florida (Zhou, 2008) and Virginia (Cragg & Demetsky, 1995). Both studies simulated diverting traffic from the freeway to the adjacent arterial roadway due to incident-induced freeway congestion. VISTA was used for network analysis with its dynamic user equilibrium principle (Sisiopiku et al., 2007), while Paramics was adopted to model dynamic traffic signal control systems in the absence of incidents in New Zealand (Koorey et al., 2015). A number of previous studies that have used VISSIM to model traffic incident situations (Chou & Miller-Hooks, 2011; X. Liu et al., 2013; Massahi, Hadi, Xiao, Wang, & Chen, 2015; Wang, Chang, & Ioannou, 2009; Zhou & Tian,

2012). Other researchers have also compared VISSIM models with other simulation models used in incident modeling (Hadi, Sinha, & Wang, 2007; Pulugurtha, Nambisan, Dangeti, & Kaseko, 2002). Studies that were conducted more than a decade ago preferred simulation tools such as CORSIM and AIMSUN, rather than VISSIM. Newer versions of VISSIM have included tools that are more amenable to modeling incidents, hence several newer studies have used VISSIM for modeling incidents.

VISSIM offers more than one way to implement an incident. Several earlier studies used an on-street bus stop to represent an incident (Hadi et al., 2007; Massahi et al., 2015; Pulugurtha et al., 2002; Wang et al., 2009; Zhou & Tian, 2012). The bus arrival time was considered the beginning of the incident, and the dwell time was used to represent the duration of an incident. A traffic signal head, located on the incident lane was also used to induce an incident (Avetisyan, Miller-Hooks, Melanta, & Qi, 2014). For this case, the red phase can be used to represent the incident duration when lane blockage occurs. Other studies (Chou & Miller-Hooks, 2011; Hong & Yue-sheng, 2013) adopted the COM interface to add a vehicle with zero speed at the beginning of the incident, and keep it for the duration of the incident. A one-space parking lot and parking lot routing decision with a given parking duration can also be used to simulate an incident (X. Liu et al., 2013). In this method, approaching vehicles navigate to the adjacent free lanes due a partial routing decision and a connector located at the adjacent lanes of the parking lot.

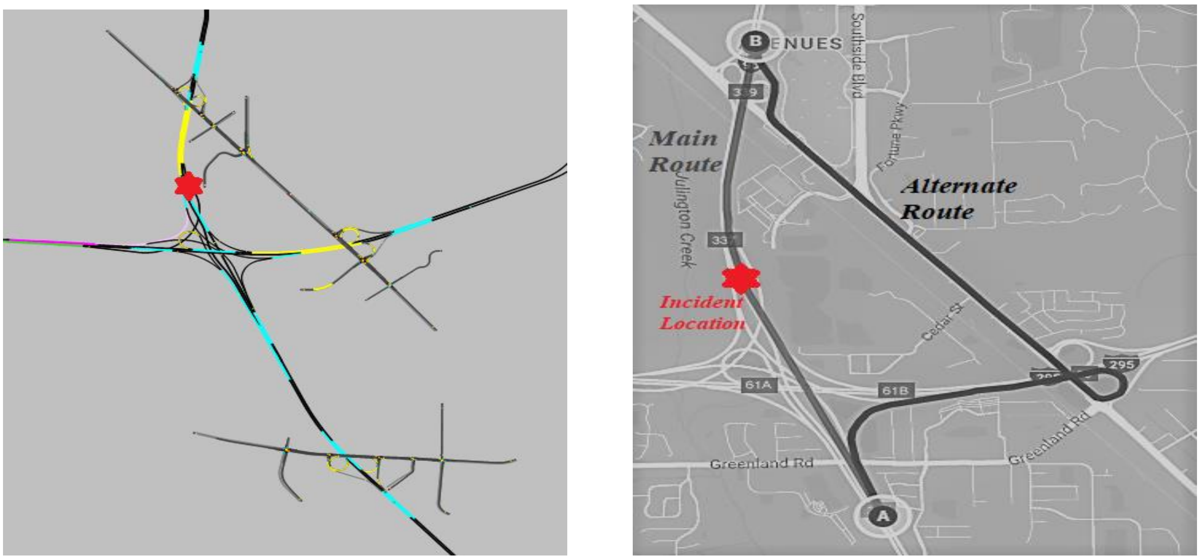
Few studies have documented the impacts of diversion onto adjacent streets. A similar study by Chou and Miller-Hooks (2011) focused on diverting the congested traffic stream onto the managed lanes from the general purpose lanes with different incident inputs and access approaches to the managed lanes (Chou & Miller-Hooks, 2011). The study concluded that the benefits from this detour method were greater for long term incidents with a continuous diversion rather than the access point diversion.

A study by Zhou (2008) used a collaboration of CORSIM and SYNCHRO to perform a detour operation with dynamic signal timing. The study determined the optimum diversion rate to be 10% (Zhou, 2008), while another study by Liu et al. (2013) found the optimum diversion rate to be 4% using a VISSIM simulation test base. An earlier study assessed the effectiveness of Variable Message Signs (VMSs) on detour operations from surveys (Peeta et al., 2000). The study concluded that VMSs play a crucial role in the decision process for drivers deciding whether or not to take the detour. Relatively no research has been conducted on estimating the performance of detour operations on different demand levels. There is a need to evaluate the impacts of freeway congestion on operational characteristics of the entire corridor.

## Methodology

### *Study Site*

The northeast quadrant of the I-95/I-295 Interchange in Jacksonville, Florida was selected as the test site for the study. I-95 is a major interstate traveling north-south along the Atlantic Coast. When an incident occurs on the northbound section of I-95, just north of the I-95/I-295 interchange, drivers have been observed to reroute onto US 1 (Philips Highway), another north-south thoroughfare parallel to I-95 (see Figure 3-1). For this case, drivers may exit onto I-295 to US 1 and travel US 1 to return to I-95 downstream of the incident. While the distance for the main route (MR), from the I-95/I-295 interchange to the I-95/US 1 interchange, is only 3.41 km (2.12 mi), the distance for the alternate route (AR), from the I-95/I-295 to the I-95/US 1 interchange via I-295 and US 1, is 5.45 km (3.38 mi), over 2.0 km (1.26 mi.) longer than the main route. This study location was deemed suitable for the intended analysis since there were no other arterial roadways parallel to I-95 in the vicinity.




(a) (b)

**Figure 0-1:** Main Route (MR), Alternate Route (AR) and incident location snapshots (a) from simulation (b) from Google Maps

*Data Sources*

The traffic input data (volumes, origin-destination matrices, and signal controllers) were obtained from Reynolds Smith & Hills (RS&H) Inc., a consulting firm headquartered in Jacksonville, Florida. For validation of the test base, historical travel time data for main and alternate routes were extracted from BlueTOAD devices, maintained by Traffic Cast International Inc. In addition, archived traffic incident data were mined from the SUNGUIDE software, operated and maintained by the Florida Department of Transportation.

*Modeling Procedure*

For the purpose of analysis, the simulation time period was defined as 4 hours 30 minutes (16,200 s) to represent the morning traffic from 5:15 AM to 9:45 AM. Calibration and validation are one of the most important parts of the modeling exercise due to their significant impacts on experimental design (Park, B.; Schneeberger, 2003). Although the model used in this study had already been calibrated by RS&H, before the observation of the incident and diversion strategies, the corridor was validated with travel time field data for a two-year period

(2015 and 2016). Simulation data were aggregated in 15-minute time intervals to compare the model and field data. Differences between simulation and field data were set to a target of less than 10% for both facilities. Figure 3-2 indicates travel time information of the model and field data from predefined sections of the MR and AR.

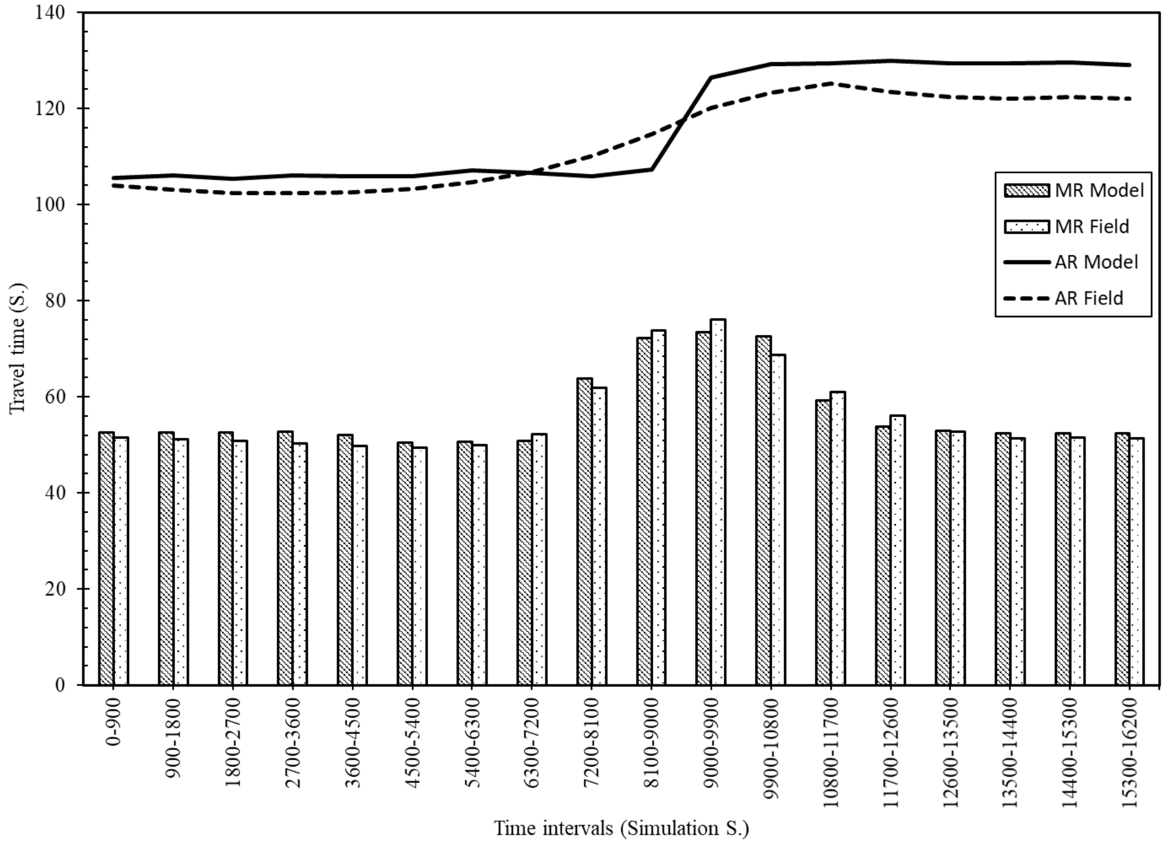



**Figure 0-2:** Validation of the calibrated simulation model.

*Incident Implementation*

As mentioned earlier, VISSIM (Version 9.0) (PTV, 2016) does not have a specific feature to model an incident. In this study, a parking lot and a parking routing decision was adopted to simulate an incident in the right lane of a three-lane basic freeway segment. Additionally, a partial route and a connector located parallel to the incident spot was used to shift approaching vehicles to the unblocked lanes. The incident location was defined by observed hotspots of archived incidents during morning peak hours along I-95 Northbound. To

exhibit realistic driving behaviors and incident-induced capacity reduction, the Vehicle Actuated Programming (VAP) interface (PTV, 2015) was employed with an occupancy detector located just before the incident location. With this configuration, speeds of approaching vehicles are dynamically reduced by the desired speed decisions located 500 feet upstream of the incident location. Hadi et al., (2007) used a similar method for time-specific and location-specific calibration. In prevailing conditions, the travel speed oscillates around the posted speed limit (65 mph). However, when an incident occurs, the 85$^{th}$ percentile speed distribution decreases to 20 mph.

*Diversion Implementation*

Modeling a dynamic diversion strategy is another challenge. Previous studies have used the COM interface to change related flow rates in a certain time interval, which simply refers the incident duration (Chou & Miller-Hooks, 2011; X. Liu et al., 2013). However, working with different v/c ratios requires more sensitive changes in dynamic assignments. Therefore, VAP interface with a detector was connected to the static routing decision which defines the route of the approaching vehicles. Through this connection, flow rates of the MR and AR simultaneously change according to traffic conditions upstream of the incident location. For instance, if a high occupancy rate is detected just upstream of the incident location, the diversion plan is activated to increase the flow rate of the AR to the predefined diversion rate and decrease the flow rate of the MR. Specifically, a simultaneous diversion plan is modeled according to the traffic conditions at the incident location.

*Modeling Scenarios*

In this study, several scenarios were systematically developed based on three main factors: v/c ratios, diversion rates, and incident durations (see Table 3-1). Freeway capacity is defined as 2,300 vehicles-per-hour-per-lane in the Highway Capacity Manual (TRB, 2016b).

This value was compared with input volumes to determine the v/c ratios. It was found that initial average hourly volume input has a 0.6 v/c ratio. To observe the effects of different demand levels, volume inputs were increased to reach v/c ratios of 0.8 and 1.0. The v/c ratio was assessed using the I-95 Northbound entrance volume input values, which represents the vehicles approaching the incident location.

The diversion rate defines the portion of approaching vehicles which circumvent the incident-induced congestion on the MR by shifting to the AR. Three different diversion rates were examined: 10%, 20%, and 30%, with the 0% or no diversion as the base scenario. Finally, incident duration was defined as the amount of time that one lane of the three-lane freeway was blocked to the traffic flow by the incident, and three different incident durations were considered: 30, 45, and 60 minutes.

Table 0-1: Scenario Management

| **Scenario Factors** | **Values** |
|---|---|
| v/c Ratio | 0.6 |
| | 0.8 |
| | 1 |
| Diversion Rate | 0% |
| | 10% |
| | 20% |
| | 30% |
| Incident Duration | 30 min |
| | 45 min |
| | 60 min |

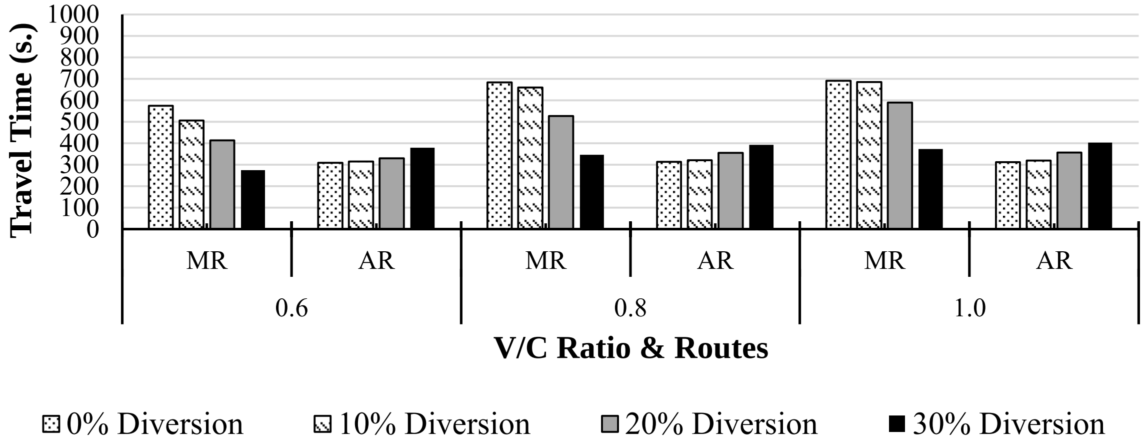
Every combination of scenario factors was composed of 10 simulation runs with one increment of the random seed value on each run from 45 to 55. The random seed is a feature of traffic simulation software that provides a stochastic nature of traffic with different sequences and traffic flow changes (PTV, 2016). For all of the aforementioned scenarios, incidents were designated to emerge at the 2,700$^{th}$ second of simulation to provide enough time

for warm-up, and to correspond with 6:00 AM, the time when morning traffic begins to increase.

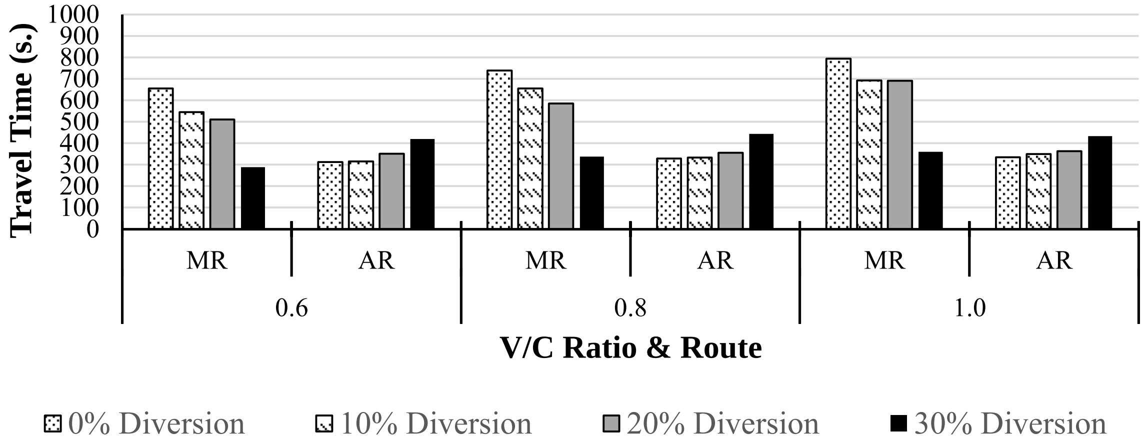
## Results

*Average Travel Time Comparison*

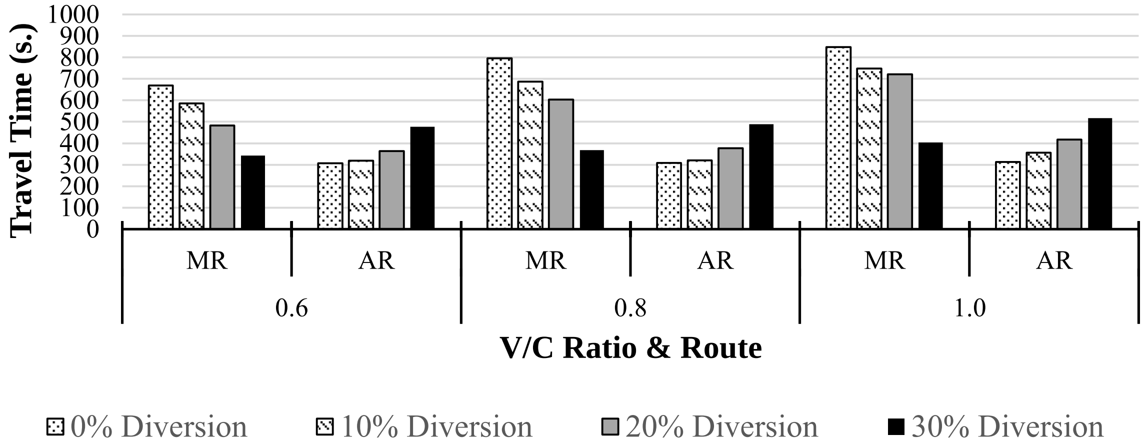
Travel time was measured as the time a vehicle travels from point A to point B, shown in Figure 3-1(b). Discrete travel time measurements were used for the MR and the AR, and average travel time was calculated from 10 replications. Results presented in Figure 3-3 indicate that average travel times are considerably longer for the MR facility than for the AR corridor for all three analyzed incident durations (30, 45, and 60 minutes). Despite the longer travel distance and lower speed limit of the AR, travel times were observed to be longer for the MR facility due to the incident. Without a traffic diversion, the differences in travel time on the MR and AR were observed to be 86% for the incident duration of 30 minutes at a 0.6 v/c ratio and 172% for the incident duration of 60 minutes at a 1.0 v/c ratio. However, when the diversion strategy was implemented, the average travel time on the MR progressively decreased, while the average travel time on the AR smoothly increased, due to the diverted traffic flow. According to the graphs shown in Figure 3-3, at a 30% diversion rate, the MR had a lower average travel time in comparison to AR. The differences in travel time range from 7% (30 min duration 1.0 v/c ratio) to 31% (45 min duration 0.6 v/c ratio).




(a)




(b)




(c)

**Figure 0-3:** Average travel time results for incident durations
(a) 30 min, (b) 45 min, and (c) 60 min incident durations

*Queue Length Analysis*

The queue analysis presented in this section was based on a 30-minute incident duration and the v/c ratio of 0.6 (see Figure 3-4). The definition of the queue varies in different studies and depends on several factors such as type of facility. For instance, for an arterial roadway with a 45 mph posted speed limit, the traffic stream is assumed to be in queue form when the speeds fall below five mph. On the other hand, drivers expect to drive at higher speeds on freeways compared to the arterial network. Therefore, traffic is assumed to be in a queue state when the speed fall to or below 15 mph. VISSIM default values in terms of queue are five mph to begin and 10 mph to end.

The results show that diversion strategies significantly affect the queue length in terms of maximum distance, accumulation, and recovery time. The maximum distance refers to the longest distance from the incident location to the beginning of the queue, while accumulation assigns to the time that the queue keeps growing even after incident duration. More importantly, recovery time denotes the time between incident occurrence and traffic flow returning to the normal condition.

Initially, the maximum queue length was observed as 19,131.39 ft. (5831.2 m), at 45 min after roadway clearance time in a no-diversion situation. However, these measurements decreased to 3,689.15 ft. (1124.5 m) at 15 minutes after the roadway clearance time for the 30% diversion rate strategy. Recovery time was estimated as the time that the maximum queue length was discharged, and were determined at 75 min, 60 min, 45 min, and 30 min in ascending order of diversion rates. Specifically, as the diversion rate increases, impacts of the incident on the traffic flow terminate earlier.

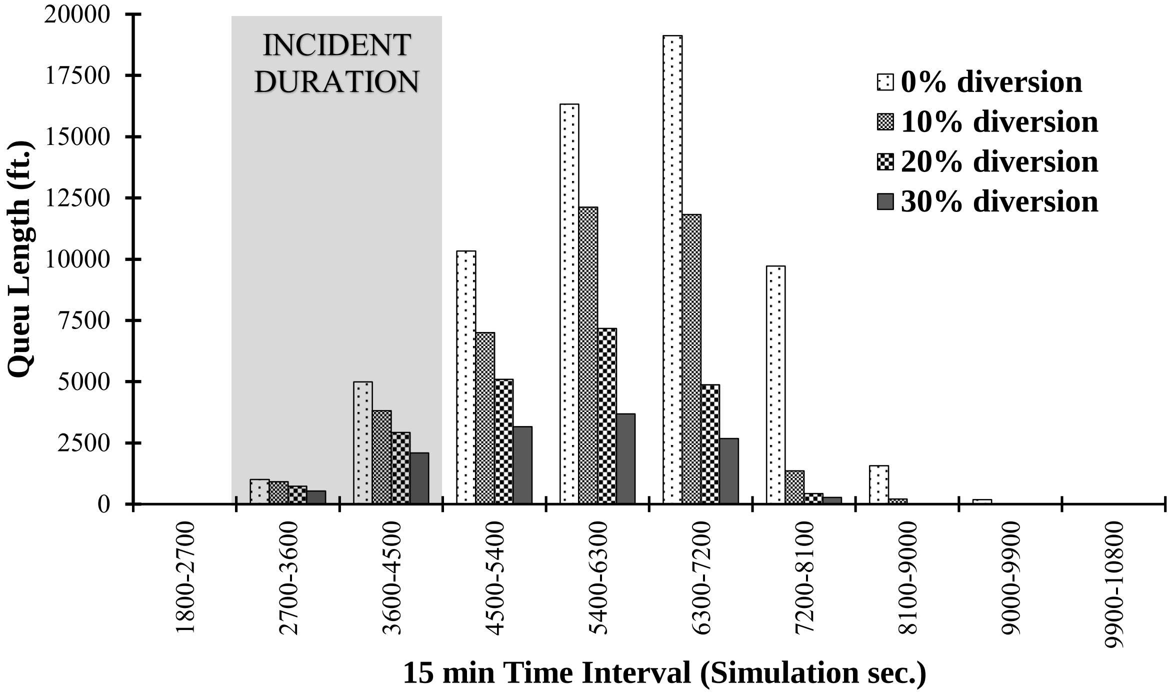



**Figure 0-4:** Queue length results for 30 min incident duration and 0.6 V/C ratio.

*Design of Experiment*

In the present study, a $2^3$ full factorial spherical Central Composite Design (CCD) was adopted to quantify the effects of incident duration, diversion rate, and demand level on the performance of the congestion management. Corridor Delay (CD) was defined as the response factor and calculated with delay and throughput data of the MR and AR (Eq. 1) (X. Liu et al., 2013). VISSIM calculates the delay by subtracting the theoretical free flow travel time of the studied section from the actual travel time for every vehicle. Then, total delay is divided by the number of vehicles to obtain the average vehicle delay in second per vehicle (s/veh) (PTV, 2016). In Equation 3-1, CD refers to the delay of a vehicle which travels through one of the facilities of the corridor during predefined traffic conditions.

$$CD = \frac{D_{MR} * TP_{MR} + D_{AR} * TP_{AR}}{TP_{MR} + TP_{AR}} \qquad (3\text{-}1)$$

$CD = Corridor\ Delay\ (s/veh)$ $\qquad D = Delay\ (s/veh)$

$TP = Thorughput,\ number\ of\ vehicles\ completed\ the\ studied\ section$

Spherical CCD puts all the factorial (cubic) and axial (star) design points on the surface of a sphere of radius $\sqrt{k}$ ($k$= number of control factors) (Montgomery, 2005). The radius of sphere represents the distance between the center point and the axial design points. Table 3-2 shows the conversion of natural variables to dimensionless variables $(x_1, x_2, x_3)$, with the coded values of i) cubic design points at low (-1) and high (+1) levels; ii) axial design points at low $(-\sqrt{3})$ and high $(+\sqrt{3})$ levels; and iii) at the center point (0). Natural values at cubic design points $(L_{(-1)}, H_{(+1)})$ are selected from aforementioned scenario managements. Natural values of axial points $(NV_{ax})$ are determined with their coded value $(x)$ (Eq. 3-2). Then additional simulation models are ran to collect the response at axial design points.

$$x * \frac{(H_{(+1)} - L_{(-1)})}{2} + \frac{(H_{(+1)} + L_{(-1)})}{2} = NV_{ax} \qquad (3\text{-}2)$$

Table 0-2: Independent variables and their coded levels for CCD

| Control Factors | Symbol | Coded variable levels | | | | |
|---|---|---|---|---|---|---|
| | | $-\sqrt{3}$ | -1 | 0 | +1 | $+\sqrt{3}$ |
| Incident Duration (min) | $x_1$ | 19.02 | 30 | 45 | 60 | 70.98 |
| Diversion Rate (%) | $x_2$ | 2.68 | 10 | 20 | 30 | 37.32 |
| Demand Level (v/c) | $x_3$ | 0.45 | 0.6 | 0.8 | 1 | 1.15 |

The replication on the simulation for each combination is considered for different blocks on the design experiment. The arrangement of CCD, as summarized in Table 3-3 , allows the development of the second-order polynomial regression equation with the coded values of control factors (Ahmadi, Vahabzadeh, Bonakdarpour, Mofarrah, & Mehranian, 2005; Montgomery, 2005).

Table 0-3: Summary of the central composite design experiment

| Design Summary | | | | Point Types | |
|---|---|---|---|---|---|
| Factors: | 3 | Replicates: | 10 | Cube points: | 80 |
| Base runs: | 15 | Total runs: | 150 | Center points in cube: | 10 |
| Base blocks: | 1 | Total blocks: | 10 | Axial points: | 60 |

The estimation of the response (y) is correlated with a set of regression coefficients: the intercept ($\beta_0$), linear ($\beta_1, \beta_2, \beta_3$), pure quadratic ($\beta_{11}, \beta_{22}, \beta_{33}$) and 2-way interaction ($\beta_{12}, \beta_{13}, \beta_{23}$). Minitab software (version 18.1) was employed to analyze and formulize the experiment.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2 + \beta_{33} {x_3}^2 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 \quad (3\text{-}3)$$

To define the significant factors on the variation of corridor delay, the backward elimination method was employed with α=0.05. Particularly, the variation due a single factor is compared with the pure error in the system with an F distribution. If the P-value of the single factor is higher than α, the effect of that particular factor on the system variation is accepted in the pure error and insignificant. If the P-value is lower than α, that particular factor has its own noise which can be eliminated with the second-order regression equation to estimate the response. The model starts with all the factors including the effects of blocks (replications in this study). At each step, the factor that has the highest P-value is excluded and 1 degree of freedom is added to the error to increase the accuracy. The process continues until no factor that has P-value higher than 0.05. Table 3-4 indicates the final analysis of variance (ANOVA) with the factors that they have their own noise in the system.

Coefficients are the expected impacts on the system when their factors are altered with one-unit. In this regard, regression equations for coded variables and un-coded variables are

represented with Equations 3-4 and 3-5, respectively. It should be noted that the tool used in the analysis of experimental data, namely ANOVA, assumes that the residuals follow a normal distribution (Arif, Tiryakioglu, Bird, Harris, & Kweder, 2015). Therefore, a diagnostic test was implemented and found that the differences between actual response and estimated response follow a normal distribution. According to the model summary, the model can reflect the 85.47% of total variance of the system with a mean squared error of 49 (s/veh). Also, the model was 83.85% accurate in estimating the corridor delay with incident duration, diversion rate, and demand level (see Table 3-5).

Table 0-4: Final Step of ANOVA

| Source | DF | Adj. SS | Adj. MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 7 | 2004601 | 286372 | 119.49 | 0.000 |
| Linear | 3 | 1842011 | 614004 | 256.19 | 0.000 |
| $x_1$ Incident Duration (ID) | 1 | 1617046 | 1617046 | 674.70 | 0.000 |
| $x_2$ Diversion Rate (DR) | 1 | 112587 | 112587 | 46.98 | 0.000 |
| $x_3$ Demand Level (V/C) | 1 | 112378 | 112378 | 46.89 | 0.000 |
| Square | 3 | 134029 | 44676 | 18.64 | 0.000 |
| ${x_1}^2$ | 1 | 82474 | 82474 | 34.41 | 0.000 |
| ${x_2}^2$ | 1 | 88986 | 88986 | 37.13 | 0.000 |
| ${x_3}^2$ | 1 | 11723 | 11723 | 4.89 | 0.029 |
| 2-Way Interaction | 1 | 28561 | 28561 | 11.92 | 0.001 |
| $x_1 * x_2$ | 1 | 28561 | 28561 | 11.92 | 0.001 |
| Error | 142 | 340328 | 2397 | | |
| Total | 149 | 2344929 | | | |

Table 0-5: Model summary

| RMSE | $R^2$ | $R^2$ (adj.) | $R^2$ (pred.) |
|---|---|---|---|
| 48.96(s/veh) | 85.49% | 84.77% | 83.85% |

Regression Equation in coded variables:

$$y = 246.5 + 107.47x_1 - 28.36x_2 + 28.33x_3 + 35.88{x_1}^2 + 37.27{x_2}^2 + 13.53{x_3}^2 - 18.89x_1x_2 \quad (3\text{-}4)$$

Regression Equation in un-coded variables:

$$CD = 443 - 4.67 * [ID] - 12.07 * [DR] - 399 * [V/C]$$

$$+0.1595 * [ID]^2 + 0.3727 * [DR]^2 + 338 * [V/C]^2$$
$$-0.1260 * [ID] * [DR] \quad (3\text{-}5)$$

The 3-dimensional response surface can be drawn with the regression equation. The Z-axis is dedicated for the Corridor Delay (CD) as the response. The X-axis represents the Diversion Rate (DR) (%), while the Y-axis indicates demand level with v/c ratios. Figures 3-5(a) and (b) indicate the response surface for a 30 min Incident Duration (ID) and 60 min ID, respectively. Results show that until a certain point, an increase in the diversion rate decreases the corridor delay; however, after that point, the delay started to increase as diversion rate increased. The optimum diversion rate, which provides the minimum corridor delay, depends on both demand level and incident duration.

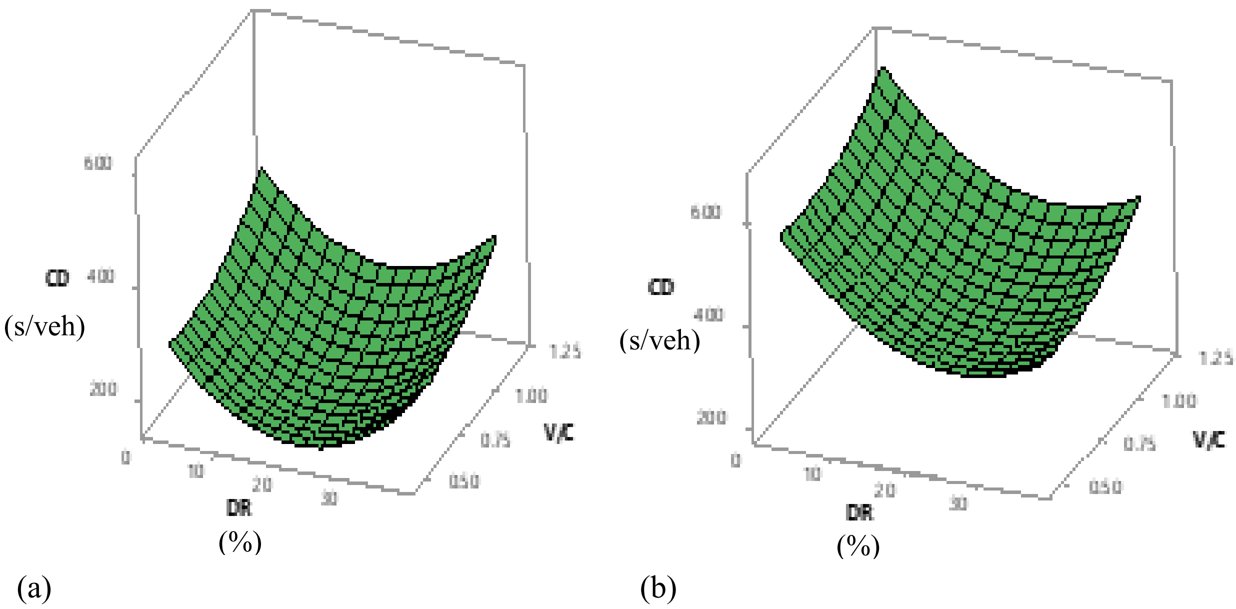



**Figure 3-5:** Corridor delay against diversion rate and demand level for incident durations (a) 30 min, and (b) 60 min incident durations

**Conclusions and Recommendations**

Detour operations on a freeway-arterial corridor were studied in the presented work with a calibrated and validated simulation model. The south intersection of I-95 and I-295 in

Jacksonville, Florida was selected as a test site, and the corridor was identified as the northbound direction of I-95 and US 1 as the freeway and the arterial roadway, respectively. Despite the higher posted speed and shorter driving distance route along the freeway (I-95), it was observed that in case of an incident on the freeway, there is a tendency among motorists to shift to the arterial roadway (US 1) and return to the freeway downstream of the incident. In the simulation test bed the routes were termed Main Route (MR) for the freeway and Alternate Route (AR) for the arterial roadway (see Figure 3-1). The simulation model was calibrated by RS&H Inc. and validated with travel time field data extracted from BlueTOAD software for the morning peak hours for weekdays.

Different demand levels were created on the freeway by altering the volume input and duration of the incident. For each demand level, variable diversion rates were tested to measure the influence on the freeway and arterial roadway separately. Average travel time comparison expressed that as the diversion rate increased, the average travel time of the MR progressively decreased, while the average travel time of AR smoothly increased due to the diverted traffic flow. The queue length results showed that as the diversion rate increased, the accumulation time for the queue shortened, as well as the recovery time.

To quantify the effects of incident duration, diversion rate, and demand level on the performance of the congestion management, a $2^3$ full factorial spherical Central Composite Design (CCD) was employed. Corridor Delay (CD) was determined as the response factor and calculated with the delay and throughput data of the MR and AR. A second-order polynomial regression equation was developed to estimate the performance of detour operations through corridor delay. Results indicate that the model can reflect the 85.47% of total variance of the system with a root mean squared error of 49 (s/veh). Traffic agencies can employ the equation to decide whether or not a detour should be implemented. Furthermore, with the estimation of the incident durations and the current v/c ratios on the freeway, the diversion rate that results

in minimum corridor delay can be implemented. With the advent of intelligent transportation systems, such as loop detectors, located on off-ramps and on the freeway itself, the actual diversion rate is controllable.

# CHAPTER 4: OVERALL CONCLUSIONS

Despite the increasing attention on minimizing the effects of traffic incidents on single transportation facility, little attention has been placed on detour operations as a congestion management strategy. This thesis focused on detouring traffic, a common countermeasure, to alleviate the impact of a traffic incident. A freeway-arterial corridor was analyzed as a system through Integrated Corridor Management (ICM). The corridor consisted of Northbound sections of I-95 and US 1 (Philips Highway) as the freeway and arterial roadway, respectively. The presented work evaluated the justification and the optimization of traffic detour strategies to increase the mobility and safety of the corridor.

The study defined the impacts of archived traffic incidents by considering a variety of traffic demand levels at different times of day, days of the week, and sections along the corridor using operation speeds. Then a deterioration rate on the freeway and the arterial roadway due to traffic accidents of different types, such as crash, disabled vehicle, and debris on the roadway, was determined. According to the results, the deterioration rates at different times of day for each type of incident follow a lognormal distribution, indicating a detour operation during peak hours may reduce the congestion by 88% and 78% for crash and disabled vehicle incident types, respectively.

VISSIM traffic simulation software was employed to measure the efficiency of variable detour operations on different demand levels. Average travel time and queue length results show that as the diversion rate increases, operational characteristics of the freeway improve while driving conditions on the arterial route worsen. The study employed an experiment with $2^3$ factorial spherical central composite design to find a regression equation for the best performance of detour operations. Table 4-1 indicates the diversion rates that minimize the corridor delay in cubic and center design points of incident duration and demand levels. Traffic

agencies and decision makers can define the optimum diversion rate with the equation according to the duration of incident and current demand level.

Table 0-1: Optimum diversion rates and corresponding corridor delays

| **Incident duration (min)** | *Optimum Diversion Rate (%)* | | | *Corresponding Corridor Delay (s/veh)* | | |
|---|---|---|---|---|---|---|
| | **0.6 v/c** | **0.8 v/c** | **1.0 v/c** | **0.6 v/c** | **0.8 v/c** | **1.0 v/c** |
| **30** | 21.2695 | 21.2540 | 21.2400 | 159.5 | 174.3 | 216.2 |
| **45** | 23.8053 | 23.8042 | 23.8035 | 226.3 | 241.1 | 282.9 |
| **60** | 26.3430 | 26.3367 | 26.3309 | 360.1 | 374.9 | 416.7 |

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- Analysis, modeling and simulation of integrated corridor management strategies.
- Processing of historical traffic data with R studio.
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- Preparing improvement reports in NATM tunnels technical office.
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- University Transportation Center 5th Annual Conference for the Southeastern Region, November 2017.
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- Modeling and Simulation of Transportation Networks, MIT Professional Education - Short Programs, July 2017.
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## PUBLICATIONS

### Journal Papers Under Review

Karaer, A., Sando, T., Haule, H., Chuan, C., Lentz, R., and Tiryakioglu, M. "Quantifying the Impacts of Freeway Incidents on Adjacent Facilities: Jacksonville Case Study". *Journal of Transportation Engineering, Part A: Systems.*

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