2021

A Microscopic Simulation Approach for Developing Ramp Metering Activation Guidelines For Weekends

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A MICROSCOPIC SIMULATION APPROACH FOR DEVELOPING RAMP METERING ACTIVATION GUIDELINES FOR WEEKENDS

By

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A thesis proposal submitted to the school of Engineering
In partial fulfillment of the requirements for the degree of
Masters of Science in Civil Engineering

UNIVERSITY OF NORTH FLORIDA
COLLEGE OF COMPUTING, ENGINEERING, AND CONSTRUCTION
December 2021

THESIS CERTIFICATE OF APPROVAL

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DEDICATION

.....to my beloved parents: My mother, Eunice N Kasomi, and Dad, Thomas G Kasomi.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to every person who, in one way or another, contributed to developing the idea for this thesis work. I am overwhelmed with gratitude for your devotional assistance in making this work a success.

I acknowledge and give my warmest thanks to my supervisor, Dr. Thobias Sando, who made this work possible. His extensive support, patience, guidance, encouragement, and corrective work have greatly supported this thesis work's execution. May God bless you abundantly.

I also extend my sincere thanks to my committee members, Dr. Priyanka Alluri and Dr. Ramin Shabanpour, for the learning opportunity that you provided. Thank you for taking the time to review and comment on my work. Your reviews and comments have taken my work to greater heights!

I would like to give special thanks to my family, Mr. Thomas G Kasomi and Mrs. Eunice N Kasomi, for their continued support and prayers, which led me through all the difficulties. Your encouragement during the tough times is highly appreciated.

Lastly, I would like to thank ALL current UNF transportation lab members and former UNF transportation lab members: Dr. Henrick Haule, Gwamaka Njobelo, and John Kodi, who have worked with me in one way or another to realize this work. Thank you for taking the time to guide me and review my work. May God bless you all.

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
ADOT	Arizona Department of Transportation
ALINEA	Asservissement Linéaire d'Entrée Autoroutière
AM	Ante Meridiem
ANOVA	Analysis of Variance
API	Application Programming Interface
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System.
ATMS	Advanced Traffic Management System
BI	Buffer Index
CADD	Computer-Aided Design and Drafting
Caltrans	California Department of Transportation
CCTV	Closed-Circuit Television
CDOT	Colorado Department of Transportation
COM	Component Object Model
COVID-19	Corona Virus Disease 2019
CRMS	Central Ramp Meters System
CTOD	Central Time of the Day
D/C	Demand-to-Capacity

DTA	Dynamic Traffic Assignment
FCT	Floating Car Technique
FDOT	Florida Department of Transportation
FFS	Free-flow Speed
FHWA	Federal Highway Administration
FHP	Florida Highway Patrol
FLC	Fuzzy Logic Controller
HCM	Highway Capacity Manual
HOV	High Occupancy Vehicle
INFORM	Information FOR Motorists
JSO	Jacksonville Sheriff's Office
KDOT	Kansas Department of Transportation
LHS	Left Hand Side
LOS	Level of Service
LTOD	Local Time of the Day
MoDOT	Missouri Department of Transportation
NB	North-Bound
NDOT	Nevada Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
NYSDOT	New York State Department of Transportation

OD	Origin-Destination
ODOT	Oregon Department of Transportation
PennDOT	Pennsylvania Department of Transportation
PM	Post Meridiem
RBC	Ring Barrier Controller
RCI	Roadway Characteristics Inventory
RHS	Right Hand Side
RITIS	Regional Integrated Traffic Information System
RMS	Ramp Metering Signal
SB	South-Bound
TMC	Transportation Management Center
TSM&O	Transportation Systems Management and Operations
TTI	Travel Time Index
UDOT	Utah Department of Transportation
V/C	Volume-to-Capacity
VHT	Vehicle-Hours-Traveled
VISSIM	Verkehr In Städten Simulationsmodell
VMT	Vehicle-Miles-Traveled
WisDOT	Wisconsin Department of Transportation
WisDOT	Washington Department of Transportation

ABSTRACT

Traffic congestion is one of the major concerns in urban motorways. Agencies are implementing various Transportation Systems Management and Operations (TSM&O) strategies to reduce traffic congestion on roadway networks. Ramp metering is a TSM&O strategy that utilizes signals installed at freeways' on-ramps to dynamically manage traffic entering the freeway. RMSs have been effective at alleviating recurring congestion. Recurring congestion, however, constitutes less than half of all congestion. More than half of all congestion is due to non-recurring events such as incidents, work zones, adverse weather conditions, special events, etc., that adversely affect the performance of a highway. Non-recurring congestion on freeways, especially during the weekend, could be alleviated by activating RMSs based on prevailing traffic conditions along the freeway corridor. This study focused on establishing a set of guidelines for activating RMSs during weekend non-recurring congestion. A microscopic simulation model was used to establish the guideline considering non-recurring congestion due to traffic incidents. It also took account of several incident attributes, including incident location, clearance duration, and the number of lanes blocked. Sensitivity analysis and statistical tests were performed to develop the guidelines. The results showed that, for a two-lane blockage incident, activation of RMSs upstream of the incident location was necessary when ramp volume was above 800 vphpl and freeway mainline volume was above 950 vphpl, whereas for a three-lane blockage incident, activation was needed when ramp volume was higher than 750 vphpl and freeway mainline volume exceeded 850 vphpl. For both incident scenarios, RMSs needed to be activated when speeds were less than 50 mph. Furthermore, activation of RMSs on the weekend improved the average speed of the study roadway network by at least 7 % and reduced the delay by at least 15%.

Keywords: Ramp metering, incident clearance, non-recurring congestion, sensitivity analysis

CHAPTER 1

INTRODUCTION

Background

Ramp meter signals (RMSs) are traffic signals placed on freeway ‘s on-ramps that control traffic entering the freeway (Balke, 2009a). RMSs regulate the traffic entering the freeway by optimizing the use of available gaps for vehicles to merge. Over the years, RMSs have improved travel time reliability, mobility, safety, and the environment while preserving freeway capacity at a lower cost than other capacity improvements, such as adding lanes (Berk et al., 2017). Figure 1 shows a typical ramp metering configuration.

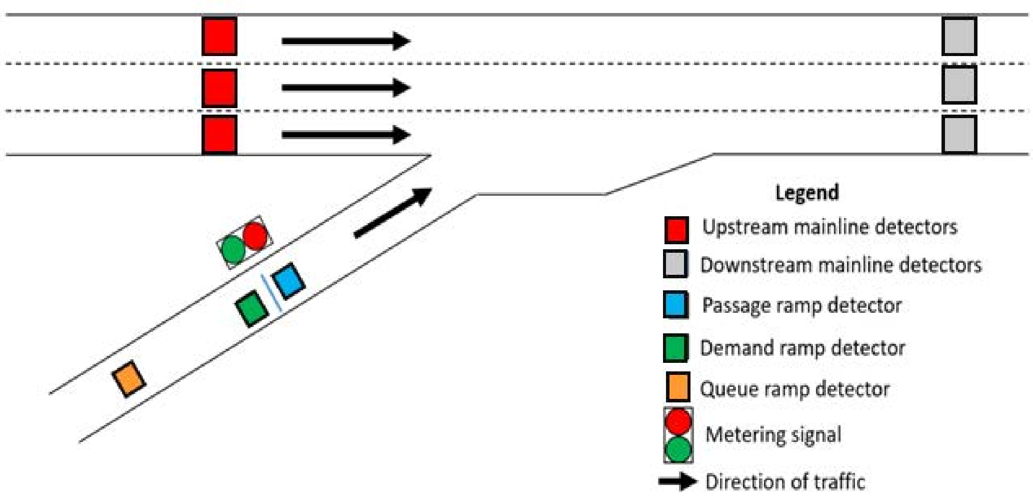


Figure 1: Ramp metering configuration

RMSs are usually activated during weekday peak hours to alleviate recurring congestion. However, the recurring congestion during peak hours constitutes less than half of all congestion; more than half of all congestion results from non-recurring events such as traffic incidents, work zones, adverse weather conditions, and special events which adversely impact the performance of the freeway. Non-recurring congestion on freeways, especially during the weekend, could be alleviated by dynamically activating RMSs based on prevailing traffic conditions along the freeway corridor. For corridors with RMSs already installed, activating these signals in response to non-recurrent events does not require significant resources and could be a relatively inexpensive strategy to reduce traffic congestion in real-time. Therefore, the established guidelines are necessary to justify the activation of the RMSs during the weekend.

Study Objectives

This study aimed to develop guidelines for activation of RMSs on the weekend non-recurring congestion caused by incidents. The study aimed at establishing traffic-related guidelines based on volume and speed. Various incident attributes were also considered including, incident type, location, and the number of lanes closed. The study further aimed to quantify the potential benefits of activating RMSs in response to the weekend non-recurring congestion.

Thesis Organization

This thesis contains 5 Chapters. Chapter 1 provides a general background of the study and an overview of the research problem and the study's objectives. Chapter 2 reviews literature relevant to the study, including a review of existing guidelines for activating RMSs and the appropriate metrics used in developing these existing guidelines. It also provides an overview of ramp metering strategies. Chapter 3 focuses on the approach and methodology used in the study, including the study site, model development and verification, selection of the algorithms for activation of RMSs, and description of other tools used in the study. Chapter 4 presents the results obtained from the study and gives a discussion of the results. Chapter 5 provides conclusive highlights based on the results and important findings for the study.

CHAPTER 2

LITERATURE REVIEW

Ramp meter activation guidelines could be derived from warrants for deploying RMSs and existing guidelines for activating RMSs for non-recurrent congestion during peak hours. There have been a number of attempts to develop warrants for ramp metering. The freeway operation is one of the factors that must be considered in evaluating the appropriateness of the metering system (Piotrowicz & Robinson, 1995). Warrants for ramp metering are categorized into five major groups: traffic-related warrants, geometric characteristics warrants, safety-related warrants, and alternate route warrants (Wilbur Smith Associates, 2006).

Traffic-Related Warrants for Deploying the Ramp Metering Signals

Ramp metering is mainly focused on recurrent congestion during peak hours (Cambridge Systematics Inc., 2001). In general, time-of-day scheduling is used as a basis for activation (Fartash, 2017), regardless of traffic conditions. However, the necessity of ramp metering during peak hours varies, depending on each Agency's needs and traffic requirements. In connection to this fact, Agencies have developed several traffic-related warrants for deploying RMSs. Table 1 summarizes the traffic parameters threshold used by various Agencies in the United States (U.S) to warrant RMSs deployment.

Table 1: Traffic-related warrants for the deployment of RMSs

Criteria	State	Threshold	Remarks
Mainline volume (vphpl)	FL, WI	> 1,200	
Mainline volume (vph)	CO	> 2,650, > 4,250, > 5,850	Thresholds for freeways with 2, 3, and 4 lanes, respectively.
	NV	> 2,650, > 4,250, > 5,850, > 7450, > 9,050, > 10,650	Thresholds for freeways with 2, 3, 4, 5, 6, and > 6 lanes, respectively.
Rightmost lane volume (vphpl)	FL	> 2,050	
Two rightmost lanes (vphpl)	TX	> 1,600	Length of acceleration lanes ≤ 500 ft.
Ramp volume (vph)	TX	> 300	
	FL	240 – 1,200, 400 – 1,700	Thresholds for single lane and multi-lane ramps.
	CA	> 900	
Mainline + ramp volume (vph)	FL, UT	> 2,650, > 4,250, > 5,850, > 7,450, > 9,050, > 10,650	Thresholds for freeways with 2, 3, 4, 5, 6, and > 6 lanes, respectively.
	NV	> 2,100	
Rightmost lane + ramp volume (vphpl)	TX	> 2,300	Length of acceleration lanes ≤ 500 ft.
Speed (mph)	AZ	< 50	
	NV	< 50	
	TX	< 50	
	VA, WI	< 30	
Occupancy (%)	WI	≥ 18	
	WA, MN	20 - 30	
Level of Service (LOS)	NV, NY, VA	LOS E or LOS F	

Volume

The most common criteria for warranting RMSs installation is volume. The warrants include consideration of mainline volume, ramp volume, or a combination of mainline and ramp traffic volume. Warrants can also be based on the traffic volume on all lanes or specific lanes (e.g., right-most lane) along the freeway mainline.

The Florida Department of Transportation (FDOT) and Wisconsin Department of Transportation (WisDOT) warrant ramp metering when the average mainline volume during peak hour is exceeded 1200 vehicles per hour per lane (vphpl) (Gan et al., 2011; Wilbur Smith Associates, 2006). The Colorado Department of Transportation (CDOT) considers ramp metering when the upstream traffic volume exceeds different thresholds, depending on the number of lanes (Gaisser & DePinto, 2015). The ramp meters are warranted on a freeway with two, three, and four lanes when the traffic volume exceeds 2,650 vph, 4,250 vph, and 5,850 vph, respectively. Similarly, the Nevada Department of Transportation (NDOT) considers ramp metering when the total mainline volume exceeds 2,650 vph, 4,250 vph, 5,850 vph, 7,450 vph, 9,050 vph, and 10,650 vph for a freeway with two, three, four, five, six and more than six mainline lanes, respectively (Jacobs Engineering Group Inc., 2013).

Ramp metering can be warranted based on traffic volumes in specific freeway lanes. FDOT guidelines warrant ramp metering when peak hour traffic volume in the right-most lane exceeds 2,050 vph (Gan et al., 2011). The Texas Department of Transportation (TxDOT) considers ramp metering when the average traffic flow rate in the two-right most lanes exceeds 1,600 vphpl during peak hours for lanes with acceleration lane lengths ≤ 500 feet. Also, ramp metering is warranted when the combined traffic flow rate in the right-most lane and the entrance ramp during peak periods exceeds 2,300 vphpl for entrance ramps with acceleration lane lengths ≤ 500 feet (Texas Department of Transportation [TxDOT], 2014).

FDOT warrants ramp metering when the peak hour ramp volume is 240 – 1,200 vph and 400 – 1,700 vph for single-lane and multi-lane ramps, respectively (Gan et al., 2011). (California Department of Transportation [Caltrans], 2000) considers single-lane ramp metering when ramp traffic volume exceeds 900 vph and two- or three-lane ramp metering when it exceeds 900 vph, and the facility requires high occupancy vehicle (HOV) lanes CDOT considers single-lane ramp metering for ramp volumes up to 900 vph and two-lane ramp metering for ramp volume above 900 vph (Gaisser & DePinto, 2015). Similarly, the Nevada Department of Transportation (NDOT) warrants ramp metering when ramp volume during the peak hour exceeds 240 vphpl (Jacobs Engineering Group Inc., 2013). Ramp metering may be considered on Texas freeway ramps with a minimum flow rate of 300 vph during peak periods (TxDOT, 2014).

Ramp metering may also be considered based on the combination of the mainline and ramp volumes. In Florida, ramp metering can be regarded as when the combined mainline and ramp volumes during peak hour exceeds 2,650 vph, 4,250 vph, 5,850vph, 7,450 vph, 9,050 vph, and 10,650 vph on a freeway with two, three, four, five, six, and more than six mainline lanes in one direction, respectively (Gan et al., 2011). The Arizona Department of Transportation (ADOT) considers the combined volumes on the entrance ramp and the right-most freeway lane of greater than 2,050 vph during a typical 15-minute period as criteria for warranting ramp metering and the entrance ramp volume during the same period must also exceed 400 vph (Simpson et al., 2013). In Nevada, NDOT considers a combined right lane and ramp volume exceeding 2,100 during the peak hour as a warrant for freeway ramp metering (Jacobs Engineering Group Inc., 2013). The Utah Department of Transportation (UDOT) considers ramp metering when the total mainline and ramp volumes, combined, exceed 2,650 vph, 4,250 vph, 5,850 vph, 7,450 vph, 9,050 vph, and 10,650 vph for a freeway with two, three, four, five, six, and seven mainline lanes, respectively.

Speed

Mainline traffic speed is used as one of the criteria for ramp metering deployment. ADOT warrants ramp metering when the speed of the general-purpose lanes is less than 50 mph due to recurring congestion within two miles downstream of the entrance ramp (Simpson and Yasmin, 2013). NDOT considers ramp metering when the freeway operates at speeds lower than 50 mph for at least 30 minutes in more than 200 days per year (Jacobs Engineering Group Inc., 2013). TxDOT may consider ramp metering when the freeway speed is less than 50 mph for at least 30 minutes during the peak period. In Virginia and Wisconsin, ramp metering may be considered when the freeway operates at speed less than 30 mph during the peak periods (Arnold, 1998; Wilbur Smith Associates, 2006).

Occupancy

Occupancy, a traffic flow parameter, is used as one of the warrants for ramp metering. WisDOT considers ramp metering on freeways with a traffic occupancy of ≥ 18% and a volume-to-capacity ratio of 0.7 (Wilbur Smith Associates, 2006). In other jurisdictions, including Seattle, Washington, Chicago, Illinois, and Minneapolis, Minnesota, ramp metering is warranted when the traffic occupancy is between 20% and 30% (Wilbur Smith Associates, 2006).

Level of Service

Some Agencies use level-of-service (LOS) when considering time-of-day activation of ramp metering. NDOT uses LOS to warrant ramp metering on Nevada freeways when the LOS is less than a LOS D during the peak period. The New York State Highway Design Manual and Virginia Transportation Research recommend the same threshold (LOS D) as a warrant for ramp metering.

Criteria for Activating the Ramp Metering Signals During Non-Recurrent Congestion

In addition to time-of-day scheduling, RMSs can be activated for non-recurrent congestion resulting from variations in traffic demand, traffic incidents, and adverse weather conditions. Table 2 summarizes the criteria used by different Agencies in the U.S. for activating RMSs due to non-recurrent congestion.

Table 2: Criteria for activating RMSs due to non-recurrent congestion

Criteria	State	Threshold
Congestion level	CA	Heavy traffic.
	FL	As determined by the operator.
	NY	Heavy traffic.
	NV	As determined by the operator.
Volume	TX	Rightmost lane traffic volume > 1,600 vphpl
Speed	CA	< 30 mph and v/c ratio of 0.6 – 0.8
	OR	< 30 mph
	MI	35 – 45 mph
Occupancy	MI	10% - 13%
Incident characteristics	FL	Congestion, as determined by the operator, is due to an incident not causing lane blockage.
		Lane blockage (e.g., all lanes, > 2 lanes, ≤ 2 lanes blocked)
	MN	The incident is cleared.
Rainfall	FL	Heavy rain (> 0.25 in/hr)

Note: v/c = volume-to-capacity.

Congestion Level

Freeway traffic conditions are monitored by the RMSs operators, using closed-circuit television (CCTV) cameras in the Transportation Management Centers (TMCs). Based on their judgment, the operators determine whether the freeway traffic is congested or not (Hadi et al., 2017). In Florida, the RMSs can be activated earlier than the start of the peak period or deactivated later than the end of the peak period if the operator determines that the corridor is highly congested (Fartash, 2017). Similarly, the RMSs in Nevada can also be activated/ deactivated outside of normal operations, but only by trained operators familiar with typical traffic patterns (Jacobs Engineering Group Inc., 2013). The New York State Department of Transportation (NYSDOT) included special afternoon hours in its ramp metering time-of-day scheduling to alleviate heavy traffic. The time-of-day schedule could also be changed remotely from the TMC or manually at the controller (Magalotti, 2011). The RMSs in California are activated during off-peak hours, weekends, and holidays due to their significant effect in reducing traffic congestion. For example, in Los Angeles, some RMSs are operational due to heavy traffic at all times of the day (Balke et al., 2009).

Traffic Flow Parameters

Traffic flow parameters, such as traffic volume, speed, and occupancy, are used as criteria for activating and deactivating the RMSs during non-recurrent congestion. The use of these parameters is supported by the presence of detectors on freeways collecting real-time traffic data. For example, RMS operation guidelines in Texas indicate that the general activation and deactivation times during peak periods could be adjusted based on traffic demand. For high traffic demand, mainly observed near high-volume ramps located in suburban areas, RMS activation could be considered when the traffic volume in the right-most lane of the freeway reached approximately 1,600 vphpl (Balke, 2009b).

In some Caltrans districts, metering hours are selected based only on traffic speed and volume-to-capacity (v/c) ratio (Lu, 2019). The RMSs are activated at any time of the day when the speed is less than 30 mph, and the v/c ratio is between 0.6 and 0.8. In Oregon, ODOT started weekend ramp metering, using time-of-day scheduling, following an increase in complaints related to weekend congestion (Bertini et al., 2004). A traffic study was performed along the corridor in the complaints, and results revealed that speeds were reduced to less than 30 mph during weekend congestion. Therefore, weekend ramp metering was implemented from May through December from 12:00 pm to 6:00 pm to address the issue under consideration. In Michigan, RMSs controlled by several remote control units were activated during off-peak periods in situations that caused a drop in traffic speeds of 35 – 45 mph (Kostyniuk et al., 1988). The RMSs were deactivated when traffic speeds returned to 50 – 60 mph. The activation and deactivation of the RMSs in Michigan also considered the traffic occupancy. RMSs were activated during off-peak periods for roadway events that resulted in an increase in traffic occupancy of 10% – 13% (Kostyniuk et al., 1988). The RMSs were deactivated when traffic occupancy returned to 6% – 9%.

Incident Characteristics

Few transportation Agencies have realized the advantages of activating the RMSs during non-recurrent congestion due to incidents. Operators are assigned to activate the RMSs based on traffic conditions observed using CCTV cameras (Fartash, 2017). FDOT guidelines suggest activation of the first adjacent upstream RMS in the case of a traffic incident not requiring lane blockage but causing congestion. The procedure involves the activation and deactivation of the downstream RMS, adjacent to the incident, during peak and off-peak hours, respectively. NDOT requires an operator to change the RMS operation hours during emergencies or unique situations (Jacobs Engineering Group Inc., 2013). Conversely, Minnesota TMCs use CCTV cameras to view crash locations and temporarily deactivate the RMSs until the incident is cleared (Athey Creek,Consultants, 2019).

Lane blockages affect the capacity of freeways and interrupt the regular traffic flow. FDOT District 6 established guidelines, shown in Table 3, regarding actions to be taken for a lane blocking incident at locations with RMSs (Zhu et al., 2010). In addition to activating or deactivating RMSs, the guidelines indicate the number of RMSs to be activated along the corridor. In a recent study, Fartash (2017) considered the demand-to-capacity ratio (D/C) due to lane blockage to determine whether RMSs should be activated on the study corridor with 10 RMSs installed. The need for activating the RMSs was derived from the predicted demand values in the next 15 minutes and the estimation of the forecasted D/C ratio for the next 15 minutes. Results indicated a need for activating all 10 RMSs due to lane blockage incidents during peak hours.

Table 3: Guidelines for activating RMSs for traffic incidents in Florida

Event	Upstream RMS	Downstream RMS
All Lanes Blocked	Activate all RMS	Deactivate temporarily.
		Activate immediately after the blockage is cleared.
> 2 Lanes Blocked	Activate all RMS	Deactivate the 1st adjacent RMS or temporarily deactivate during the peak period.
		Deactivate other downstream RMS based on the level of congestion OR use a higher metering rate.
		Activate immediately after the blockage is cleared.
≤ 2 Lanes Blocked	• Activate 1st adjacent RMS • Activate other RMSs depending on queuing conditions	Activate and use a higher metering rate.
		Deactivate the 1st adjacent RMS or temporarily deactivate during the peak period.
		Adjust back to the regular operation or deactivate once after the freeway has returned to a free-flow condition and the event is cleared.

Metrics for Activating and Deactivating the Ramp Metering Signals

Several metrics have been used to assess the performance of RMSs activated due to recurrent and non-recurrent congestion. The metrics included but were not limited to travel time, travel time reliability, traffic speeds, traffic delays, level of service (LOS), traffic volume, and traffic throughput. Table 4 summarizes the metrics used to evaluate the effect of activating RMSs and their focus location. The following subsections discuss in detail these performance metrics.

Table 4: Performance metrics used to evaluate RMSs activation

Metric	Freeway mainline	Entrance ramp	Arterial
Travel time	✓	✓	
Travel time reliability	✓		
Traffic speed	✓		✓
Traffic delays	✓	✓	✓
Traffic volume	✓	✓	✓
Traffic throughput	✓		
Level of service (LOS)	✓		

Travel Time

Several studies have used travel time as a metric for the benefits of activating the RMSs (Cohen et al., 2017; Karim, 2015; Kansas Department of Transportation [KDOT] & Missouri Department of Transportation [MoDOT], 2011). The travel time data were collected using either traffic detectors or the floating car technique (FCT) (Cambridge Systematics Inc., 2001; Cohen et al., 2017; KDOT & MoDOT, 2011). In a joint study, the Kansas Department of Transportation (KDOT) and the Missouri Department of Transportation (MoDOT) (2011) analyzed the travel time on a ramp metered corridor before and after the start of metering operations using the FCT. The study focused on morning peak hour periods. Results indicated significant improvements in travel time during morning peak hours with RMSs activated.

In a recent study, Cohen et al. (2017) derived travel times from flow, occupancy, and speed to estimate the benefits of activating the RMSs on a 40-mile section of the A25 roadway linking Socx and Lille in France. Cambridge Systematics, Inc. (2001) collected travel time data to evaluate the benefits of RMS activation on freeway entrance ramps. Results revealed that the travel time when the RMSs were deactivated was 2.3 minutes shorter than when the RMSs were activated (Cambridge Systematics Inc., 2001).

Travel Time Reliability

Travel time reliability measures the consistency of travel time and reflects the road user's experience in commuting. Metrics used to indicate the travel time reliability can be grouped as variation metrics, probabilistic measures, and the percentile index (Kidando et al., 2019). Variation metrics are based on the measures of the central tendency, which include standard deviation, variance, mean, median, coefficient of variation, and kurtosis (Lomax et al., 2003). Probabilistic measures include misery index, congestion frequency, and percentage of on-time arrivals. The percentile index uses a percentile, such as the 10^{th}, 50^{th}, 90^{th}, and the 95^{th} percentile, of travel time distributions to estimate metrics, such as buffer index (BI), planning time index, travel time index (TTI), and the skew statistic (Lomax et al., 2003). The TTI is calculated as the ratio of actual travel time to the travel time under free-flow speed (FFS) or posted speed limit. The BI is calculated as the ratio of the difference between the 95th percentile and the average travel time to the average travel time. Lower TTIs and BIs indicate reliable travel times along a corridor.

In the study by Cohen et al. (2017), the variance of travel times was used to show the benefits of activating the RMSs on the A25 roadway connecting Socx to Lille in France during morning peak hours on weekdays. Study findings indicated that activating the RMSs reduced the variation of travel time along the study corridor. Results also indicated that travel time on the study corridor varied more when ramp meters were deactivated. Alluri et al. (2020) showed the benefits of activating RMSs by comparing the BIs along a corridor with ramp metering in Florida. The study compared the BIs when the RMSs were activated with BIs when the signals were deactivated due to system malfunction. Findings indicated that starting the RMSs was associated with a 22% reduction in the BI values when mainline traffic was at LOS C and LOS D. Also, activating the RMSs was associated with a 30% reduction in the B.I. Values when mainline traffic was at LOS E and LOS F (Alluri et al., 2020). Using the TTI and BI, Xie et al. (2012) demonstrated the improvements in travel time reliability resulting from activating RMSs along a corridor in Las Vegas, NV. Similarly, KDOT and MoDOT (2011) showed that TTIs after activating the RMSs were lower than before activation along the study corridor.

Travel Speed

Travel speed is another metric that can be used to evaluate the performance of RMSs. In a joint study by KDOT and MoDOT (2011), travel speeds along with metered segments before and after the start of RMSs operations were compared. Results showed that most of the segments increased after activating RMSs during morning and evening peak hours. Two separate studies evaluated the benefits of RMSs in the twin cities of Minneapolis and St. Paul, MN (Cambridge Systematics Inc., 2001; Hourdakis & Michalopoulos, 2007). These studies compared the travel speeds when RMSs were deactivated and activated and found that, on average, speeds increased by 14% when the RMSs were activated. Hourdakis and Michalopoulos (2007) used traffic simulation to analyze the benefits of activating the RMSs using travel speeds. Analysis results indicated a 13% to 26% mainline speed improvement on the simulated study corridors. Trinh (2000) used travel speeds to show the Fuzzy Logic algorithm's benefits in ramp metering before implementation in Washington State (Trinh, 2000). From the analysis, it was observed that the algorithm increased the speeds by 7 to 20 mph. However, in another study, average travel speeds on HOV lanes did not improve due to activating the RMSs on a Las Vegas corridor (Xie et al., 2012).

Travel speeds also showed the benefits of activating the RMSs on arterials parallel to the metered freeways. A study conducted by Cambridge Systematics Inc. (2001) showed that changes in the travel speeds on parallel arterials were insignificant when RMSs were activated. The insignificance of changes was attributed to the traffic signal control of many intersections along the arterials used in the study. Results suggest that, without significant changes in arterial volumes that can cause gridlock at intersections, travel speeds along arterials are expected not to change because of ramp metering operations (Cambridge Systematics Inc., 2001).

Traffic Delays

The reduction in traffic delays on the freeway mainline, entrance ramps, and arterials can show the benefits of activating the RMSs. Traffic delay is estimated as the excess travel time on a trip, facility, or freeway segment beyond what would occur in ideal conditions (Cambridge Systematics Inc., 2001; Sun et al., 2013). Using traffic simulation, Sun et al. (2013) estimated the traffic delays in work zones when RMSs were activated and deactivated. The total vehicular delay, which included traffic delay on the mainline and entrance ramp, indicated that activating the RMSs is beneficial for work zones. Results showed a 24% and 19% decrease in delay in traffic with a low and high truck percentage, respectively.

In a study by Drakopoulos et al. (2004), delays on entrance ramps were used to assess the need for more RMSs along a corridor in Milwaukee, WI. Findings indicated that the activation of more RMSs would significantly increase entrance ramp delay (Drakopoulos et al., 2004). Hourdakis and Michalopoulos (2007) observed improvements on some ramps and a significant increase in delays on other ramps using a traffic simulation. For some ramps, the estimated delay was as high as 11 minutes of average wait time. Levinson and Zhang (2006) suggest that despite positive impacts on the freeways, ramp metering might increase traffic delays on-ramps. Neel and Gibbens (2001) evaluated the impact of activating RMSs on adjacent arterials in Seattle, WA. The study collected traffic data before and after the start of morning RMS operations. Results indicated a reduction of the queue length for one of the adjacent arterials due to activating the RMSs (Neel & Gibbens, 2001).

Traffic Volume and Throughput

Several studies used traffic volume to show the benefits of activating RMSs. Cambridge Systematics, Inc. (2001) evaluated the traffic volume data collected during morning and afternoon peak hours when RMSs were activated and deactivated for five weeks each. An average of 9% reduction in the traffic volume along freeways was observed when the RMSs were deactivated. Moreover, the freeway throughput during peak traffic conditions, measured by vehicle-miles-traveled (VMT), declined by 14% when ramp meters were deactivated. Bertini et al. (2004) assessed the benefits of activating the RMSs on weekends using mainline throughput calculated in terms of VMT and vehicle-hours-traveled (VHT). Results indicated a 5.8% increase in the VHT and a 0.7% increase in the VMT along the corridor due to activating the RMSs on Saturdays. Slight improvements in VHT (1.8%) and VMT (1.0%) were observed due to activating the RMSs on Sundays.

Diversion in the traffic using an entrance ramp was also used to show the benefits of activating RMSs. Horowitz et al. (2004) analyzed the diversion of traffic amongst ramps caused by ramp metering operations. Traffic diverted from one metered ramp may come back to the freeway through different downstream ramps. This procedure resulted in reducing the traffic queue on the former ramp. Results from the study indicated significant traffic diversions between entrance ramps when RMSs were activated (Horowitz et al., 2004). Moreover, approximately more than 10% of vehicles were diverted between different entrance ramps.

Diversion of traffic from the freeway to parallel arterials is another positive benefit of activating the RMSs (Horowitz et al., 2004). Cambridge Systematics, Inc. (2001) collected traffic volume data on selected arterials parallel to the metered freeway. The analysis showed minimal diversion of traffic from the freeway to parallel arterials when ramp meters were deactivated. It was concluded that freeway traffic might have diverted to arterials that were not included in the study or during other periods. Horowitz et al. (2004) indicated that traffic diversion from the freeway to arterials when the RMSs were activated was less than 10 percent. However, the traffic diverted from the freeway was not equal to the total increase in traffic on the parallel arterials, suggesting that traffic did not divert only to the arterials included in the analysis. Using an analytic model, Zhang (2007) indicated that activating the RMSs does not worsen traffic conditions on all arterials in the network. Owing to the network equilibrium, some arterials might experience better traffic conditions, while others might be impacted negatively (L. Zhang, 2007).

Level of Service (LOS)

The level of service on a freeway is based on density and speed. Cohen et al. (2017) used LOS to measure the benefits of activating the RMSs. Their study collected conventional traffic data to estimate LOS, i.e., flow, occupancy, and speed. Additional data were also collected to provide further insights into conditions when RMSs were activated and deactivated, including incidents, planned construction work, and adverse weather conditions. LOS was estimated using fundamental traffic flow diagrams to assess the mobility improvements due to ramp metering operations and the combination of ramp metering and variable speed limits (Cohen et al., 2017). The study reported insignificant changes but indicated that LOS gains are limited to the regulated section and have no impact on downstream sections.

Ramp Metering Strategies

Ramp metering strategies can be classified into fixed time, adaptive, and proactive strategies (Kristeleit, 2014), (Papageorgiou et al., 1997). Over a long period of time, fixed time strategy aims to maintain traffic conditions based on the prescribed traffic pattern. Adaptive strategies aim to maintain the freeway operation conditions at prespecified, desired values using real-time measurements. Meanwhile, the proactive strategy maintains optimal traffic conditions based on freeway network demand predictions (Hasan, 1999) (Fartash, 2017). Ramp metering strategies can be used in the metering rate selection, metering activation strategy, and on ramp meter algorithms

Metering Rate Selection

Metering rate selection mode can be static, or proactive (predictive) or adaptive (traffic responsive) (Fartash, 2017). In static mode, the metering rate is calculated based on the assumption that the traffic patterns tend to be the same over time. Adaptive ramp metering rate is calculated based on actual traffic conditions on the freeway mainline and ramp. Similarly, the proactive calculates the metering rate based on real-time data in order to prevent traffic complications such as traffic breakdown (Fartash, 2017).

Metering Activation Strategy

Activation of RMSs can either be done manually, scheduled, or in response to current or predicted traffic conditions within the proactive and adaptive strategies. Under the manual strategy, CCTV cameras are mostly used where operators watch live traffic conditions and adjust the metering rate accordingly (Fartash, 2017). The dynamic activation strategy uses the current traffic measurements or predicted measurements to prevent breakdown and congestion. However, it has also been noted that automated activation strategies are increasingly more used than manual activation (Fartash, 2017).

Ramp Metering Algorithms

Ramp metering algorithm can be classified based on the number of ramps being metered. Local algorithm focuses on only one ramp as an isolated element, and system-wide (coordinated) algorithm considers multiple ramps (Fartash, 2017). Studies have been carried out on the performance evaluation of ramp meter algorithms at reducing recurring congestion during peak hours. It has been proved that coordinated (system-wide ramp meter algorithms) perform better than local ramp meter algorithms (Taale et al., 1996). System-wide metering is more effective than local metering since it can prevent and delay traffic breakdowns at a particular location through metering multiple upstream ramps rather than relying on metering the ramp immediately upstream of the bottleneck. This dependence on one ramp may not be enough to produce the desired effect required for the system (Fartash, 2017). Systemwide RMSs require detectors to be placed on the ramp along the entire metering section. In contrast, the local metering algorithms, both schedule-based and responsive, only require detectors to be located around the vicinity of a ramp area (Hadj-Salem et al., 1990).

Local Ramp Metering Algorithms

Several local ramp meter algorithms have been developed over the years. This algorithm works by considering one ramp as an isolated element. This section discusses the three mostly referenced local metering algorithms: ALINEA algorithm, demand-capacity algorithm, and percent-occupancy algorithm.

ALINEA Algorithms

One of the most common local ramp metering strategies is the Asservissement Linéaire d'Entrée Autoroutière (ALINEA) algorithm. ALINEA was developed by Papageorgiou in 1997 and was initially deployed in Paris, Amsterdam, and Munich (Kristeleit, 2014). The ALINEA algorithm is a local traffic responsive control algorithm with a feedback regulator (Papageorgiou et al., 1997). The main aim of ALINEA is to maintain the traffic flow by maintaining the capacity of the downstream merge area to a desired critical occupancy value. The desired metering rate is thus updated based on the downstream measurements as shown in Equation 1:

$$r(K) = r(K-1) + KR[\hat{o} - O_{out}(K-1)] \quad (1)$$

where,

r(K)	=	metering rate at time interval K,
KR	=	constant regulator parameter (veh/hr),
Oout (K-1)	=	last measured upstream occupancy value,
ô	=	value for downstream occupancy (predefined).

ALINEA algorithm has been the widely deployed local ramp metering strategy since it's simple and has low implementation costs. It mainly targets performance goals because the on-ramp has sufficient storage (Shaaban et al., 2016). Studies have been performed to evaluate the potential benefits of the ALINEA ramp metering algorithm. Berk, H (Berk et al., 2017) did a performance evaluation on the I-405 freeway in California under both current and non-current congestion. Demiral (Berk et al., 2017) used ALINEA for a single lane merging ramp for Istanbul, Turkey. Bhouri (Bhouri et al., 2013) performed an evaluation study on the A6W motorway in Paris, France, to compare the improvement in the travel time reliability. According to Hadj-Salem (Hadj-Salem et al., 1990), ALINEA is one of the most widely cited and implemented strategies in Europe. Over time, multiple extensions of it have been developed to deal with different issues and challenges. FL-ALINEA, UF-LAINEA, UP-ALINEA, X-ALINEA/Q and MALINEA (Fartash, 2017)

FL-ALINEA algorithm is an extension that modifies the original ALINEA equation to overcome occupancy measurements issues. It modifies the original ALINEA equation by substituting occupancy with the downstream flow since it is recommended to keep the critical flow at least 10% below capacity (Fartash, 2017). On the other hand, the UF-ALINEA algorithm, which estimates the downstream flow instead of measuring it, was developed to modify FL-ALINEA. In the FL ALINEA, both the downstream and upstream mainline flows are considered. The UP-ALINEA algorithm is an extension that addresses the issues of occupancy in scenarios where only the upstream occupancy is available, and the ALINEA algorithm needs to be modified to calculate the downstream occupancy based on the upstream measurements (Hasan, 1999). Additional measurements of the entering flow from the on-ramp to the freeway and upstream of the freeway are required to calculate the downstream occupancy. Ramp metering may cause the formation of large queues on the ramp, which may affect the surrounding street (Fartash, 2017). The X-ALIANEA/Q requires measuring the ramp and queue length to account for this queue on the ramp (Hasan, 1999). Lastly, the MALINEA algorithm measures the upstream occupancy of the freeway segment and the time lag between the upstream and downstream measurements in order to incorporate the upstream conditions in te metering rate equation.

Demand-Capacity Algorithm

This algorithm is one of the initial traffic responsive ramp metering algorithms and is considered as a fundamental for other metering algorithms. This algorithm utilizes conditions from up and downstream of the ramp, such as real-time freeway flow or occupancy measurements (Fartash, 2017). The metering rate is calculated as a function of the difference between upstream occupancy and desired occupancy (Kristeleit, 2014). The demand-capacity algorithm advantage lies on its simplicity. Its limitation is that the level of congestion on the freeway cannot only be determined using the upstream freeway occupancy.

Percent-Occupancy Algorithm

This algorithm relies on the linear relationship between the metering rate and upstream occupancy measurements to determine the level of congestion and does not require downstream occupancy measurements (Fartash, 2017). Equation 2 demonstrates how the metering rate is calculated, where K0 is the constant value of freeway capacity and K1 is the slope of occupancy to flow line in the congested part of the fundamental diagram(Hasan, 1999) (Fartash, 2017).

$$r(k) = K_0 - k_1 O_{in}(k-1) \tag{2}$$

Where

r(k) = metering rate at time interval k,

K_0 = constant value of freeway capacity (veh/hr) and,

$O_{in}(K\text{-}1)$ = last measured upstream occupancy (%).

System-Wide Ramp Metering Algorithms

System-wide ramp metering algorithms are classified as cooperative, competitive, or integral. The metering rate is calculated based on local conditions and adjusted according to system-wide considerations in cooperative ramp metering. The metering rate for competitive algorithms is calculated at both system-wide and local levels. The integral algorithm calculates both rates and then simultaneously incorporates them in the metering rate calculation to determine the optimal metering rates (Fartash, 2017) (Bertini et al., 2004). This section discusses some of the mostly referenced systemwide ramp metering algorithms

The Linked Ramp Algorithm

The linked ramp meter algorithm is a cooperative algorithm that utilizes the historical traffic flow data to calculate the maximum and minimum metering rates at each ramp. Based on the local capacity estimated from historical data, the maximum metering rate is calculated, which is the difference between the target traffic flow (considering capacity) and upstream traffic flow (Kristeleit, 2014).

The Helper Algorithm

The helper algorithm is a cooperative algorithm that includes the local traffic responsive algorithm enhanced with a system override feature (Kristeleit, 2014). This algorithm first determines the metering rate for each on-ramp using a local traffic-responsive algorithm and simultaneously monitors the on-ramp queue using the queue detectors. When the queue occupancy on a queue detector exceeds the predefined threshold, the ramp is identified as a critical ramp, and this algorithm's system override feature is activated. The system override feature increases the metering rate of the critical ramp while reducing the metering rate of the upstream ramps to mitigate the congestion in the vicinity of the critical ramp (Bertini et al., 2004).

The SWARM Algorithm

The System-Wide Area Ramp Metering (SWARM) algorithm is a competitive systemwide algorithm that divides the freeway into continuous sections bounded by the bottleneck locations that are identified by loop detectors. The metering rate values for each section are produced by the SWARM modes, and the restrictive metering rate is selected (Fartash, 2017). SWARM is a predictive algorithm, and its performance is highly dependent on the accuracy of the prediction. The predictive features enable the algorithm to prevent bottlenecks. High-accuracy predictions are required in the SWARM algorithms, in accurate prediction may produce very poor results. ALINEA and the bottleneck algorithms have proven to produce accurate results than the SWARM algorithm with a five-step ahead prediction (M. Zhang et al., 2001).

Seattle Bottleneck Algorithm

Seattle bottleneck algorithm is another example of a competitive systemwide ramp meter algorithm. In this algorithm, the local and bottleneck metering rates are calculated using the upstream mainline occupancy at each ramp obtained for local-responsive detector data and bottleneck information for bottleneck metering. The lower metering rate between the local and bottleneck is assigned to each ramp. The local metering rate is the difference between the real-time upstream volume and estimated capacity. The volume-capacity relationship is used to estimate the capacity. The volume to capacity relationship is calculated using the historical data upstream of the ramp (Jacobson et al., 1989). Once the metering rate is set as the lowest value of local and bottleneck metering rates, the rates need to be adjusted considering the queues on the ramp, a ramp volume adjustment, and an advance queue override (Fartash, 2017).

Washington Fuzzy Logic Algorithm

The Washington Fuzzy Logic algorithm is an integral system-wide control responsive to local and system-wide real-time traffic conditions (Mizuta et al., 2014). The Washington Fuzzy Logic Algorithm was developed in response to the limitation of the Seattle Bottleneck algorithm. The combination of Seattle's population, which was 47 % of the Washington's state population, with its geography created the problem of mobility on the freeway system (Jacobson et al., 1989). Using the Seattle bottleneck algorithm alone was a challenge in that when queuing occurs, the metering rate was adjusted upwards without trying to reduce the metering rate at nearby meters, and this resulted in the development of the Washington Fuzzy Logic algorithm

The Washington Fuzzy Logic algorithm utilizes various traffic conditions upstream and downstream of the ramp in managing and controlling traffic on the freeway network. It established the metering rates through a three-step procedure: Fuzzification, activation of rules, and generation of numerical rates (i.e., defuzzification) (Taylor et al., 2000). Fuzzy Logic-based algorithms are popular because of their simplicity and fast reconfiguration.

A review of existing literature showed few studies had been done to compare the Fuzzy Logic algorithm with local and bottleneck algorithms (Jacobson et al., 1989). The project's scope did not include comprehensive, system-wide testing but rather a preliminary study site testing to determine whether the Fuzzy Logic Ramp Metering Algorithm was beneficial relative to the other ramp metering algorithms. In Holland, the Fuzzy logic Controller was tested for online ramp mitering on the A12 freeway between the Hague and Utrecht. The controller produced 35 percent fast travel times and a 5 to 6 percent greater bottleneck capacity (Taale et al., 1996).

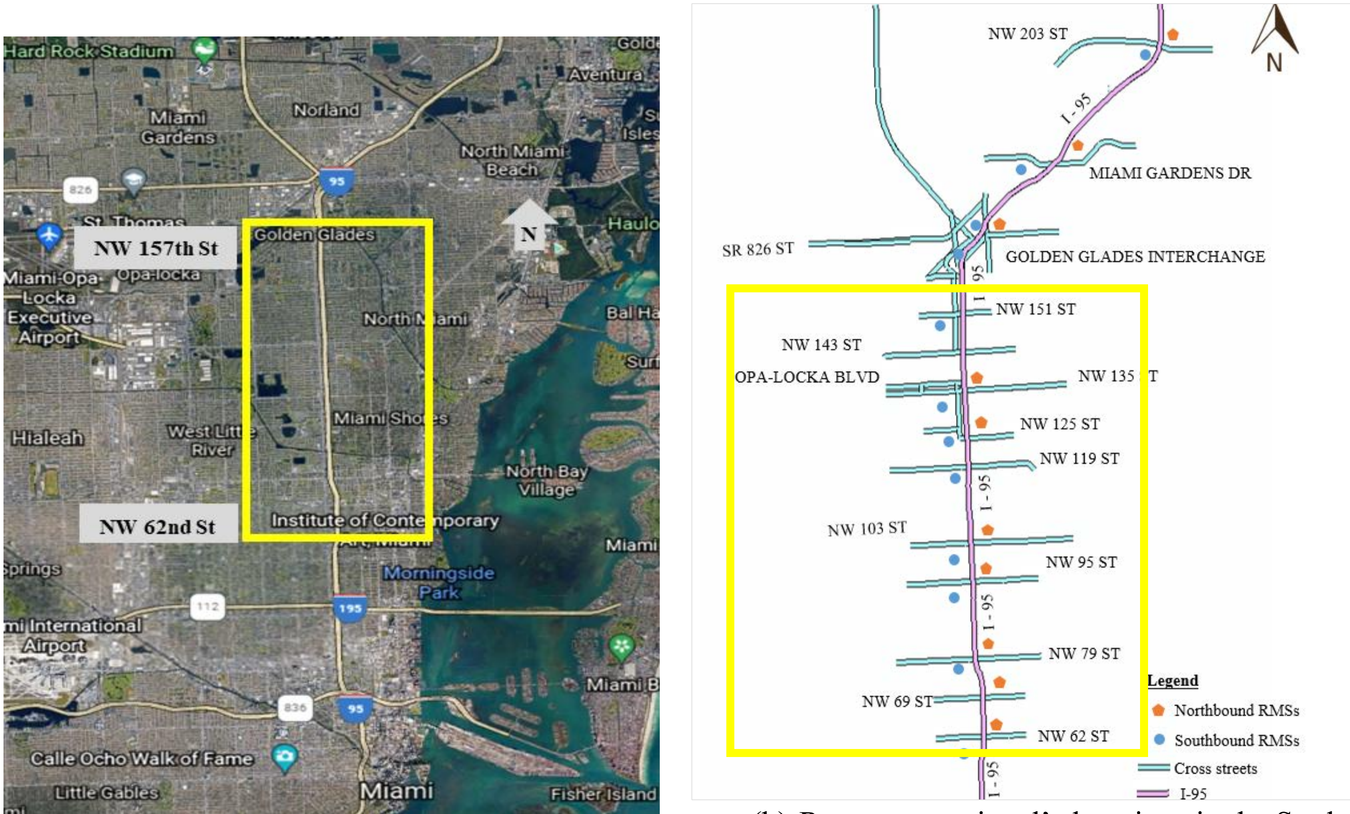
CHAPTER 3

METHODOLOGY

Study Area

A section along I-95 in Miami-Dade County, Florida, was selected as a study corridor for the microscopic simulation of the weekend non-recurring congestion. This approximately 6.5 miles road segment of I-95, spanning between Northwest (NW) 157th Street and NW 62nd Street in Miami, Florida Figure 2 (a) consists of seven on-ramps and six off-ramps in the north-bound direction. On the other hand, there are six on-ramps and seven off-ramps in the south-bound direction Figure 2 (b). The freeway in both directions has seven lanes, whereby two lanes in each direction are express lanes. The study location was extracted from the base model, which is an 18 miles road segment extending from SW 17th Avenue in S Dixie Highway to Ives Dairy Road in Miami, Florida.

Ramp metering operations in the study area began in 2009 and are operated and managed by FDOT District 6. The RMSs in the study area are operational during the morning peak for the SB direction and the afternoon peak for the NB direction. The morning peak for this corridor is typically from 6:00 am to 10:30 am, while the afternoon peak is between 3:00 pm and 7:00 pm. Activation and deactivation of the RMSs also depend on traffic conditions; thus, the RMSs are not necessarily activated at the same time. Also, the RMSs in the study area are used for traffic management during non-recurring congestion due to incidents or special events (e.g., sports events.



(a) Study area along I-95 South

(b) Ramp meter signal's locations in the Study area

Figure 2: Study corridor

Data Description

One dataset was used to develop the guidelines for activating the RMSs on the weekend non-recurring congestion: traffic flow data for weekends. The following section describes the data used in this study in detail.

Weekend Traffic Flow Data

Weekends data was obtained from the detectors located in the study corridor using the Regional Integrated Transportation Information system (RITIS). RITIS is an automated data sharing, dissemination, and archiving system that includes real-time data feeds and archive data analysis tools, such as a probe, detector, and transit data analytics. RITIS stores and disseminates data from various sources, including data vendors such as HERE Technologies, INRIX, and TomTom and detectors maintained by FDOT.

The data in RITIS was collected using detectors maintained by FDOT District 6 and extracted in aggregated one-hour intervals for a duration of one year from January 2019 to December 2019. The reason for choosing this time frame is that since the COVID-19 pandemic in 2020, there were changes in traffic patterns due to lockdown restrictions. Therefore, January 2019 to December 2019 was the latest data with actual traffic patterns. The detectors used for the mainline were located just upstream of the on-ramp were used. The passage detectors located immediately downstream of the ramp signal's stop bar were used to collect the on-ramp data. On the other hand, for the off-ramp, it was calculated by taking the difference between the summation of the mainline detector and passage detector to the mainline detector near the off-ramp detector. Figure 3 illustrates the locations of the detectors that collect data along the freeway mainline between NW 62nd Street and NW 157thStreet.

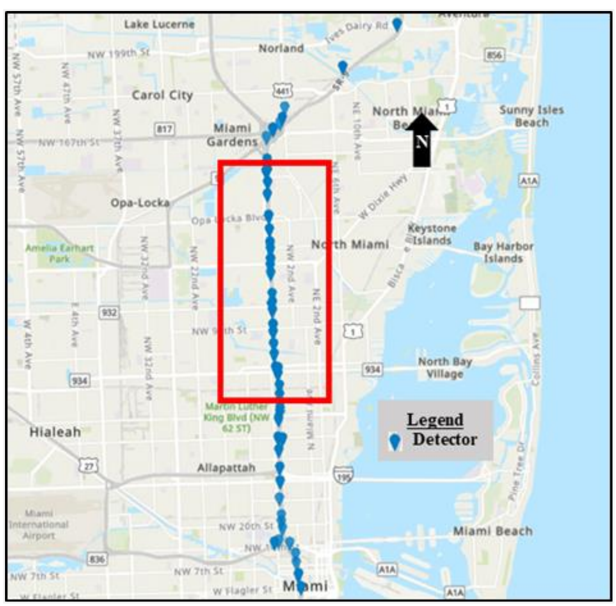


Figure 3: Sample detector locations for traffic data along the study corridor

Data Cleaning Process

The average weekend volume obtained from RITIS was used as input volume in the calibrated VISSIM Model. The data was first processed into ArcGIS pro software to plot their coordinates to confirm their location in the study area. The data was then cleaned to remove outliers that could bring abnormal average traffic volume results for each ramp, off-ramp, and freeway mainline. Data cleaning was done using the boxplots plotted in the Minitab software, and the average volumes were computed and attributed in the ArcGIS Pro, ready for input into the VISSIM model

VISSIM Microscopic Simulation

The real-world data for when the RMSs are operational were not found because in Florida RMSs are not operational during the weekends. Thus, the VISSIM microsimulation approach was used to develop guidelines for the activation of RMSs on weekends.

VISSIM simulation tool is a powerful multimodal modeling software used due to its capabilities in the traffic modes such as express lanes and freeways. VISSIM was selected for this study due to its strong capabilities in modeling various freeways segments and ramps to match the actual traffic conditions. The simulation conducted for the study was microscopic. Microscopic models produce stochastically real roadway networks, traffic volume, driver characteristics, and vehicles on a timestep basis through lane change rules and gap acceptance by using computers.

The model of the freeway study area was modeled by VISSIM using relevant roadway characteristics and calibrated and validated to represent real-world traffic situations. Traffic data required for traffic volume was obtained from the RITIS database through the detectors along the study corridor. The volume data was then introduced in the model and processed to create vehicle routes based on Origin to Destination (OD) matrices generated for three hours, i.e., 10800 simulation seconds, to account for the variability in traffic.

The freeway consisted of seven lanes, five of which were general purpose lanes, and two were the express lanes. Two scenarios of the incident, i.e., two-lane blockage and three-lane blockage blocking 40% and 60 % of the general purpose lanes, respectively, were modeled and simulated in the VISSIM microsimulation tool both with and without the ramp meter signal activation. A sensitivity analysis test was performed where the traffic demand for the ramps and freeway was systematically varied to simulate the travel demand variability in real situations. Systemwide RMSs activation upstream of the incident was done using the Washington fuzzy logic algorithm. Data collection points in VISSIM were used to collect the speed, volume, and occupancy data upstream of the incident in the simulation for all incident scenarios both with and without the ramp meter signal in operation. The study's findings were then used to develop the criteria for activation of RMSs using a paired t-test. Furthermore, the study analyzed how activation of RMSs on the weekend non-recurring congestion impacted the roadway network. The quantification of the potential benefits was done by analyzing the impacts relating to traffic flow conditions, i.e., average speed and delay of vehicles in the roadway network.

Base Model Development and Calibration

The microsimulation model was developed to replicate the existing traffic characteristics in the study area. FDOT provided the base model, and it served as a baseline on which other alternatives were made. The model provided by FDOT and was already calibrated following the FDOT Traffic Analysis Handbook (HCM, 2016) guidelines.

Creating a Scaled Base Model

Various methods were used to create a base model. According to the FDOT Traffic Analysis Handbook, It is recommended that any base model be created from computer-Aided Design and Drafting (CADD) image or scaled background images such as an orthorectified aerial image or (FDOT, 2014). Scaled background images in VISSIM can be imported from Bing maps and Google maps. For this study, The scaled base model was created from a Bing Map following VISSIM software guidelines (PTV, 2021).

Road Network Geometry

The road network geometry in VISSIM can be created using links and connectors available in the network editor. The images from the Bing map were used to provide accurate geometry for the lanes in the study area, which were used with the PTV 2021 VISSIM guidelines. Below are some of the important parameters considered in creating a road network

- Areas with off-ramp were created so that the lane-changing movement started at least half a mile before vehicles exited the freeway.
- The single link was used to code freeway mainline with similar geometry to minimize unnecessary segmentation along the corridor
- Overlap links and connectors were minimized in areas where segmentation was required.

Desired Speed

The desired speed for each freeway and ramp segment was modeled based on existing speed limits available in the study location. This study used the section between NW 62nd street and NW 157th street. In VISSIM, the empirical distribution of desired speed was developed as per Currin (2001) guidelines. In this study, the desired speed was modeled by the FDOT in the base model for all vehicle types such as single occupancy, high occupancy, vanpool, and trucks.

Vehicle Composition

According to the Project Development and Environment Studies (PD&E), the FDOT provided the percentage of vehicle composition in the model for the study segment. The FDOT provided the percentage of vehicle composition for the cars, trucks, single occupancy vehicles, and high occupancy vehicles in the study area. The guidelines that this study developed were based on these percentages of vehicles that the FDOT provided.

Traffic Signal Controller

The traffic signal controllers were used for ramp meters in this study. The VISSIM microscopic models use external software such as VISTRO and SYNCRO for signal coordination and optimization. The outputs produced by these softwares were the Ring Barrier Controllers (RBCs), which were then imported into respective VISSIM signal controllers. The signal controllers have respective signal heads that replicate the signal heads in real traffic conditions.

Base Model Verification

Model verification was performed to ensure the base model did not contain errors. Efficient model calibration has a significant influence on the development of an error-free base model. The model verification process was done using a VISSIM Model error checking checklist provided in the FDOT Traffic Analysis Handbook (FDOT, 2014).

Number of Simulation Runs

VISSIM assigns different random numbers for each run to replicate the stochasticity of traffic flow in real-world traffic flow patterns. Random seeding returns different outputs for each run. The random seed helps to vary the properties of vehicles entering the network, such as the time a vehicle enters a network, the driver’s aggressive behavior, the decision on the type of vehicle entering the network, and the vehicle’s interaction in the network (Russo, 2008). If you vary the random seed, the stochastic functions in VISSIM are assigned a different value sequence, and the traffic flow changes (PTV, 2021).

The preliminary number of runs (10 runs) is assumed adequate by the FDOT Traffic Analysis Handbook (FDOT Systems Planning Office, 2014). However, the required number of runs was calculated as recommended by the Traffic Analysis Handbook using Equation 3:

$$n = \left(\frac{s * t_{\frac{\alpha}{2}}}{\mu * \varepsilon}\right)^2 \quad (3)$$

where

n	=	required number of simulation runs,
s	=	standard deviation of the system performance measure based on the previous simulation runs,
$t_{\frac{\alpha}{2}}$	=	critical value of a two-sided Student t-statistic at the confidence level of α and $n - 1$ degree of freedom,
μ	=	mean of the system performance measure, and
ε	=	tolerable error, specified as a fraction of μ, desirable value of 10%.

The optimal number of simulation runs for the model was determined from the preliminary simulation runs. The standard deviation was calculated using different seed values. The volume, speed, and travel time were used as a metric for the analysis of the standard deviation. Ten preliminary simulation runs as recommended by FDOT (2014) were carried out, and the standard deviations were obtained, as shown in Table 5.

Table 5: Preliminary simulation run's average performance measure

Simulation Run	Seed Number	Average		
		Speed (mph)	Volume (veh/h)	Travel Times (hours)
1	10	54.672	3375	976.64
2	15	54.722	3397	976.37
3	20	54.453	3399	982.05
4	25	54.516	3380	979.72
5	30	54.71	3388	975.76
6	35	53.927	3429	991.47
7	40	54.862	3365	973.47
8	45	54.251	3405	985.76
9	50	54.743	3400	974.68
10	55	54.989	3348	971.19
Average		54.58	3388	978.71
Standard deviation		0.31	22	6.18
Maximum		54.989	3429	991.47
Minimum		53.927	3348	971.19

Based on the preliminary simulation runs, the resulting average speed, total traffic volume, and travel time were 54.58 mph, 3388 veh/h, and 978.71 hours, respectively. A 95% confidence level was used as recommended in the study by Russo (Russo, 2008), where $t_{\alpha/2} = 2.262$, and error tolerance $\varepsilon = 10\%$ as recommended by the Traffic Analysis Handbook. The number of simulation runs was computed using Equation 3 and was less than 5. Therefore, ten (10) simulation runs were chosen as recommended in the Traffic Analysis Handbook by the Florida Department of Transportation (FDOT).

Error Checking

Error checking step of the microsimulation analysis process is important in ensuring that a working model doesn't have distorted features, leading to wrong simulation results. Efficient model results rely mostly on eliminating all errors in-demand coding and network coding.

According to the FHWA, the error checking process for the coded demand and network features is done in three different stages: a review of software errors, an evaluation of input coding, and a view of animations to spot less obvious errors (Dowling et al., 2004). It is further recommended that the residual error to be checked when the model does not perform to the satisfaction of analysts based on existing field conditions. Hereunder are the error-checking checklists performed for this study.

(a) Software

All the Ring Barrier Controllers (RBC) errors were checked and corrected. The errors due to the tolling script for the express lanes were also checked and corrected. There were no runtime warnings or errors that affected the simulation results

(b) Model Run Parameters

The initialization period was checked and confirmed that it was twice a vehicle's travel time through the entire network

(c) Network

The unusual traffic characteristics for lane change restrictions on the links and at intersections were checked. Link geometrics were checked to whether they matched the lane schematics.

(d) Traffic Control

Vehicle entering the freeway from entrance ramps were checked to see whether they reacted properly according to RMSs.

(e) Vehicle Characteristics

Vehicles were checked and ensured there were no lane changes in unrealistic locations, and all the lane changes were done upstream in the appropriate location.

Data Input into VISSIM

Since the calibrated VISSIM model from FDOT contained AM and PM peak traffic volume, the traffic volume had to be changed to reflect the traffic pattern on the weekends. In this case, the weekend traffic volume extracted from RITIS was inputted in the calibrated VISSIM model. The Dynamic Traffic Assignment (DTA) was used to assign the input traffic volume on the weekend in the calibrated VISSIM model. Note that the same method was used by the FDOT for AM and PM peak periods traffic. The DTA is an iterative process of generating route flows based on an Origin to Destination (OD) demand model. The DTA used the origin and destination pairs to calculate vehicles' optimal paths to reach the required destinations with minimum travel time at a minimal cost. The DTA approach was used because the network was extensive with no predefined path and multiple ways to get from the origins to destinations. As will be explained below, the route selection was based on a logit model where the paths with the highest utilities were chosen.

Destination Selection Process

In the DTA process, the origin and destination zones in VISSIM were marked by the parking lots. The parking lots served as zone connectors connecting origins and destinations. Vehicles in the network first had to select which destination zone they had to go to. The selection of which destination parking lot to go to was based on several factors such as the parking fee, attraction to that destination, distance from the origin to that destination, general cost, and availability of that parking space. The selection of a destination depended on a Logit model in VISSIM, which is essentially a decision model that incorporates utility functions. The destination selected is usually the one with the highest utility.

Path Selection Process

In VISSIM microsimulation, vehicles had to choose which path to take to reach the required destination. Each path had a cost associated with them, and this cost was not only the financial cost but also the travel time information, the distance of the path, and other surcharges defined by the user. Equation 4 represents the cost equation associated with each path.

$$\mathrm{Cost}_j = \alpha t + \beta d + \Upsilon To + \Sigma S \quad (4)$$

Where ;

t	=	travel time,
d	=	travel distance,
To	=	tolling,
S	=	other surcharges,
α	=	cost coefficients associated with travel time,
β	=	cost coefficients associated with travel distance,
Υ	=	cost coefficients associated with tolling,
$\boldsymbol{\Sigma}$	=	cost coefficients associated with other surcharges.

The coefficients were based on vehicle types, where different weights were assigned based on vehicle type. For instance, private vehicles may want to avoid toll roads and any other financially higher paths. In contrast, delivery trucks may emphasize the travel time and so would have a higher weight on the travel time than private vehicles. From Equation 4, the travel distance and other cost surcharges depended mainly on the network's structure. Still, the travel time was constantly updated as the simulation was run so that vehicle could react to the traffic conditions. The cost assignment in VISSIM follow the Kirchoff utility function shown in Equation 5

$$\mathrm{Uj} = \frac{1}{\mathrm{cost}_j} \tag{5}$$

Where;

Uj = utility of path j,

$cost_j$ = as defined in Equation 4.

For vehicles to choose which path to take, the utility function was applied to the path probability function shown in Equation 6.

$$\mathrm{p(Rj)} = \frac{\mathrm{U}_\mathrm{j}^k}{\Sigma U^k} \tag{6}$$

Where;

p(Rj) = probability of vehicle R in choosing path j,

Uj = utility of path j,

ΣU^k = summation of all path utilities k,

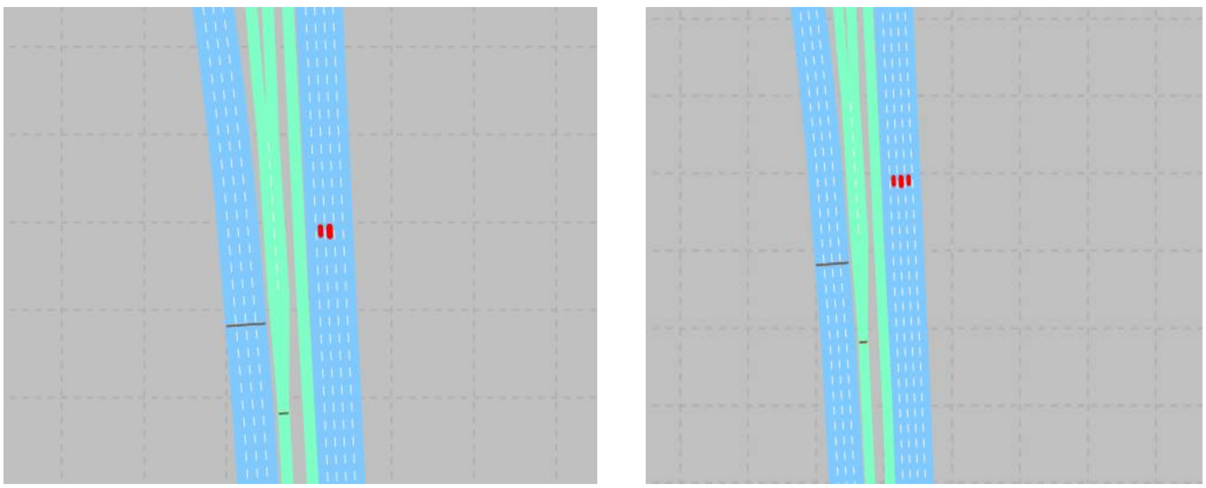
k = kirchoff's sensitivity exponent supplied by VISSIM.

Incident Scenarios

The freeway segment consisted of seven lanes, five of which were general purpose lanes and two were express lanes. The pairwise simulation was conducted for the incident scenarios on the general purpose lanes where two lanes out of five were blocked (40%) and three lanes out of five were blocked (60%).

- Incidents with 60-minutes incident clearance duration and two-lane blockage (40%)
- Incidents with 60-minutes incident clearance duration and three-lane blockage (60%)
- Incidents with 90-minutes incident clearance duration and two-lane blockage (40%)
- Incidents with 90-minutes incident clearance duration and three-lane blockage (60%)

These incident scenarios were modeled using the Component Object Model Application Programming Interface (COM API), where the incident modeling was done by writing and running the Python script to create incident scenarios. Both incident scenarios were simulated at about 500 ft north of NW 157th Street in the NB direction. Since it is impossible to simulate the actual incident in the VISSIM model, the disabled vehicle with zero speed was introduced in the VISSIM model to reflect the incident scenarios. As illustrated in Figure 4 (a) and Figure 4 (b), the incident with two-lane and three-lane blockage, respectively, were simulated.



(a) Two-lane blockage incident (b) Three-lane blockage incident

Figure 4: VISSIM incident scenarios

Two-lane Blockage (40%)

Two vehicles were programmed to stop at the freeway to represent a crash on the chosen location for an allocated time interval. The vehicles were also programmed to depart following the end of the allocated time, representing an incident duration. The study simulated two incident durations (60-minute and 90-minute) in all simulations. The incident durations selected were in the mean duration of the freeway incident with a closed lane according to Exhibit 11-22 of the 2016 Highway Capacity Manual (HCM, 2016) shown in Table 6.

Three-lane Blockage (60%)

Three vehicles were programmed to stop at the freeway to represent a crash on the exact location where the two-lane blockage incident occurred. The vehicles were also programmed to depart following the end of the allocated time, representing an incident duration. The study simulated two incident durations (60-minute and 90-minute) in all simulations. The incident durations selected were according to Exhibit 11-22 of the 2016 Highway Capacity Manual (HCM, 2016) shown in Table 6.

Table 6: Mean duration of freeway incident (HCM, 2016)

	Incident Severity Type				
Parameter	Shoulder Closed	1 Lane Closed	2 Lanes Closed	3 Lanes Closed	4+ Lanes Closed
Distribution (%)	75.4	19.6	3.1	1.9	0
Duration (mean)	34	34.6	53.6	67.9	67.9
Duration (std. dev.)	15.1	13.8	13.9	21.9	21.9
Duration (min.)	8.7	16	30.5	36	36
Duration (max.)	58	58.2	66.9	93.3	93.3

Simulation with and without Ramp Meter Activation

A sensitivity analysis was conducted on the VISSIM traffic volume inputs in developing the guidelines for RMSs activation. By systematically varying the vehicle inputs (traffic volume) on the freeway and the entrance ramp for various incident scenarios discussed above, the study determined the traffic conditions at which RMSs activation significantly improved operations in the mainline and on entrance ramps. The traffic data, i.e., speed, were collected from the detectors placed in the VISSIM model, both with and without RMSs. These data were collected on the freeway mainline for all the incident scenarios simulated. Table 7 lists all the cases considered as part of the sensitivity analysis.

Table 7: List of cases considered in the sensitivity analysis

Scenario	Case Number	Ramp Volume (Vphpl)	Freeway Mainline Volume (Vphpl)
Incidents with 60-minute incident clearance duration	I	150	300
	II	650	850
	III	850	1150
	IV	1000	1350
Incidents with 90-minute incident clearance duration	V	150	300
	VI	650	850
	VII	850	1150
	VIII	1000	1350

The travel speed on the freeway mainline recorded after the activation of RMSs was used to determine the significance of RMSs activation on the freeway operation. A paired *t*-test was performed to determine a statistically significant difference in travel speed with and without RMSs. The null hypothesis states that, there was no difference between the mean travel speed with and without RMSs. On the other hand, the alternative hypothesis states that there is a difference with the mean of the travel speed whereby the mean of the travel speed without RMS activation is less than with RMS activation at a 95% confidence level. Equation 7 presents the formulated hypothesis tests.

Hypothesis on mean travel speeds:

Null hypothesis (H_0): $\mu_1 - \mu_2 = 0$ (7)

Alternative hypothesis (H_1): $\mu_1 - \mu_2 < 0$

Where;

μ_1 = average travel speed without RMS activation

μ_1 = average travel speed with RMS activation

Quantification of the Potential Benefits of Activating the RMSs

The primary objective of ramp metering is to improve the traffic flow conditions on the freeway mainline. For this reason, average speed and delay were used as performance metrics to assess the effectiveness of RMSs. The network evaluation in VISSIM was performed to examine how each of these parameters impacted the road network operation with and without the RMSs. The following variables were considered in the simulation.

Lane blockage: In this study, two-lane and three-lane blockage scenarios were created in VISSIM to simulate an incident at the chosen location for an allocated duration. The study simulated two incident clearance durations, i.e. (60 minutes and 90 minutes).

Ramp volume: This variable represents the number of vehicles on the freeway's entrance ramp. The selection of this ramp volume was based on the sensitivity analysis conducted in this chapter, where, for a two-lane blockage incident with a 60-minute and 90- minute incident clearance duration, the threshold for RMSs activation was established. Similarly, for a three-lane blockage incident with a 60-minute and 90-minute incident clearance duration, the ramp volume above which RMSs activation was necessary was established. The worst-case scenario ramp volume was then used in the microsimulation study to quantify the potential benefits of activating the RMSs with respect to a two-lane and a three-lane blockage incident scenario, respectively. The average speed and delay were used as the performance metrics to assess the effectiveness of RMSs

Freeway mainline volume: This variable represents the traffic volume on the freeway mainline. From the sensitivity analysis conducted in this chapter, for a two-lane blockage incident with a 60-minute and 90-minute incident clearance duration, RMSs activation threshold was developed. Similarly, for a three-lane blockage incident with a 60-minute and 90-minute incident clearance duration, the freeway mainline above which RMSs activation was needed was established. The worst-case scenario for the freeway volume for a two-lane and three-lane blockage incident scenario, respectively, was used to quantify the potential benefits for RMSs activation using a microsimulation study. The average speed and delay were used as the performance metrics to assess the effectiveness of RMSs

Washington Fuzzy Logic Algorithm

For activation, three entrance ramps upstream of the incident location were activated using the Washington Fuzzy Logic algorithm. The Washington Fuzzy Logic algorithm is a system-wide control responsive to local and system-wide real-time traffic conditions (Mizuta et al., 2014). The Washington Fuzzy Logic algorithm works by taking occupancy and speed values as inputs collected from different detector locations on the mainline and entrance ramps and applying the rule weighting to give a suitable metering rate as the output. The metering rate is established through a three-step procedure: Fuzzification, activation of rules, and generation of numerical rates (i.e., defuzzification) (Taylor et al., 2000).

Fuzzification

The initial step was to convert the numerical inputs into fuzzy classes, also known as linguistic variables. It essentially decomposes system inputs and outputs into one or more fuzzy sets. Fuzzification mainly uses triangular and or trapezoidal shaped membership functions since they are most common and easier to represent in embedded controllers (Taylor et al., 2000).

Algorithm Inputs

The input to the ramp meter algorithm was calculated from the detector data located at various detector locations. On the other hand, mainline detectors used for RMSs activation are the mainline detectors both upstream and downstream of the entrance ramp. On the other hand, the queue detector is used for RMSs activation for the entrance ramp, as summarized in Table 8. For each simulation run, the metering rate was provided accordingly based on these prevailing traffic conditions

Table 8: Washington fuzzy logic algorithm inputs

Crisp Input	Typical Detector Locations
Local occupancy	Mainline just upstream of merge
Local speed	Mainline just upstream of the merge
Upstream occupancy	Next Upstream mainline Station
Downstream occupancy	Multiple downstream locations
Downstream speed	Same as for Downstream occupancy
Queue occupancy	Queue detector on the ramp
Advance queue occupancy	The tail end of the available queue storage

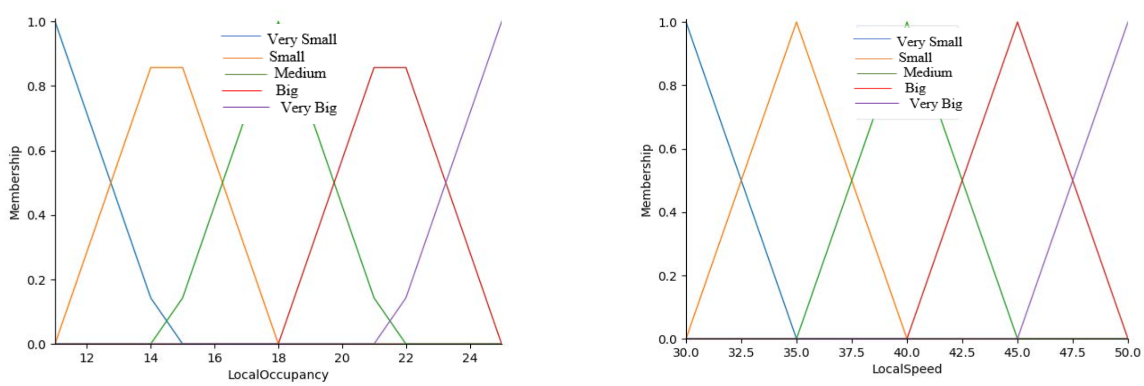
The local occupancy and local speed inputs were obtained from the mainline loop detectors located upstream of the on-ramp merge. The downstream occupancy is the maximum occupancy of specified downstream stations, and the downstream speed input was associated with maximum downstream occupancy. The upstream occupancy was only used when the local occupancy detector provided insufficient data that were unusable over the previous time. In this scenario, upstream occupancy was used instead of local occupancy unless good data resumes. The queue occupancy input varies from ramp to ramp, and the detector will obtain it halfway between the ramp metering stop bar and the end of the ramp storage. The advance queue detector is placed near the ramp entrance to provide the backup required when the ramp fails to capacity. It will also detect the ramp volume for adjusting the metering rate accordingly.

Local Speed and Local Occupancy

In cities like Seattle, Washington, Chicago, Illinois, and Minneapolis, Minnesota, ramp metering is activated when the traffic occupancy is between 20% and 30% (Wilbur Smith Associates, 2006). In Michigan, RMSs were activated during off-peak periods for roadway events, resulting in an increase in traffic occupancy of 10% – 13% (Kostyniuk et al., 1988). The study thus opted for occupancy of 10-25% and 26-30% for the microsimulation as used by Seattle, Illinois, Minneapolis, and Michigan.

According to the Oregon Department of Transportation (ODOT), ramp meters are activated on weekends when speeds are reduced to less than 30 mph (Bertini et al., 2004). In Michigan, ramp meters are activated when there is a drop-in, drop-in speed of 35 mph to 45 mph on incident occurrence (Kostyniuk et al., 1988). Therefore, the values of speeds and occupancy opted for this study were 30-50 mph and 10-25 %, respectively. These values were used as inputs values in the Fuzzy Logic Controller (FLC).

In the FLC, the local occupancy inputs between 11 % and 25 %, and the local speed between 30 to 50 mph were both classified into five auto membership triangle functions called: Very Big, Big, Medium, Small, and Very Small, as shown in Figure 5 (a) and (b). Classification was done using the python programming language, and for this classification, the degree of activation typically ranged between 0 to 1. The degree of activation in the fuzzy logic controller usually measures each membership class's trueness. Each function's trueness is considered the probability or likelihood, as the fuzzy logic is based on the Bayesian Set Theory (Jovanović et al., 2021).

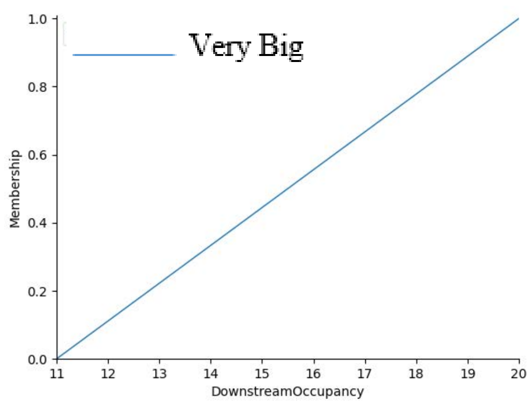


(a) Local occupancy (b) Local speed

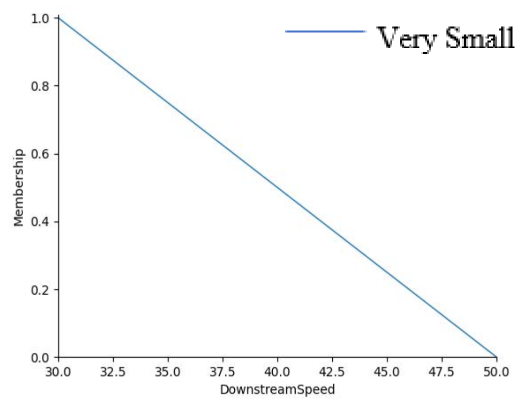
Figure 5: Upstream input

Downstream Occupancy and Speed

The downstream occupancy is the maximum occupancy of specified downstream stations, and the downstream speed input is the speed associated with the maximum downstream occupancy. For the study, the downstream occupancy was in the range of 11 to 21 %, while the downstream speed was 30 to 50 mph. The downstream speed and occupancy were classified in only one class each. This means, for instance, for the downstream speed activation started when the vehicle speed was 50 mph and reached full activation when the speed was at 30 mph, as shown by the triangle functions in Figure 6.



(a) Downstream occupancy

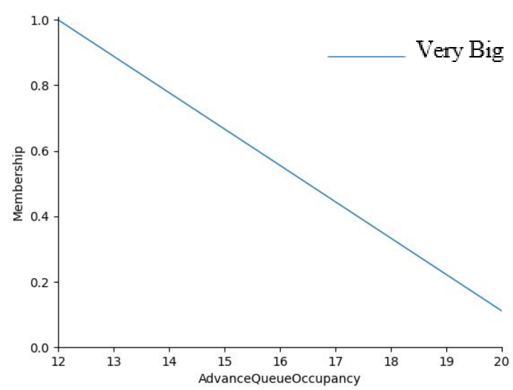


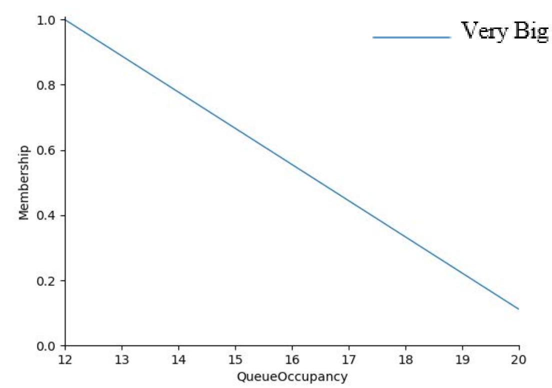
(b) Downstream speed

Figure 6: Downstream input

Advance Queue Occupancy and Queue Occupancy

The queue occupancy and advance queue occupancy were in the range of 12 to 30% and classified as one class: Very Big class. This means the default activation began at an occupancy value of 12 % and reached full activation at 30 %, as shown in Figure 7.





(a) Advance queue occupancy (b) Queue occupancy

Figure 7: On-ramp input.

Algorithm Output

The result of all Washington fuzzy logic inputs was the metering rate of the ramp signal. This output was classified by python programming language into five auto membership triangle functions: Very Big, Big, Medium, Small, and Very Small, in the range of 0 to 20. as shown by Figure 8.

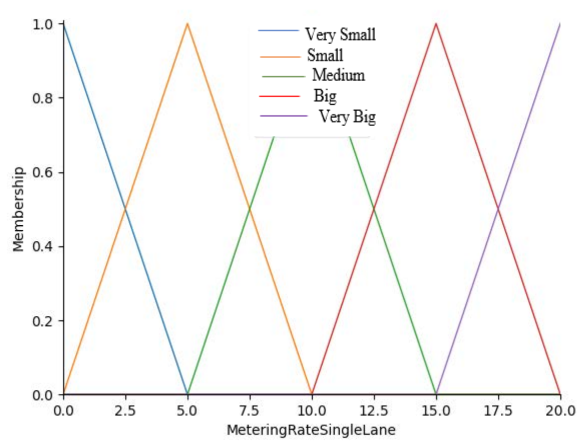


Figure 8: Metering rate output for the FLC

Rule of Evaluation

The Fuzzy Logic Systems are formed based on "IF-THEN" rules. "IF" part of the rule is a premise, "THEN" represents a consequence (Jovanović et al., 2021). In this case, "THEN" represents the five metering rate classes. Rules were given different weights from 1 and above, with the minimum rule weight being 1.0 while the highest was 4.0. These weights were defined by subjective expert opinions and were based on field experience. The reason for baring non-zero value is to avoid the possibility of no rule activating within the rule base. Table 9 represents a set of various rules and the weight assigned to each.

Table 9: Rule logic and rule outcome

Rule No	Rule Logic		Rule Outcome-THEN Metering Rate is	Rule Weight
1	If Local Occupancy is	Very Big	Very Small	2.5
2		Big	Small	1
3		Medium	Medium	1
4		Small	Big	1
5		Very Small	Very Big	1
6	If Local Speed and Local Occupancy respectively are	Very Small and Very Big	Very Small	3
7		Very Big and Very Small	Very Big	1
7	If Local speed is	Small	Small	1
8		Decent	Decent	1
10	If Downstream Speed and Occupancy, respectively are	Very Small and Very Big	Very Small	4
11	If Queue Occupancy is	Very Big	Very Big	2
12	If Advance Queue Occupancy is	Very Big	Very Big	4

Rule 1 through 6 had a higher weight. The reason was to provide a higher metering rate when the mainline is not highly congested and restrict the metering rate when vehicles cannot merge into the mainline. For better performance system-wide, vehicles were better off stored on the ramp than at the merge. Otherwise, a mainline bottleneck formed due to a merge, delaying all drivers going through that section.

The objective of rule 10 was to prevent a downstream bottleneck. When speed was reduced and the occupancy level increased, there was a high possibility of a downstream bottleneck. When this congestion began to form, a restrictive metering rate was preferred. The increased weight of this rule showed how to ramp metering benefits the mainline performance.

Rule 11 and 12: A secondary queue may form on the metered ramp when the freeway is highly congested. This rule was designed to prevent excessive queue formation on the ramp. For most ramps, the advanced queue detector was located near the ramp entrance, in which case a substantial weighting was needed to prevent vehicles from blocking the arterial. In addition, the Queue occupancy detector was placed in the middle of a ramp. They both ensured that the ramp did not fail to capacity and the desired balance between alleviating mainline congestion and reducing queue on the on-ramp.

Rule Changes

Adjustments were made based on the performance of the model. First, the implication of each rule was examined and its impact on the freeway segment. Initially, the downstream speed weighting was shown in Table 10.

Table 10: Design changes on rule logic

Rule	Rule Category	Rule Logic	Rule Outcome	Rule Weight
1	Downstream Speed	If Downstream Speed is Small	Metering Rate is Small	1
2		If Downstream Speed is Medium	Metering Rate is Medium	1

The freeway performance was first evaluated based on this rule weighting. Low weight on the downstream speed resulted in a formation of a downstream bottleneck. This, in turn, affected the network performance by reducing the speed in the network and increasing the travel time on the entrance ramps. The study adjusted the weighting of the downstream conditions to improve conditions on the freeway and entrance ramp. These changes were implemented in the methodology, and analysis showed there was no downstream bottleneck formed. Also, balancing the queue conditions on the ramp and upstream of the ramp balanced the resulting restrictive metering rate of rule 10. When desired, the other rules pulled the metering rate back to the other end.

Local occupancy detectors were also observed, and for unreliable results they produced, the upstream detector was used. However, the downstream detectors provided the best system-wide performance to prevent the downstream bottleneck. Rules in Table 11 were to be implemented for unreliable detector results

Table 11: Design changes for upstream occupancy

Rule	Rule Category	Rule Logic	Rule Outcome	Rule Weight
1	Upstream Occupancy	If Upstream Occupancy is Medium	Metering Rate is Medium	1
2		If Upstream Occupancy is Small	Metering Rate is Big	1
3		If Upstream Occupancy is Very Small	Metering Rate is Very Big	1

Deffuzification

The last step in the Fuzzy Logic Controller was to produce a single number from the output of the aggregated fuzzy set. Then, it is used to transfer fuzzy inference results to a crisp output, a specific metering rate, or cycle time (Vulkanovic & Ernhofer, 2006). Several methods are used to defuzzify, such as the centroid, maxima, and weighted average (Taylor et al., 2000). For this research purpose, since the rules were given weights, the weighted average method was used i.e., each rule's involved area is multiplied by the rule weighting as shown by Equation 8.

$$Metering\ rate = \frac{\sum_{i=1}^{N} X_i C_i A_i}{\sum_{i=1}^{N} X_i A_i} \tag{8}$$

Where

X_i = weighting of the rule,

C_i = centroid of the output,

A_i = implicated area of the output class.

For instance, for a Local occupancy of 12%, downstream occupancy 15%, local speed 50mph, downstream speed 58mph, queue occupancy 20%, and advance queue occupancy of 25%, the metering Rate of the ramp was 11.82 seconds, as shown in Figure 9. This process was repeated throughout the simulation period, and metering rates were continuously updated.

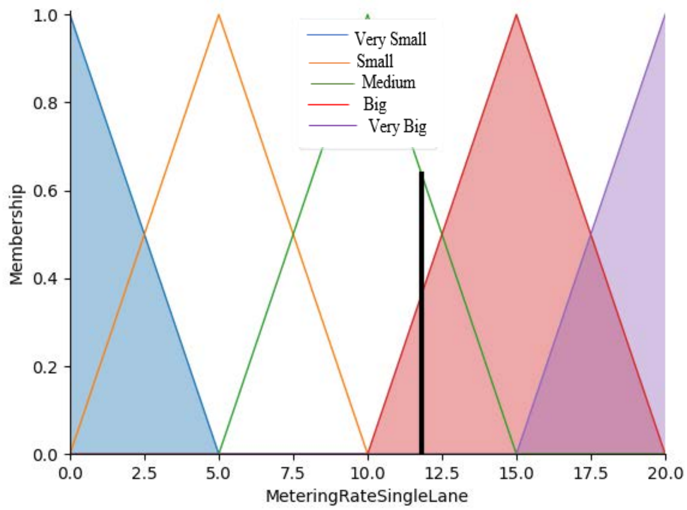


Figure 9 : Defuzzification output

CHAPTER 4

RESULTS AND DISCUSSION

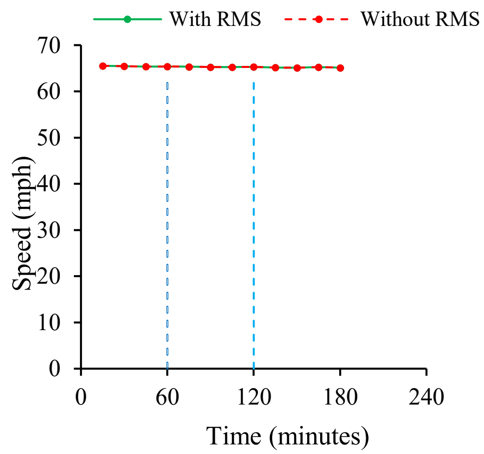
This section discusses the guidelines to activate and deactivate RMSs in response to non-recurrent congestion on weekends. Specifically, the guidelines were developed using VISSIM microscopic simulation. The two incident scenarios with two lanes and three lanes blockage were modeled in VISSIM to reflect the actual incident scenarios. The guidelines were based on the traffic volume and speed recorded on the upstream ramps of the incident, as discussed in the following subsection.

Guidelines for Activating and Deactivating RMSs on Weekends

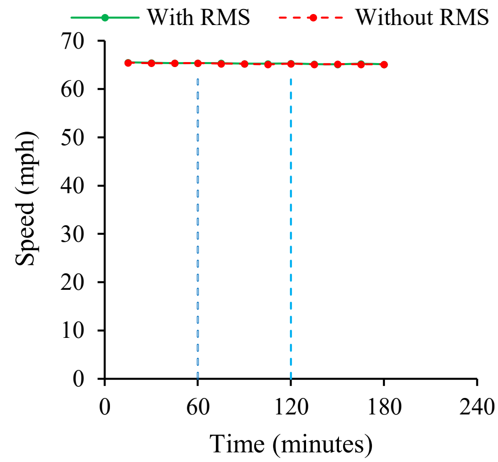
This study systematically varied the freeway and ramp volumes to examine how these parameters impact the freeway operations during an incident with and without RMSs. As stated earlier, the study used the traffic detectors in the VISSIM model to replicate the existing freeway surveillance detectors in the actual situation. Such detectors were placed in the freeway upstream and downstream of an entrance ramp and on the ramp. These detectors were then used for measuring the freeway speed for different freeway and ramp demand volumes, both with and without the RMSs activation.

Incidents with 60-Minute Incident Clearance Duration

The speed profiles for a 60-minute incident clearance duration were developed at various freeway and entrance ramp traffic volumes. Figure 10 presents the speed profiles at lower traffic volumes (i.e., ramp volume 150 vphpl and mainline volume 300 vphpl) for both cases (i.e., Two-lane blockage and Three-lane blockage). No changes were observed in travel speed with RMSs and without RMSs activation at lower traffic volume on the freeway mainline and the entrance ramp. This implies that at lower traffic volume on the mainline and on the entrance ramp, there is no need to activate RMSs due to incidents.



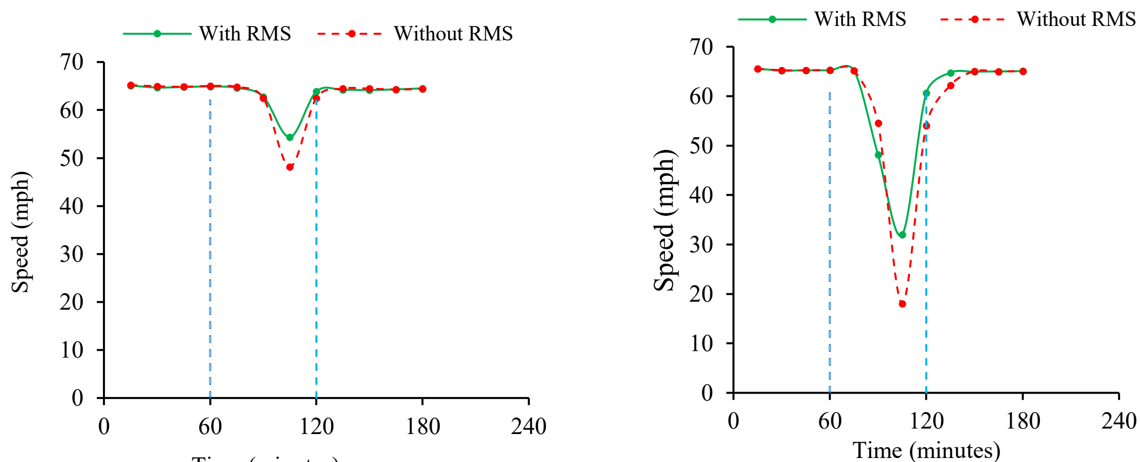
(a) Ramp volume 150 vphpl, freeway volume 300 vphpl



(b) Ramp volume 150 vphpl, freeway mainline volume 300 vphpl

Figure 10: Speed profiles (a) two-lane (b) three-lane blockage, case I

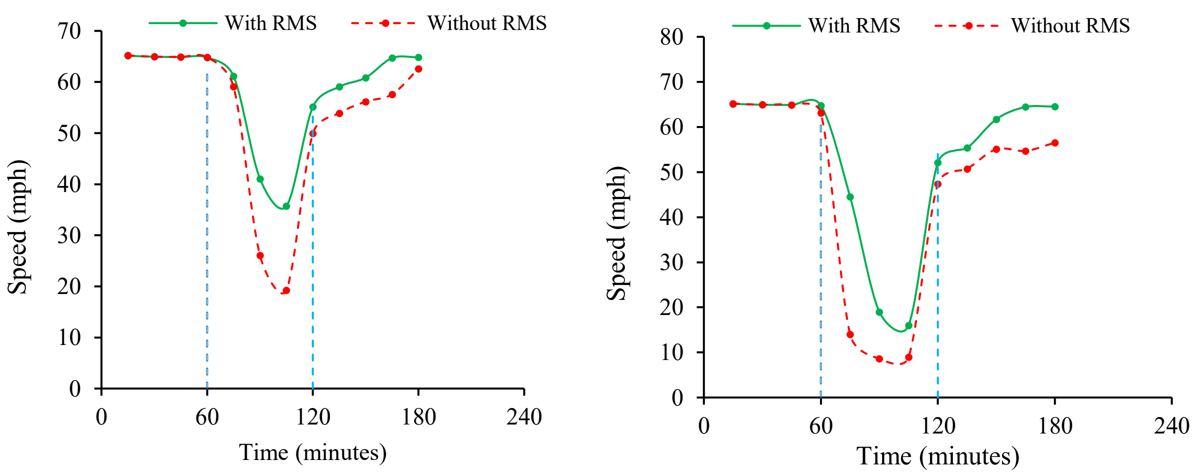
At higher traffic volumes, the lines presenting the travel speed with RMSs were above the line showing the travel speed without RMSs during the incident clearance time. This implies that the travel speed with RMSs activation was higher than without RMSs activation during the incident clearance time. Figures 11-13 present the speed profile at higher traffic volumes (i.e., ramp volume greater than 650 vphpl and mainline volume greater than 850 vphpl) for both cases (i.e., two-lane blockage, three-lane blockage). The travel speed was seen to decrease at the beginning of an incident, i.e., one hour after stimulation begins. Eventually, it returned to normal after the incident was cleared, i.e., 60-minute later. Also, the travel speed decreases as the traffic volume increase during the incident clearance time. An incident with a three-lane blockage caused a much higher drop in speed than an incident with a two-lane blockage. Changes were observed in travel speed with RMSs and without RMSs activation at higher traffic volume on the freeway mainline and on the entrance ramp. This implies that at these traffic volume ranges on the mainline and the entrance ramp, the activation of RMSs due to incidents will significantly increase travel speed.



(a) Ramp volume 650 vphpl, freeway volume 850 vphpl

(b) Ramp volume 650 vphpl, freeway volume 850 vphpl

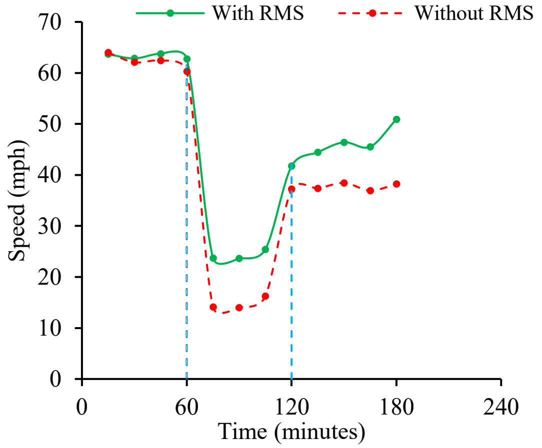
Figure 11: Speed profiles (a) two-lane (b) three-lane blockage, case II



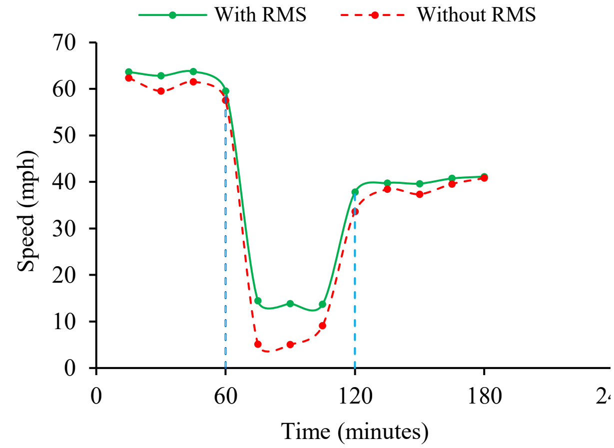
(a) Ramp volume 850 vphpl, freeway volume 1150 vphpl

(b) Ramp volume 850 vphpl, freeway volume 1150 vphpl

Figure 12: Speed profiles (a) two-lane (b) three-lane blockage, case III



(a) Ramp volume 1000 vphpl, freeway volume 1350 vphpl



(b) Ramp volume 1000 vphpl, freeway volume 1350 vphpl

Figure 13: Speed profiles (a) two-lane (b) three-lane blockage, case IV

In all incident scenarios, it is noted that travel speed on the mainline freeway was higher when with RMSs than without RMSs activation. This suggests that the RMSs improved freeway operation by producing smoother traffic flow on the freeway mainline. Also, it was observed that the longer the incident duration, the lower the travel speed values with or without RMSs activation. Moreover, for the incident with Three-lane blockage, the drop in travel speed was much higher than the incident with two-lane blockage.

Based on the speed profiles at different traffic volumes, the threshold for RMSs activation and deactivation were tested for significance for each incident scenario. A paired *t*-test was performed to determine the freeway and the ramp demand traffic volume that will significantly change travel speed with RMSs and without RMSs. Tables 12 presents the traffic volume thresholds for RMSs activation for the incident with 60-minute clearance time for both two-lane and 3-lane blockage.

Table 12: RMSs activation guidelines for a 60-minute incident duration scenario

Scenario	Ramp Volume (Vphpln)	Freeway Mainline Volume (vphpln)							
		300	850	950	1050	1100	1150	1350	1800
Two-Lane Blockage (40%)	150	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×
	750	×	×	×	×	×	×	×	×
	800	×	×	×	×	×	×	×	×
	950	×	×	×	×	✓	✓	✓	✓
	1000	×	×	✓	✓	✓	✓	✓	✓
Three-Lane Blockage (60%)	150	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×
	750	×	×	×	×	✓	✓	✓	✓
	800	×	×	×	×	✓	✓	✓	✓
	950	×	×	×	×	✓	✓	✓	✓
	1000	×	✓	✓	✓	✓	✓	✓	✓

Note: × denotes a situation where using RMSs did not produce a statistically significant difference in speed on the freeway mainline at a 95% confidence level ; ✓ denotes a situation where using RMSs produced a statistically significant difference in speed on the freeway mainline at 95% confidence level

As presented in Table 12, significant RMSs activation for a 60-minute incident duration for a two-lane blockage scenario was observed when the ramp traffic volume was greater than 950 vphpl, and mainline traffic volume was greater than 950 vphpl. Also, for a 3-lane blockage, a significant change in travel speed was observed when the ramp traffic volume was greater than 750 veh/hr /ln, and the mainline traffic volume was greater than 850 vphpl. Therefore, based on the *t*-test results presented in Table 15 and the speed profiles are shown in Figures 10-13, the RMSs upstream of the incident location can be activated based on the following criteria:

Incidents with two-lane blockage (40%)

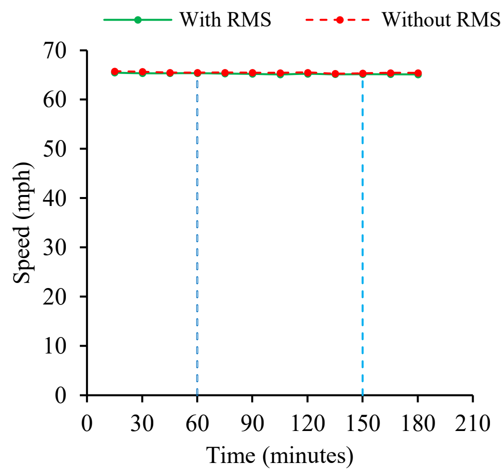
- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 950 vphpl
    b. Freeway mainline traffic volume exceeds 950 vphpl
    c. Average speed on the mainline drops below 50 mph.
- Deactivate if the incident was cleared and when the average speed on the mainline reaches 50 mph.

Incidents with three-lane blockage (60 %)

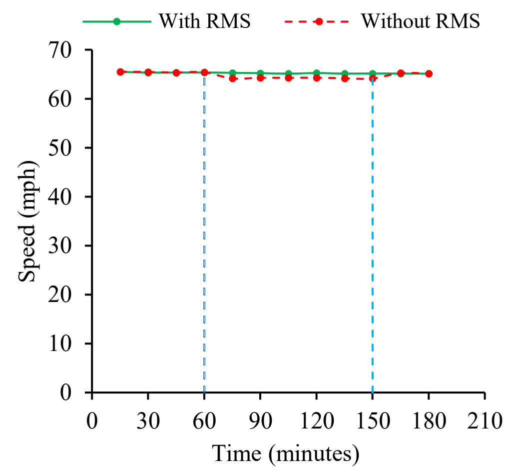
- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 750 vphpl
    b. Freeway mainline traffic volume exceeds 850 vphpl
    c. Average speed on the mainline drops below 50 mph.
- Deactivate if the incident was cleared and when the average speed on the mainline reaches 50 mph.

Incidents with 90-Minute Incident Clearance Duration

The speed profiles for a 90-minute incident clearance duration were developed at various freeway and entrance ramp traffic volumes. Similar to a 60-minute incident duration, at higher traffic volumes, the lines presenting the travel speed with RMSs were above the line presenting the travel speed without RMSs during the 90-minute incident clearance time. This implies that the travel speed with RMSs activation was higher than without RMSs activation during the incident clearance time. Figure 14 presents the speed profile at lower traffic volumes (i.e., ramp volume 150 vphpl and mainline volume 300 vphpl) for both cases (i.e., two-lane blockage and three-lane blockage). No changes were observed in travel speed with RMSs and without RMSs activation at lower traffic volume on the freeway mainline and the entrance ramp. This implies that at lower traffic volume on the mainline and on the ramp, there is no need to activate RMSs due to incidents.



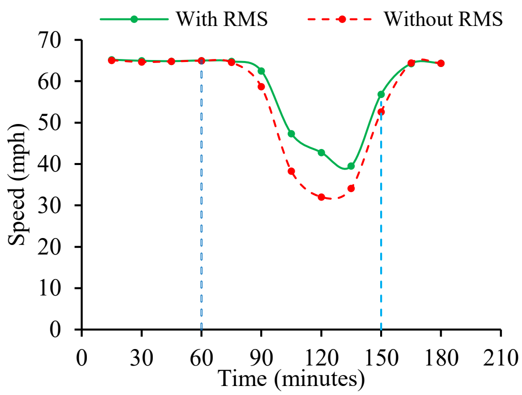
(a) Ramp volume 150 vphpl, freeway volume 300 vphpl



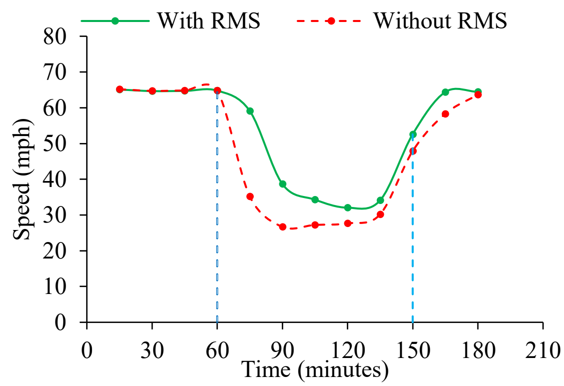
(b) Ramp volume 150 vphpl, freeway volume 300 vphpl

Figure 14: Speed profiles (a) two-lane (b) three-Lane blockage, case V

Figures 15-17 present the speed profiles at higher traffic volumes (i.e., ramp volume greater than 650 vphpl and mainline volume greater than 850 vphpl for both cases (i.e., two-lane blockage and three-lane blockage). The travel speed was seen to decrease at the beginning of an incident, i.e., one hour after stimulation begins. Eventually, it returned to normal after the incident was cleared, i.e., 90-minute later. Also, the travel speed decreases as the traffic volume increase during the incident clearance time. An incident with a three-lane blockage caused a much higher drop in speed than an incident with a two-lane blockage. Changes were observed in travel speed with RMSs and without RMSs activation at higher traffic volume on the freeway mainline and on the entrance ramp. This implies that at these traffic volume ranges on the mainline and the ramp, the activation of RMSs due to incidents will significantly increase travel speed.

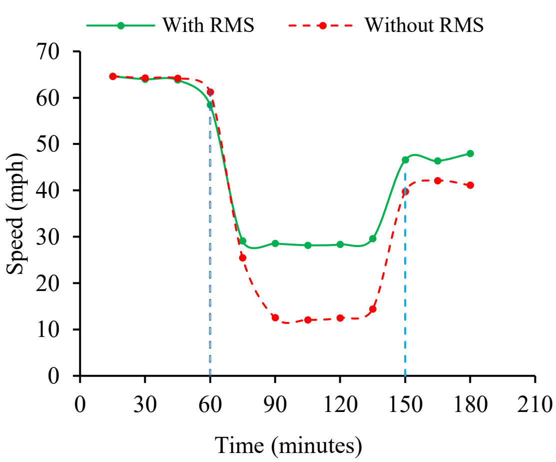


(a) Ramp volume 650 vphpl, freeway volume 850 vphpl

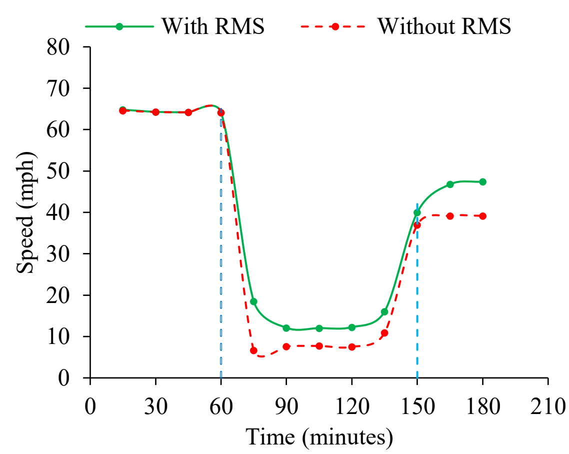


(b) Ramp volume 650 vphpl, freeway volume 850 vphpl

Figure 15: Speed profiles (a) two-lane (b) three-lane blockage, case VI

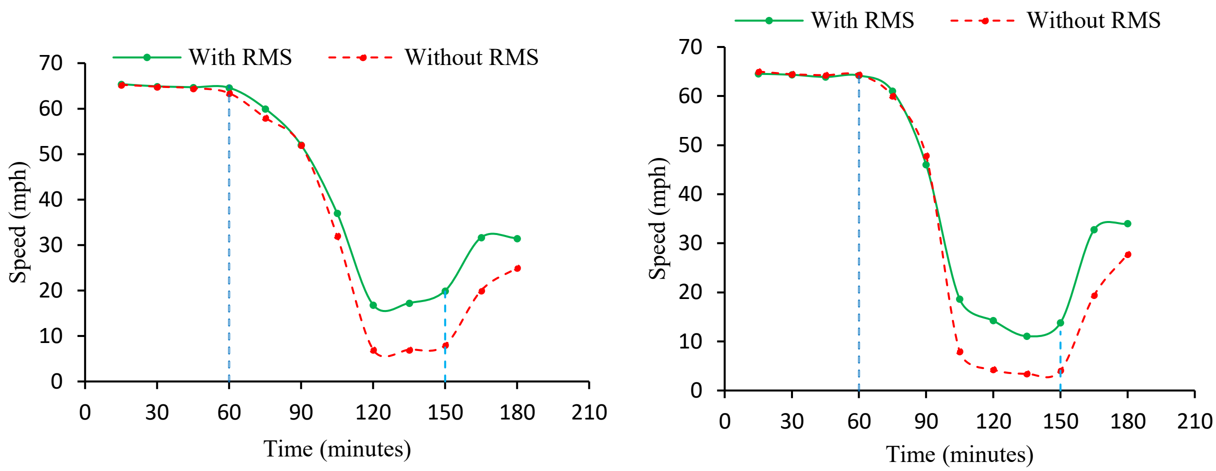


(a) Ramp volume 850 vphpl, freeway volume 1150 vphpl



(b) Ramp Volume 850 vphpl, freeway Volume 1150 vphpl

Figure 16: Speed profiles (a) two-lane (b) three-lane blockage, case VII



(a) Ramp volume 1000 vphpl, freeway volume 1350 vphpl

(b) Ramp volume 1000 vphpl, freeway volume 1350 vphpl

Figure 17: Speed profiles (a) two-lane (b) three-lane blockage, case VIII

In all incident scenarios, it is noted that travel speed on the mainline freeway was higher when with RMSs than without RMSs activation. This suggests that the RMSs improved freeway operation by producing smoother traffic flow on the freeway mainline. Also, it was observed that the longer the incident duration, the lower the travel speed values with or without RMSs activation. Moreover, for the incident with three-lane blockage, the drop in travel speed was much higher than the incident with two-lane blockage.

Based on the speed profiles at different traffic volumes, the threshold for RMSs activation and deactivation were tested for significance for each incident scenario. A *t*-test was performed to determine the freeway and ramp demand traffic volume significantly changes travel speed with RMSs and without RMSs. Tables 13 presents the traffic volume thresholds for RMSs activation for the incident with a 90-minute incident duration for both two-lane and three-lane blockage. For example, an incident with a 90-minute clearance duration resulted in a two-lane blockage. The RMS can be activated if the mainline traffic volume exceeds 1050 vphpl and the traffic volume on the entrance ramp exceeds 800 vphpl.

Table 13: RMSs activation guidelines for a 90-minute incident duration scenario

Scenario	Ramp Volume (Vphpln)	Freeway Mainline Volume (vphpln)							
		300	850	950	1050	1100	1150	1350	1800
Two-Lane Blockage (40%)	150	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×
	750	×	×	×	×	×	×	×	×
	800	×	×	×	✓	✓	✓	✓	✓
	950	×	×	✓	✓	✓	✓	✓	✓
	1000	×	×	✓	✓	✓	✓	✓	✓
Three-Lane Blockage (60%)	150	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×
	750	×	×	×	×	×	×	×	×
	800	×	×	✓	✓	✓	✓	✓	✓
	950	×	×	✓	✓	✓	✓	✓	✓
	1000	×	✓	✓	✓	✓	✓	✓	✓

Note: × denotes a situation where using RMSs did not produce a statistically significant difference in speed on the freeway mainline at a 95% confidence level ; ✓ denotes a situation where using RMSs produced a statistically significant difference in speed on the freeway mainline at 95% confidence level

As presented in Table 13, significant RMSs activation for a 90-minute incident duration for a two-lanes blockage scenario was observed when the ramp traffic volume was greater than 800 vphpl, and mainline traffic volume was greater than 950 vphpl. Also, for a three-lane blockage, a significant change in travel speed was observed when the ramp traffic volume was greater than 800 veh/hr /ln, and the mainline traffic volume was greater than 850 vphpl.

Therefore, based on the *t*-test results presented in Table 10 and the speed profiles are shown in Figures 14-17, the RMSs upstream of the incident location can be activated based on the following criteria:

Incidents with two-lane blockage (40 %)

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 800 vphpl
    b. Freeway mainline traffic volume exceeds 950 vphpl
    c. Average speed on the mainline drops below 50 mph.
- Deactivate if the incident is cleared and when the average speed on the mainline reaches 50 mph.

Incidents with three-lane blockage (60 %)

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 800 vphpl
    b. Freeway mainline traffic volume exceeds 850 vphpl
    a. Average speed on the mainline drops below 50 mph.
- Deactivate if the incident was cleared and when the average speed on the mainline reaches 50 mph.

Summary of Guidelines

This study focused on developing the guidelines for activating and deactivating RMSs during weekends. In summary, the observed real-time traffic data were used to establish the RMSs activation and deactivation guidelines in response to the incident during the weekends. Based on the sensitivity analysis and speed profiles, Table 14 summarizes the guidelines for activating and deactivating RMSs on weekends due to incidents.

Table 14: RMSs activation and deactivation guidelines on weekends

Incident Duration	Thresholds			
	Incident Duration	Activation	Activation	Deactivation
Two-lane Blocakge (40 %)	60	Ramp Volume > 950 vphpl & Mainline Volume > 950 vphpl & Speed ≤ 50 mph	Ramp Volume > 800 vphpl, Freeway Volume 950 vphpl	Incident cleared & speed > 50 mph mph
	90	Ramp Volume > 800 vphpl & Mainline Volume > 950 vphpl & Speed ≤ 50 mph		
Three-lane Blockage (60 %)	60	Ramp Volume> 750 vphpl & Mainline Volume > 950 vphpl & Speed ≤ 50 mph	Ramp Volume > 750 vphpl, Freeway Volume 850 vphpl	Incident cleared & speed > 50 mph
	90	Ramp Volume > 800 vphpl & Mainline Volume >850 vphpl & Speed ≤ 50 mph		

Note:40% and 60% are the percentages of lane blockage for general purpose lanes.

As it can be noted, for a two-lane blockage incident with a 60-minute incident clearance duration, RMSs activation was needed when the ramp volume was higher than 950 vphpl and freeway mainline volume was higher than 950 vphpl whereas, for a 90-minute incident clearance duration, RMSs activation was necessary when the ramp volume exceeded 800 vphpl and freeway mainline volume exceeded 950 vphpl. The worst-case scenario, i.e., ramp volume higher than 800 vphpl and freeway volume greater than 950 vphpl were finally selected as the thresholds for RMSs activation. This means that for a two-lane blockage incident, activation of RMSs should be done when the ramp volume is higher than 800 vphpl and when the freeway volume exceeds 950 vphpl

For a three-lane blockage incident with a 60-minute incident clearance duration, RMSs activation was needed when the ramp volume exceeded 750 vphpl, and freeway volume exceeded 950 vphpl whereas, for a 90-minute incident clearance duration, RMSs activation was necessary when the ramp volume exceeded 800 vphpl and freeway mainline exceeded 850 vphpl. The worst-case scenario, i.e., ramp volume of 750 vphpl and freeway volume of 850 vphpl were selected as the thresholds for RMSs activation with respect to a three-lane blockage incident scenario. This means that for a three-lane blockage incident, RMSs should be activated when the ramp volume is higher than 750 vphpl and when the freeway volume exceeds 850 vphpl.

The guidelines that this study developed were based on the percentage of vehicles that the FDOT provided in the base model, where the percentage of vehicle composition for the single occupancy vehicle was 75.7%, trucks were 2.8%, high occupancy vehicle with three or more occupants was 5.4%, and high occupancy vehicle of two or more occupants was 16%.

Statistical Analysis Test Results

The travel speed on the freeway mainline recorded after the activation of RMSs was used to determine the significance of RMSs activation on the freeway operation. A paired *t*-test was performed to determine a statistically significant difference in travel speed with and without RMSs. The null hypothesis states that there was no difference between the mean travel speed with and without RMSs. On the other hand, the alternative hypothesis states that there is a difference with the mean of the travel speed whereby the mean of the travel speed without RMS activation is less than with RMS activation at a 95% confidence level. Equation 7 presents the formulated hypothesis tests.

Hypothesis on mean travel speeds:

Null hypothesis (H_0): $\mu_1 - \mu_2 = 0$ (7)

Alternative hypothesis (H_1): $\mu_1 - \mu_2 < 0$

Where;

μ_1 = average travel speed without RMS activation

μ_1 = average travel speed with RMS activation

Table 15: Statistical analysis for speed difference with RMSs and without RMSs

Duration	Incident Scenario	Mainline Volume (vphpln)	Ramp Volume (vphpln)	N	Mean	SE Mean	*p*-value	Significant
60-Minute	Two-lane Blockage (40%)	300	150	12	0.034	0.022	0.071	NO
			650	12	0.092	0.020	1.0	NO
			750	12	0.0342	0.021	0.929	NO
			800	12	1.212	0.768	0.929	NO
			950	12	0.037	0.012	0.991	NO
			1000	12	0.038	0.013	0.993	NO
		850	150	12	0.037	0.016	0.976	NO
			650	12	0.092	0.020	1.000	NO
			750	12	-0.034	0.674	0.480	NO
			800	12	-0.035	0.675	0.480	NO
			950	12	-1.409	1.09	0.112	NO
			1000	12	-1.410	1.110	0.114	NO
		950	150	12	-1.02	0.182	0.999	NO
			650	12	-0.990	0.141	0.985	NO
			750	12	-0.930	0.182	0.992	NO
			800	12	-0.480	0.190	0.897	NO
			950	12	-0.440	0.608	0.304	NO
			1000	12	-0.260	0.132	0.010	YES
		1050	150	12	0.0183	0.007	0.986	NO
			650	12	2.840	1.110	0.986	NO
			750	12	-0.404	0.301	0.102	NO
			800	12	-0.405	0.302	0.103	NO
			950	12	-1.040	0.250	0.983	NO
			1000	12	-6.820	1.660	0.009	YES
		1100	150	12	2.720	2.40	0.860	NO
			650	12	0.166	0.139	0.871	NO
			750	12	0.165	0.137	0.869	NO
			800	12	-5.070	1.570	0.054	NO
			950	12	-5.340	1.342	0.041	YES
			1000	12	-5.440	1.350	0.001	YES
	Three-lane Blockage (60%)	300	150	12	0.483	0.064	1.000	NO
			650	12	0.586	0.145	0.999	NO
			750	12	0.584	0.142	0.995	NO
			850	12	-1.770	1.910	0.187	NO
			950	12	-0.164	0.137	0.126	NO
			1000	12	-0.166	0.139	0.129	NO
		850	150	12	0.167	0.036	1.000	NO
			650	12	-3.830	3.010	0.115	NO
			750	12	-3.828	2.999	0.114	NO
			800	12	-0.166	0.139	0.129	NO
			950	12	-0.650	0.137	0.146	NO
			1000	12	0.060	0.132	0.001	YES
		950	150	12	0.049	0.012	0.997	NO
			650	12	3.240	2.090	0.992	NO
			750	12	0.934	0.707	0.863	NO
			800	12	-0.932	0.705	0.137	NO
			950	12	-1.770	1.910	0.113	NO
			1000	12	-6.820	1.660	0.001	YES

Table 15 : Statistical analysis for speed difference with RMSs and without RMSs (continued)

Duration	Incident Scenario	Mainline Volume (vphpln)	Ramp Volume (vphpln)	N	Mean	SE Mean	*p*-value	Significant
60-Minute	Three-lane Blockage (60%)	1050	150	12	1.327	0.706	0.957	NO
			650	12	0.936	0.808	0.864	NO
			750	12	-0.670	1.680	0.966	NO
			800	12	-0.270	1.481	0.983	NO
			950	12	-5.070	1.570	0.004	YES
			1000	12	-7.560	2.730	0.009	YES
		1100	150	12	4.020	2.82	0.909	NO
			650	12	-2.510	1.960	0.114	NO
			750	12	-2.190	1.940	0.012	NO
			800	12	-3.590	1.040	0.003	YES
			950	12	-2.700	1.770	0.010	YES
			1000	12	-2.460	1.590	0.016	YES
90-Minute	Two-lane Blockage (40%)	300	150	12	-0.405	0.302	0.103	NO
			650	12	0.092	0.020	1.000	NO
			750	12	0.084	0.01	0.998	NO
			800	12	1.212	0.768	0.929	NO
			950	12	0.037	0.012	0.990	NO
			1000	12	0.038	0.013	0.993	NO
		850	150	12	0.017	0.072	0.984	NO
			650	12	0.049	0.014	0.987	NO
			750	12	0.047	0.013	0.992	NO
			800	12	0.207	0.961	0.583	NO
			950	12	0.774	0.070	0.894	NO
			1000	12	0.780	1.090	0.882	NO
		950	150	12	9.830	1.880	1.000	NO
			650	12	1.620	1.380	0.868	NO
			750	12	-1.030	0.250	0.892	NO
			800	12	-0.990	0.182	0.587	NO
			950	12	-0.840	0.308	0.023	YES
			1000	12	-0.930	0.182	0.010	YES
		1050	150	12	2.840	1.110	0.986	NO
			650	12	0.667	0.420	0.930	NO
			750	12	0.664	0.418	0.928	NO
			800	12	-10.39	2.060	0.000	YES
			950	12	-3.915	1.491	0.014	YES
			1000	12	-3.920	1.590	0.016	YES
		1100	150	12	-1.410	1.110	0.114	NO
			650	12	-2.020	1.420	0.092	NO
			750	12	-1.990	1.399	0.090	NO
			800	12	-3.240	1.760	0.037	YES
			950	12	-6.780	2.090	0.004	YES
			1000	12	-4.770	1.770	0.010	YES
	Three-lane Blockage (60%)	300	150	12	4.020	2.820	0.909	NO
			650	12	1.770	1.910	0.813	NO
			750	12	1.760	1.890	0.800	NO
			800	12	-0.000	0.004	0.419	NO
			950	12	-0.850	1.470	0.282	NO
			1000	12	-0.890	1.520	0.285	NO

Table 15: Statistical analysis for speed difference with RMSs and without RMSs (continued)

Duration	Incident Scenario	Mainline Volume (vphpln)	Ramp Volume (vphpln)	N	Mean	SE Mean	*p*-value	Significant
90-Minute	Three-lane Blockage (60%)	850	150	12	0.017	0.072	0.984	NO
			650	12	0.050	0.014	0.998	NO
			750	12	0.047	0.012	0.989	NO
			800	12	-1.524	0.754	0.966	NO
			950	12	-1.640	1.190	0.097	NO
			1000	12	-1.166	0.139	0.071	YES
		950	150	12	2.020	1.020	0.964	NO
			650	12	1.410	1.110	0.886	NO
			750	12	0.031	0.015	0.971	NO
			800	12	-3.610	0.385	0.002	YES
			950	12	-6.587	2.655	0.013	YES
			1000	12	-6.590	2.660	0.015	YES
		1050	150	12	2.840	1.110	0.986	NO
			650	12	-0.550	0.527	0.159	NO
			750	12	0.207	0.961	0.583	NO
			800	12	-4.810	1.640	0.007	YES
			950	12	-3.800	1.750	0.026	YES
			1000	12	-3.240	2.090	0.008	YES
		1100	150	12	-0.550	0.527	0.159	NO
			650	12	-3.800	1.750	0.066	NO
			750	12	-0.029	0.016	0.056	NO
			800	12	-9.830	1.880	0.000	YES
			950	12	-6.774	2.070	0.004	YES
			1000	12	-4.270	1.080	0.001	YES

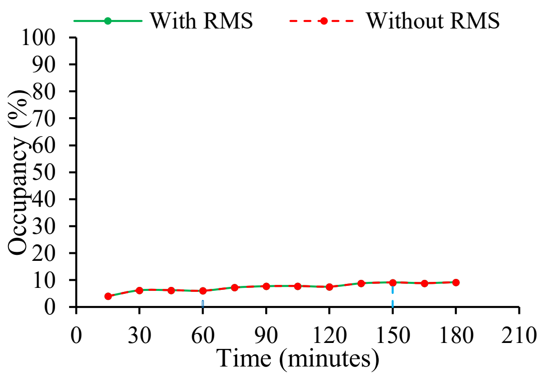
Note:40% and 60% are the percentages of lane blockage for general purpose lanes.

Analysis of Occupancy

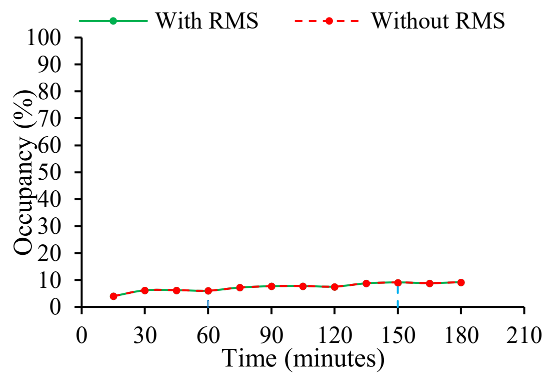
As observed earlier, the study analyzed traffic speed variation with respect to RMS and no RMS. The study also analyzed the corresponding trend in occupancy values read by the traffic detectors in the same condition as speed. These were the same detectors used for measuring the freeway mainline speed for different freeway and ramp demand volumes, both with and without the RMSs activation.

Incidents with 60-Minute Incident Clearance Duration

The occupancy profiles for a 60-minute incident clearance duration were developed at various freeway and entrance ramp traffic volumes. Figure 18 presents the occupancy profiles at lower traffic volumes (i.e., ramp volume 150 vphpl and mainline volume 300 vphpl) for both cases (i.e., two-lane blockage and three-lane blockage). No changes were observed in the occupancy of vehicles with RMSs and without RMSs activation at lower traffic volume on the freeway mainline and the entrance ramp.



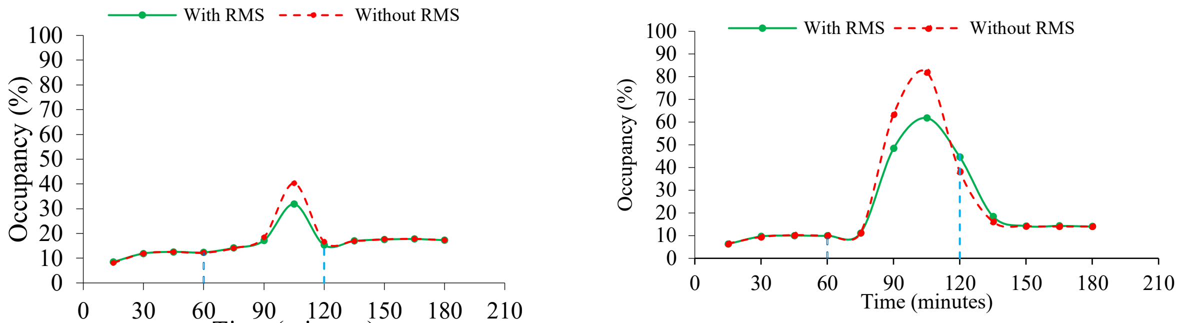
(a) Ramp volume 150 vphpl, freeway volume 300 vphpl



(b) Ramp volume 150 vphpl, freeway volume 300 vphpl

Figure 18: Occupancy profiles (a) two-lane (b) three-lane blockage, case I

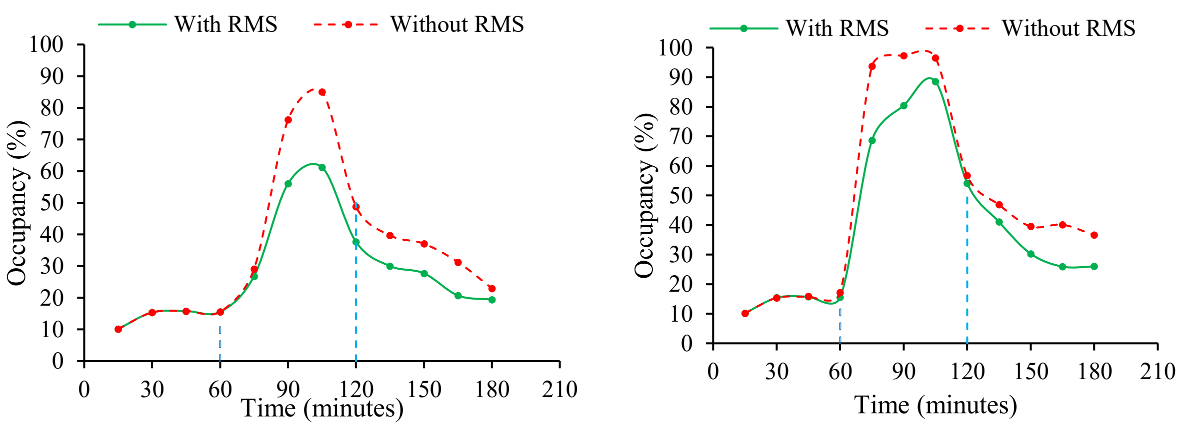
At higher traffic volumes, the occupancy with RMSs activation was lower than without RMSs activation during the incident clearance time. Figures 19-21 presents the occupancy profile at higher traffic volumes (i.e., ramp volume greater than 650 vphpl and mainline volume greater than 650 vphpl) for both cases (i.e., two-lane blockage and three-lane blockage). The occupancy was seen to increase at the beginning of an incident, i.e., one hour after stimulation begins. Eventually, it returned to normal after the incident was cleared, i.e., 60-minute later. Also, the occupancy increases as the traffic volume increase during the incident clearance time. An incident with a three-lane blockage caused a much higher increase in occupancy than an incident with a two-lane blockage.



(a) Ramp volume 650 vphpl, freeway volume 650 vphpl

(b) Ramp volume 650 vphpl, freeway volume 850 vphpl

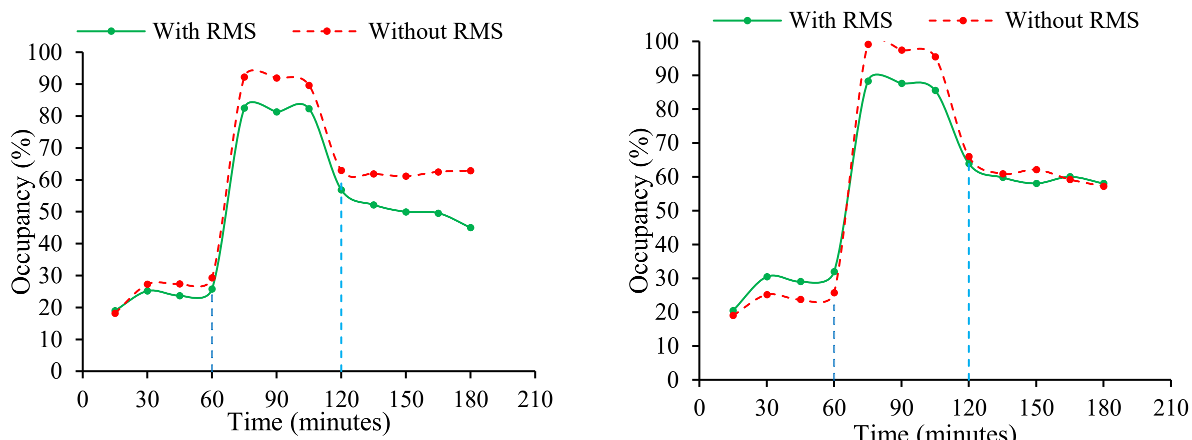
Figure 19: Occupancy profiles (a) two-lane (b) three-lane blockage, case II



(a) Ramp volume 850 vphpl, freeway volume 1150 vphpl

(b) Ramp volume 850 vphpl, freeway volume 1150 vphpl

Figure 20: Occupancy profiles (a) two-lane (b) three-lane Blockage, case III



(a) Ramp volume 1000 vphpl, freeway volume 1350 vphpl

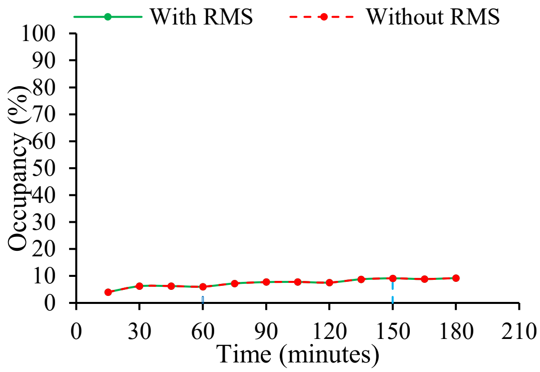
(b) Ramp volume 1000 vphpl, freeway volume 1350 vphpl

Figure 21: Occupancy profiles (a) two-lane (b) three-lane blockage, case IV

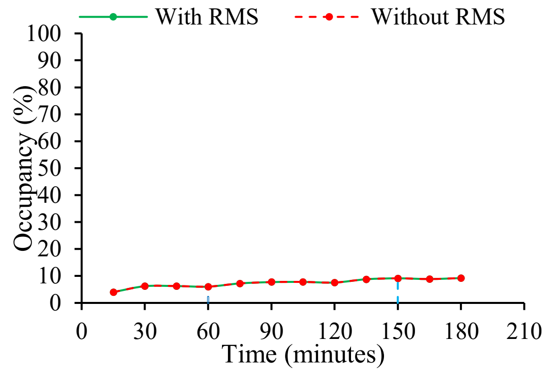
In all incident scenarios, it is noted that occupancy on the mainline freeway was lower with RMSs than without RMSs activation. This suggests that the RMSs improved freeway operation by producing smoother traffic flow on the freeway mainline. Also, it was observed that the longer the incident duration, the higher the occupancy values with or without RMSs activation. Moreover, for the incident with three-lane blockage, the increase in occupancy was much higher than the incident with two-lane blockage.

Incidents with 90-Minute Clearance Duration

The occupancy profiles for a 90-minute incident clearance duration were developed at various freeway and entrance ramp traffic volumes. Similar to a 60-minute incident duration. Figure 22 presents the occupancy profile at lower traffic volumes (i.e., ramp volume 150 vphpl and mainline volume 300 vphpl) for both cases (i.e., two-lane blockage and three-lane blockage). No changes were observed in occupancy with RMSs and without RMSs activation at lower traffic volume on the freeway mainline and the entrance ramp. This implies that at lower traffic volume on the mainline and on the ramp, there is no need to activate RMSs due to incidents.



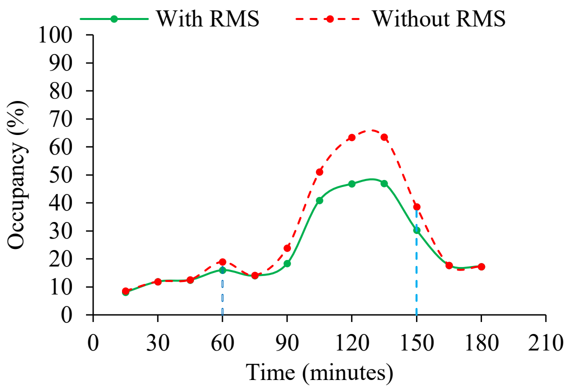
(c) Ramp volume 150 vphpl, freeway volume 300 vphpl



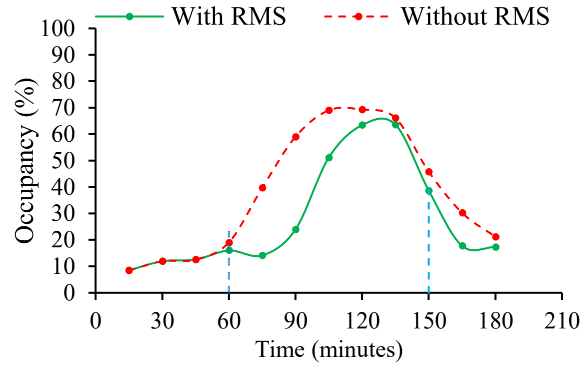
(d) Ramp volume 150 vphpl, freeway volume 300 vphpl

Figure 22: Occupancy profiles (a) two-lane (b) three-lane blockage, case V

Figures 23-24 present the occupancy profiles at higher traffic volumes (i.e., ramp volume greater than 650 vphpl and mainline volume greater than 850 vphpl) for both cases (i.e., two-lane blockage and three-lane blockage). The occupancy was seen to increase at the beginning of an incident, i.e., one hour after stimulation begins. Eventually, it returned to normal after the incident was cleared, i.e., 90-minute later. Also, the occupancy increases as the traffic volume increase during the incident clearance time. An incident with a three-lane blockage caused a much higher drop in speed than an incident with a two-lane blockage. Changes were observed in travel speed with RMSs and without RMSs activation at higher traffic volume on the freeway mainline and on the entrance ramp. This implies that at these traffic volume ranges on the mainline and the ramp, the activation of RMSs due to incidents will significantly reduce the occupancy.

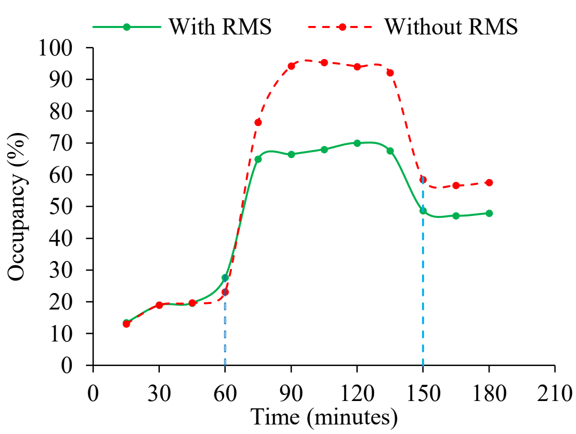


(a) Ramp volume 650 vphpl, freeway volume 850 vphpl

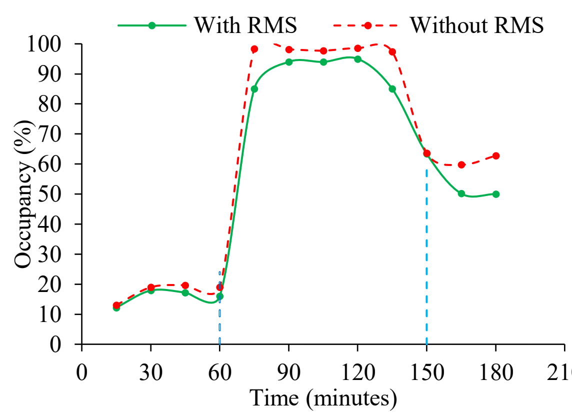


(b) Ramp volume 650 vphpl, freeway volume 850 vphpl

Figure 23: Occupancy profiles (a) two-lane (b) three-lane blockage, case VI



(a) Ramp volume 850 vphpl, freeway volume 1150 vphpl



(b) Ramp Volume 850 vphpl, freeway Volume 1150 vphpl

Figure 24: Occupancy profiles (a) two-lane (b) three-lane blockage, case VII

In all incidents scenarios, it is noted that travel speed on the mainline freeway was higher when with RMSs than without RMSs activation. This suggests that the RMSs improved freeway operation by producing smoother traffic flow on the freeway mainline. Also, it was observed that the longer the incident duration, the lower the travel speed values with or without RMSs activation. Moreover, for the incident with three-lane blockage, the drop in travel speed was much higher than the incident with two-lane blockage.

Potential Benefits of Activating RMSs on Weekends due to Incidents

This section discusses the potential benefits of activating RMSs in response to non-recurrent congestion on weekends. The real-world data for when the RMSs are operational are seldom found because in Florida ramp meters are not operational during weekends. Thus, the microscopic simulation approach was used to quantify the potential benefits of activating RMSs on weekends.

Performance Metrics

The primary objective of ramp metering is to improve the traffic flow conditions on the freeway mainline. For this reason, average speed and delay were used as performance metrics to assess the effectiveness of RMSs. The network evaluation in VISSIM was performed to examine how each of these parameters impacted the road network operation with and without the RMSs. The following variables were considered in the analysis.

Ramp volume: This variable represents the number of vehicles on the freeway's entrance ramp. The ramp volume used was based on the sensitivity analysis conducted in this chapter, where it was noted that, for a two-lane blockage incident with a 60-minute incident clearance duration, RMSs activation was needed when the ramp volume was higher than 950 vphpl whereas, for a 90-minute incident clearance duration, RMSs activation was necessary when the ramp volume exceeded 800 vphpl. On the other hand, for a three-lane blockage incident with a 60-minute incident clearance duration, RMSs activation was needed when the ramp volume exceeded 750 vphpl whereas, for a 90-minute incident clearance duration, RMSs activation was necessary when the ramp volume exceeded 800 vphpl. The worst-case scenario, i.e., 800 vphpl and 750 vphpl ramp volume, was used to quantify the potential benefits of activating the RMSs with respect to a two-lane and a three-lane blockage incident scenario, respectively.

Freeway mainline volume: This variable represents the traffic volume on the freeway mainline. From the sensitivity analysis conducted in this chapter, it was observed that for a two-lane blockage incident with a 60-minute and 90-minute incident clearance duration, RMSs activation was needed when the freeway mainline volume was higher than 950 vphpl. On the other hand, for a three-lane blockage incident with a 60-minute incident clearance duration, RMSs activation was needed when the freeway mainline volume was above 950 vphpl whereas, for an incident with a 90-minute incident clearance duration, activation was necessary when the freeway mainline volume exceeded 850 vphpl. The worst-case scenario, i.e., freeway volume of 950 vphpl and 850 vphpl for two-lane and three-lane blockage incident scenarios, respectively, were used to quantify the potential benefits for RMSs activation.

Impacts of RMSs on Average Speed

As discussed earlier, the average speed was used as the performance metric to examine the impacts of activating RMSs on weekends. The average speed represents the total distance a vehicle travels in a roadway network over a given period. The average speed in VISSIM is estimated using Equation 9. The average speed with and without RMSs activation was analyzed to quantify the potential benefits of RMSs on weekends

$$Average\ speed = \frac{d}{t} \tag{9}$$

Where ;

d = total distance ,

t = total travel time.

Table 16 summarizes the simulation results for the weighted average speed for the simulated scenarios.

Table 16: Simulation results for average speed

Incident type	Incident duration (minutes)	Activation scenario	Average speed (mph)	Increase in speed (%)
Two-lane blockage (40%)	60	Without RMSs	46.00	11
		With RMSs	51.29	
	90	Without RMSs	38.45	15
		With RMSs	44.2	
Three-lane blockage (60%)	60	Without RMSs	38.26	7
		With RMSs	40.90	
	90	Without RMSs	32.54	10
		With RMSs	35.72	

Note:40% and 60% are the percentages of lane blockage for general purpose lanes.

Two-lane blockage: Activating RMSs increased the average speed by 11% (i.e., from 46 to 51 mph) for an incident with a 60-minute incident clearance duration. On the other hand, activating RMSs increased the average speed by 15% (i.e., from 38 to 44 mph) for an incident with a 90-minute incident clearance duration. These results indicated that activating RMSs upstream of the incident location could improve traffic flow conditions on the entire study site network.

Three-lane blockage: Activating RMSs increased average speed by 7% (i.e., from 38 to 41 mph) for an incident with a 60-minute incident clearance duration. On the other hand, activating RMSs increased average speed by 10% (i.e., from 32 to 36 mph) for an incident with a 90-minute incident clearance duration. These results indicated that activating RMSs upstream of the incident location could improve traffic flow conditions on the entire study site network.

Impacts of RMSs on Average Delay

As discussed earlier, the average delay was used as the performance metric to examine the impacts of activating RMSs on weekends. The delay of a vehicle means the time lost by a vehicle when the actual speed is less than the desired speed (PTV, 2021). In this study, the desired speed for the study segment was provided in the base model by the FDOT and was a minimum of 60 mph and a maximum of 62.1 mph for single and high occupancy vehicles. On the other hand, the desired speed was a minimum of 52.5 mph for trucks and buses. The average delay represents the delay that a vehicle experiences in a roadway network over a given duration of time. It is the ratio of the total delay of all vehicles in the network to the total number of vehicles in the roadway network for a given evaluation time (PTV, 2021). The average vehicle delay with and without activation of RMSs was analyzed to quantify the potential benefits of RMSs. The average delay per vehicle in VISSIM is computed using Equation 10.

$$Average\ Delay = \frac{D}{N_{netw} + N_{arriv}} \tag{10}$$

where

D = total delay of all vehicles in the network,

N_{netw} = the number of vehicles in the network,

N_{arriv} = the number of vehicles that have arrived.

The average delays were extracted in aggregate 15-minute evaluation intervals over the entire simulation period and averaged to obtain the average delay of the entire roadway network. Table 17 summarizes the simulation results for the average vehicle delay for the simulated scenarios

Table 17: Simulation results for average delay

Incident type	Incident duration (minutes)	Activation scenario	Average delay (s/veh)	Decrease in delay (%)
Two-lane blockage (40%)	60	Without RMSs	76.94	22
		With RMSs	60.24	
	90	Without RMSs	142.60	25
		With RMSs	106.01	
Three-lane blockage (60%)	60	Without RMSs	141	15
		With RMSs	120.52	
	90	Without RMSs	208.3	18
		With RMSs	171.7	

Note:40% and 60% are the percentages of lane blockage for general purpose lanes.

Two lanes blockage incident: Activating RMSs decreased the average delay by 22% (i.e., from 76.94 to 60.24 s/veh) for an incident with a 60-minute incident clearance duration. On the other hand, activating RMSs decreased the average delay by 25% (i.e., from 142.60 to 106.01 s/veh) for an incident with a 90-minute incident clearance duration. These results indicated that activating RMSs upstream on the incident location could improve traffic flow conditions on the study site network.

Three lanes blockage incident: Activating RMSs reduced the average delay by 15% (i.e., from 141 to 120.52 s/veh) for an incident with a 60-minute incident clearance duration. Also, activating RMSs decreased average delay by 18% (i.e., from 208.3 to 171.7 s/veh) for an incident with a 90-minute incident clearance duration. These results indicated that activating RMSs upstream on the incident location could improve traffic flow conditions on the study site network.

Summary

This study discussed the potential benefits of activating RMSs on weekends using a microscopic simulation approach. The benefits were determined based on the established guidelines for activating RMSs on weekends. The average speed and average delay were used as the performance metric to estimate the benefits of RMSs on weekends. Table 18 summarizes the potential benefits of activating RMSs on weekends.

Table 18: Summary of benefits of activating RMSs on weekends

Incident type	Incident duration (minutes)	Increase in speed (%)	Decrease in delay (%)
Two-lane blockage (40%)	60	11	22
	90	15	25
Three-lane blockage (60%)	60	7	15
	90	10	18

Note:40% and 60% are the percentages of lane blockage for general purpose lanes.

Average speed: For a two-lane blockage, results showed that activating RMSs increased the average speed by 11% and 15% for an incident with a 60-minute and 90-minute incident clearance duration, respectively. For a three-lane blockage, activating RMSs improved the average speed by 7% and 10% for a 60-minute and 90-minute incident clearance duration, respectively.

This means that activation of RMSs due to the incident that occurred on weekends improved the average speed by at least 7%.

Average Delay: For a two-lane blockage, results showed that activating RMSs decreased the average delay of vehicles on the roadway network by 22% and 25% for an incident with a 60-minute and a 90-minute incident clearance duration, respectively. For a three-lane blockage, activating RMSs reduced the average delay of vehicles on the roadway network by 15% and 18% for the incident with a 60-minute and 90-minute incident clearance duration, respectively. This means that activation of RMSs due to the incident that occurred on weekends reduced the average delay of vehicles in the roadway network by at least 15%.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This study presented a microsimulation approach for developing the guidelines for RMSs activation on the freeways. The study focused on the freeway segment of I-95 South between NW 62nd street and NW 157th street. Two incident scenarios, i.e., two-lane and three-lane blockage incidents, each of 60-minute and 90-minute incident clearance duration, were simulated in VISSIM microsimulation. This study used the sensitivity analysis and statistical paired t-test to develop the guidelines for RMSs activation for the weekend non-recurring congestion using the Washington fuzzy logic algorithm for RMSs activation. Traffic volume and speed were the activation metrics that were developed from the simulation study. The study further quantified the potential benefits for activating the RMSs on the weekend non-recurring congestion using average speed and delay as the main metrics for analysis.

From the microsimulation results, it was noted that at low traffic volumes, it was not necessary to activate RMSs for both incident scenarios. However, as the traffic volume increased, the incident blocking the lanes of the freeway affected the capacity of the freeway, with a three-lane blockage incident affecting the capacity of the freeway more than a two-lane blockage incident. In support of this fact, the study noted that the RMSs activation for a three-lane blockage incident would be needed at lower traffic volumes compared to a two-lane lane blockage incident. This can be seen through the thresholds developed for both incident scenarios whereby for a two-lane blockage incident, RMSs activation upstream of the incident was necessary when the ramp volume was higher than 800 vphpl, and freeway volume was higher than 950 vphpl, whereas for a three-lane blockage incident, RMSs activation was needed when the ramp volume exceeded 750 vphpl and the freeway volume exceeded 850 vphpl.

The results also showed potential benefits of activating RMSs in response to non-recurring congestion on the weekend. These benefits were determined based on the established guidelines for activating RMSs on weekends. The average speed and delay were used as the performance metric to estimate the benefits of RMSs on the weekend, where it was noted that activation RMSs improved the average speed by at least 7% and reduced the average delay of vehicles in the roadway network by at least 15%. These findings provide Agencies with an effective means of conducting economic appraisal for the ramp metering program.

Recommendations for Future Work

This study has several limitations that could be addressed in future research. This study only developed the guidelines with respect to traffic volume and speed. Future studies can develop RMSs activation guidelines with respect to other traffic-related parameters such as occupancy. This study also quantified the mobility benefits for RMSs activation with respect to traffic speed and traffic delay, however, future studies can go beyond the scope of this study and quantify potential benefits of activating RMss with respect to safety as safety is an important aspect for any roadway network. In addition to that, future studies could analyze the impacts that activation of RMSs has on the surrounding arterials.

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