Guidelines for Activating Ramp Meters during Off-peak Hours and Weekends

Final Report

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DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

METRIC CONVERSION TABLE

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

LENGTH

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

AREA

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

VOLUME

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
fl oz	fluid ounces	29.570	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3

NOTE: volumes greater than 1,000 L shall be shown in m^3.

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

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16. Abstract

Ramp metering is a Transportation Systems Management and Operations (TSM&O) strategy that utilizes signals installed at freeway on-ramps to dynamically manage traffic entering the freeway. Ramp metering signals (RMSs) are usually activated during peak hours to alleviate recurring congestion. However, recurrent congestion during peak hours constitutes less than half of all congestion. It is the non-recurrent congestion, resulting from traffic incidents, work zones, adverse weather conditions, special events, etc., that adversely impacts the performance of the freeway.

The primary goal of this research was to develop specific guidelines to activate ramp meters during off-peak hours and on weekends in response to non-recurring congestion. The analysis was based on a 10-mile section of I-95 between Ives Dairy Road and NW 62nd Street in Miami-Dade County, Florida. Real-time traffic data were used to develop the guidelines for activating and deactivating RMSs in response to incidents and adverse weather conditions (i.e., rain) during off-peak hours on weekdays. Since the RMSs are not operational on weekends, a microscopic simulation approach was used to develop the guidelines for activating and deactivating RMSs in response to incidents on weekends.

The potential benefits of activating RMSs in response to non-recurring congestion during off-peak hours and on weekends were quantified based on the developed guidelines. Findings suggest that activating the first RMS upstream of the incident location could help improve traffic flow conditions during daytime off-peak periods. During nighttime off-peak periods, results indicated that activating the first RMS upstream and downstream of the incident location could help improve traffic conditions upstream. Findings also suggest that activating the RMSs during daytime and nighttime off-peak periods could help improve traffic flow conditions during rain. During weekends, the results indicated that activation of RMSs in response to incidents increased the average speed and also reduced the average delay of vehicles in the roadway network.

The developed guidelines were incorporated into a spreadsheet application designed to automatically determine when to activate or deactivate RMSs during off-peak hours and weekends based on prevailing traffic conditions. Recommendations for the guidelines to be included in the the Florida Department of Transportation (FDOT) District Six Standard Operating Guidelines (SOGs) were also provided. The proposed guidelines will enable the FDOT District Six to use ramp metering to improve traffic operations and safety during off-peak hours and weekends.

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EXECUTIVE SUMMARY

Agencies are implementing various Transportation Systems Management and Operations (TSM&O) strategies to reduce traffic congestion. Ramp metering is a TSM&O strategy that utilizes signals installed at freeway on-ramps to control the frequency at which vehicles enter the flow of traffic on the freeway. The strategy operates by stopping and releasing vehicles traveling from the adjacent arterials to the freeway mainline on the on-ramp segment. Ramp metering improves mobility, travel time reliability, safety, and the environment while preserving freeway capacity at a lower cost than traditional capacity improvements such as adding lanes.

Ramp metering signals (RMSs) are usually activated during peak hours to alleviate recurring congestion. However, the recurrent congestion during peak hours constitutes less than half of all congestion. It is the non-recurrent congestion, resulting from traffic incidents, work zones, adverse weather conditions, special events, etc., that adversely impacts the performance of the freeway. Non-recurrent congestion on freeways, especially during off-peak hours and weekends, could be alleviated by dynamically activating RMSs based on prevailing traffic conditions along the freeway corridor.

The primary goal of this research was to develop specific guidelines and criteria to activate ramp meters in response to non-recurring congestion during off-peak hours and on weekends. The proposed guidelines will enable the Florida Department of Transportation (FDOT) District Six to use ramp metering to improve traffic operations and safety during off-peak hours and weekends. The study results and the developed Microsoft Excel® application could also be used across Florida, wherever ramp metering will be employed.

Specific objectives of this research included:

- Develop specific procedures to identify operational conditions that justify activating ramp meters during off-peak hours and on weekends.
- Quantify the potential benefits of activating ramp meters in response to non-recurring congestion during off-peak hours and on weekends.

Developed Guidelines for Activating and Deactivating RMSs

The analysis was based on a 10-mile section of I-95 between Ives Dairy Road and NW 62nd Street in Miami-Dade County, Florida. This section has 10 RMSs in the northbound (NB) direction and 12 RMSs in the southbound (SB) direction. The guidelines for activating and deactivating RMSs in response to incidents and adverse weather conditions (i.e., rain) during off-peak hours on weekdays were developed based on the real-time traffic data. On the other hand, since the RMSs are not operational on weekends, the guidelines for activating and deactivating RMSs in response to incidents on weekends were developed using a microscopic simulation approach. These guidelines will enable FDOT District Six to use ramp metering to improve traffic operations and safety during off-peak hours and on weekends.

Guidelines for Activating and Deactivating RMSs in Response to Incidents during Off-peak Hours

Table E-1 summarizes the guidelines developed for activating and deactivating RMSs in response to incidents during off-peak hours on weekdays.

Table E-1: RMS Activation and Deactivation Guidelines due to Incidents

Period	RMS	Threshold: At Least One Lane Blockage		Threshold: No Lane Blockage	
		Activation	Deactivation	Activation	Deactivation
Daytime	Upstream	Speed ≤ 45 mph	Incident cleared & speed > 45 mph	Speed ≤ 50 mph	Incident cleared & speed > 50 mph
	Downstream	Speed ≤ 35 mph	Incident cleared & speed > 35 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph
Nighttime	Upstream	Speed ≤ 50 mph	Incident cleared & speed > 50 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph
	Downstream	Speed ≤ 35 mph	Incident cleared & speed > 35 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph

Incidents resulting in at least one lane blockage

Daytime off-peak periods: The RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 45 mph and deactivated when the incident has been cleared and the average mainline speed reaches 45 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 50 mph and deactivated when the incident has been cleared and the average mainline speed reaches 50 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Incidents with no lane blockage

Daytime off-peak periods: The RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 50 mph and deactivated when the incident has been cleared and the average mainline speed reaches 50 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period. Conversely, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Guidelines for Activating and Deactivating RMSs in Response to Rain during Off-peak Hours

Table E-2 presents the developed guidelines for activating and deactivating RMSs in response to rain during off-peak hours on weekdays.

Table E-2: RMS Activation and Deactivation Guidelines during Rain

Period	Threshold: Light Rain		Threshold: Moderate or Heavy Rain	
	Activation	**Deactivation**	**Activation**	**Deactivation**
Daytime	Speed ≤ 55 mph	Rain stops & speed > 55 mph	Speed ≤ 50 mph	Rain stops & speed > 50 mph
Nighttime	Speed ≤ 45 mph	Rain stops & speed > 45 mph	Speed ≤ 40 mph	Rain stops & speed > 40 mph

Light rain

Daytime off-peak periods: The RMSs may be activated when the average speed drops below 55 mph and deactivated when the rain stops and the average speed reaches 55 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs may be activated when the average speed drops below 45 mph and deactivated when the rain stops and the average speed reaches 45 mph for a consistent 5-minute period.

Moderate or heavy rain

Daytime off-peak periods: The RMSs may be activated when the average speed drops below 50 mph and deactivated when the rain stops and the average speed reaches 50 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs may be activated when the average speed drops below 40 mph and deactivated when the rain stops and the average speed reaches 40 mph for a consistent 5-minute period.

Guidelines for Activating and Deactivating RMSs in Response to Incidents on Weekends

Table E-3 summarizes the guidelines for activating and deactivating RMSs in response to incidents on weekends.

Incidents with 2-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 800 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,050 veh/hr/ln,
    c. Average speed on the mainline drops below 50 mph.

- Deactivate the RMSs upstream of the incident location if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

Incidents with 3-lane blockage

- Activate the RMSs upstream of the incident location if <u>all</u> of the following three conditions are met:
    a. Ramp traffic volume exceeds 750 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,000 veh/hr/ln,
    c. Average speed on the mainline drops below 50 mph.

- Deactivate the RMSs upstream of the incident location if the incident has been cleared <u>and</u> when the average speed on the mainline reaches 50 mph.

Table E-3: RMS Activation and Deactivation Guidelines on Weekends

Incident Scenario	Thresholds	
	Activation	**Deactivation**
2-lane blockage	Ramp volume > 800 veh/hr/ln & Mainline volume > 1,050 veh/hr/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph
3- lane blockage	Ramp volume > 750 veh/hr/ln & Mainline volume > 1,000 veh/hr/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph

Potential Benefits of Activating RMSs in Response to Non-Recurring Congestion

The potential benefits of activating RMSs in response to non-recurring congestion during off-peak hours and on weekends were quantified based on the developed guidelines.

Benefits of Activating RMSs in Response to Incidents during Daytime Off-peak Hours

The findings suggested that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 45%. This implies that activating the first RMS upstream of the incident location could help improve traffic flow conditions. However, based on the analysis, the results indicated that it might not be necessary to activate the RMSs further upstream and the first RMS downstream of the incident location to improve traffic flow conditions.

Benefits of Activating RMSs in Response to Incidents during Nighttime Off-peak Hours

Overall, the findings suggested that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 82%. Similarly, activating the first RMS downstream of the incident location reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 35%. These findings imply that activating the first RMS upstream and downstream of the incident location could help improve traffic flow conditions.

Benefits of Activating RMSs during Rain

Overall, activating RMSs decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 83% during daytime off-peak periods. On the other hand, activating RMSs reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 97% during nighttime off-peak periods. These findings imply that activating the RMSs could help improve traffic flow conditions during moderate or heavy rain.

Benefits of Activating RMSs in Response to Incidents on Weekends

The analysis results suggested that activation of RMSs due to incidents that occurred on weekends increased the average speed by at least 7%. Also, activating RMSs reduced the average delay of vehicles in the roadway network by at least 15%.

Tool for RMS Activation and Deactivation Guidelines during Off-peak Hours and Weekends

A tool for the RMS activation and deactivation guidelines during off-peak hours and on weekends was developed in Microsoft Excel®. A user manual for the tool is included in this report. The tool is intended to provide support and guidance to ramp metering operators in FDOT District Six to identify the need for activating or deactivating the RMSs during off-peak hours and on weekends.

The tool contains a total of six worksheets:

- Preface – includes a foreword, acknowledgments, and a disclaimer.
- Instructions – provides a brief overview of RMS and descriptions of the input variables required for activation and deactivation of the RMS.
- Worksheets for RMS activation and deactivation guidelines – includes a separate worksheet for RMS activation due to incidents, rain, and on weekends.
- Info worksheet – includes a summary of the RMS activation and deactivation guidelines.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADOT	Arizona Department of Transportation
API	Application Programming Interface
ATMS	Advanced Traffic Management System
BI	Buffer Index
Caltrans	California Department of Transportation
CCTV	Closed-Circuit Television
CDOT	Colorado Department of Transportation
COM	Component Object Model
CTOD	Central Time of the Day
D/C	Demand-to-Capacity
DTA	Dynamic Traffic Assignment
ELM	Express Lane Module
FCT	Floating Car Technique
FDOT	Florida Department of Transportation
FHP	Florida Highway Patrol
HCM	Highway Capacity Manual
HOV	High Occupancy Vehicle
KDOT	Kansas Department of Transportation
LOS	Level of Service
LTOD	Local Time of the Day
MoDOT	Missouri Department of Transportation
NB	Northbound
NEXRAD	Next Generation Weather Radar
NDOT	Nevada Department of Transportation
NOAA	National Oceanic and Atmospheric Administration
NYSDOT	New York State Department of Transportation
OD	Origin to Destination
ODOT	Oregon Department of Transportation
RITIS	Regional Integrated Traffic Information System
RMS	Ramp Metering Signal
SB	Southbound
SOG	Standard Operating Guidelines
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
VMT	Vehicle-Miles-Traveled
WisDOT	Wisconsin Department of Transportation

CHAPTER 1
INTRODUCTION

Traffic congestion is a growing concern on urban roadways. Agencies are implementing Transportation Systems Management and Operations (TSM&O) strategies to reduce traffic congestion. Ramp metering is a TSM&O strategy that utilizes signals installed at freeway on-ramps to dynamically control traffic entering the freeway. The strategy operates by stopping and releasing vehicles traveling from the adjacent arterials to the freeway mainline on the on-ramp segment. Ramp metering improves mobility, travel time reliability, safety, and the environment while preserving freeway capacity at a lower cost than traditional capacity improvements such as adding lanes. Figure 1-1 shows a typical ramp metering configuration.

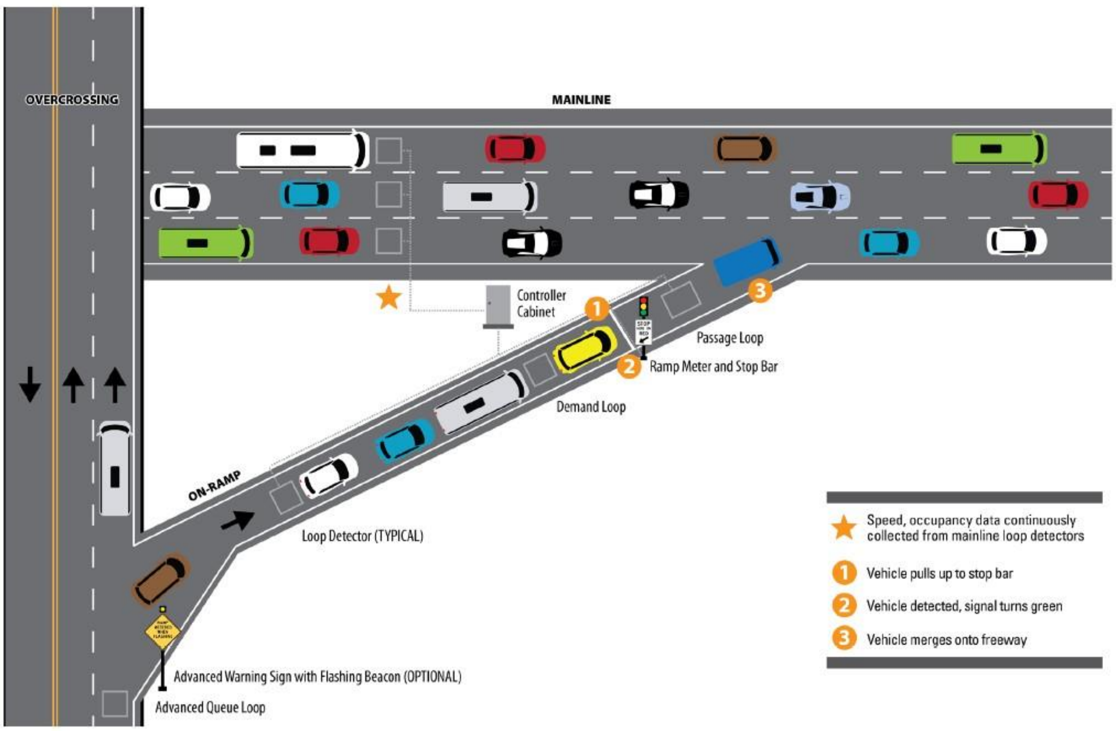


Figure 1-1: Ramp Metering Configuration (Mizuta et al., 2014).

Ramp metering signals (RMSs) are usually activated during peak hours to alleviate recurring congestion. However, the recurrent congestion during peak hours constitutes less than half of all congestion. It is the non-recurrent congestion, resulting from traffic incidents, work zones, adverse weather conditions, special events, etc., that adversely impacts the performance of the freeway. Non-recurrent congestion on freeways, especially during off-peak hours and weekends, could be alleviated by dynamically activating RMSs based on the prevailing traffic conditions along the freeway corridor. For corridors with RMSs already installed, activating these signals in response to non-recurrent congestions does not require significant resources and could be a relatively inexpensive strategy to reduce traffic congestion in real-time. However, established guidelines are necessary to justify the activation of the RMSs during off-peak hours and weekends.

1.1 Research Goal and Objectives

The primary goal of this research was to develop specific guidelines and criteria to activate ramp meters in response to non-recurring congestion during off-peak hours and on weekends. The proposed guidelines will enable the Florida Department of Transportation (FDOT) District Six to use ramp meters to improve traffic operations and safety during off-peak hours and on weekends.

Specific objectives of this research included:

1. Develop specific procedures to identify operational conditions that justify activating ramp meters during off-peak hours and on weekends.
2. Quantify the potential benefits of activating ramp meters in response to non-recurring congestion during off-peak hours and on weekends.

1.2 Report Organization

The rest of this report is organized as follows:

- Chapter 2 discusses the literature review of existing guidelines for activating and deactivating RMSs.

- Chapter 3 presents the data used to develop guidelines for activating and deactivating RMSs during off-peak hours and on weekends.

- Chapter 4 focuses on developing the guidelines for activating and deactivating RMSs in response to non-recurring congestion during off-peak hours on weekdays.

- Chapter 5 focuses on developing the guidelines for activating and deactivating RMSs in response to non-recurring congestion due to incidents on weekends.

- Chapter 6 discusses the potential benefits of activating RMSs in response to non-recurring congestion during off-peak hours and on weekends.

- Chapter 7 present the user manual for the RMS activation and deactivation tool.

- Chapter 8 provides the recommended guidelines to activate and deactivate ramp meters in response to incidents and adverse weather during off-peak hours and on weekends.

- Chapter 9 summarizes this research effort.

CHAPTER 2
LITERATURE REVIEW

This chapter focuses on identifying and reviewing the existing guidelines for activating and deactivating RMSs currently used in Florida and other states. Warrants for deploying RMSs and existing guidelines for activating RMSs in several situations, including peak hours, off-peak hours, weekends, traffic incidents, and adverse weather, were reviewed.

Warrants for ramp metering can be categorized into five major groups: traffic-related warrants, geometric characteristics warrants, safety-related warrants, funding-related warrants, and alternate route warrants (Wilbur Smith Associates, 2006). This chapter focuses on traffic-related warrants as they can be used to establish guidelines or criteria for RMS activation. Current guidelines for activating RMSs for non-recurrent events during peak hours and off-peak hours are then summarized. Metrics used to evaluate the benefits of RMS activation during off-peak hours and on weekends are also discussed.

2.1 Traffic-Related Warrants for Deploying RMSs

Ramp metering is typically focused on recurrent congestion during peak periods (Cambridge Systematics Inc., 2001). In general, the activation of RMSs during peak periods is based on time-of-day scheduling (Fartash, 2017). In other words, the RMSs are activated and deactivated at a fixed time of the day, regardless of traffic conditions. However, the necessity for ramp metering during peak hours varies, depending on each agency's needs and traffic requirements. For that reason, agencies have established several traffic-related warrants for deploying RMSs. The following sections discuss these warrants in detail.

2.1.1 Traffic Volume

Traffic volume is the most common criteria for warranting the deployment of RMSs. 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., rightmost lane) along the freeway mainline. Moreover, various time periods (e.g., 15 minutes, 30 minutes) are considered in the aggregation of traffic volume, depending on the agency’s needs.

FDOT and the Wisconsin Department of Transportation (WisDOT) warrant ramp metering when the average mainline volume during peak hour exceeds 1,200 vehicles per hour per lane (veh/hr/ln) (Gan et al., 2011; Wilbur Smith Associates, 2006). The Colorado Department of Transportation (CDOT) considers ramp metering when the mainline traffic volume exceeds 2,650 vph, 4,250 vph, and 5,850 vph for freeway with two, three, and four lanes, respectively (Gaisser & DePinto, 2015). 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 rightmost 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 veh/hr/ln during peak hours for lanes with acceleration lane lengths ≤ 500 feet. Also, ramp metering is warranted when the combined traffic flow rate in the rightmost lane and the entrance ramp during peak periods exceeds 2,300 veh/hr/ln for entrance ramps with acceleration lane lengths ≤ 500 feet (Texas Department of Transportation [TxDOT], 2014).

Ramp metering may also be considered based on the combination of the mainline and ramp volumes. In Florida, ramp metering can be considered when the combined mainline and ramp volumes during peak hour exceeds 2,650 vph, 4,250 vph, 5,850 vph, 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 rightmost freeway lane of greater than 2,050 vph during a typical 15-minute period as criteria for warranting ramp metering. 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 combined total mainline and ramp volumes 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. Moreover, vehicle classification is one of the special considerations in traffic-related warrants. Truck acceleration capability affects the required acceleration length of on-ramps and, therefore, affects the metering performance (Fartash, 2017). For instance, In California, ramp metering is warranted when the truck volumes (three axles or more) are at least 5% on entrance ramps. Table 2-1 summarizes the traffic volume threshold to warrant ramp meters in different states.

Table 2-1: Traffic Volume Threshold to Warrant RMS in Different States

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.
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.
	AZ	> 2,050	Ramp volume > 400 vph.
	NV	> 2,100	
Rightmost lane + ramp volume (vphpl)	TX	> 2,300	Length of acceleration lanes ≤ 500 ft.

Note: vph = vehicles per hour; vphpl = vehicles per hour per lane.

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) considers single-lane ramp metering when the ramp traffic volume is up to 900 vph, two-lane ramp metering when it exceeds 900 vph, but less than 1,800 vph, three-lane ramp metering when it exceeds 1,800 vph, and the facility requires high occupancy vehicle (HOV) lanes (California Department of Transportation [Caltrans], 2000). 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, 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). The traffic volume is also considered for warranting single-lane and two-lane ramp metering. Table 2-2 summarizes the conditions for different ramp metering configurations in different states.

Table 2-2: Ramp Volume Threshold in Different States

State	Ramp Volumes (vph)	HOV (%)	Recommended Lane Configuration
California	<900	-	Single-lane metered ramp
	≥ 900	-	Two or three-lane metered ramp
Florida	240 – 1,200	-	Single-lane metered ramp
	400 – 1,700		Multi-lane metered ramp
New York	240-900	-	Single-lane metered ramp
	≥ 400-(1500-1800)	-	Two-lane metered ramp
Utah	<180	-	Signaling not recommended
	180 – 600	-	Single-lane metered ramp
	600 – 900	<10%	Single-lane metered ramp
	600 –900	>10%	Single-lane metered ramp, or two-lane ramp with one lane metered and one HOV lane
	900 – 1,080	<10%	Two-lane ramp with both lanes metered
	900 – 1,080	>10%	Two-lane ramp with both lanes metered, or two-lane ramp with one lane metered and one HOV lane
	1,080 – 1,350	<10%	Two-lane ramp with both lanes metered
	1,080 – 1,350	>10%	Two-lane ramp with both lanes metered, or three-lane ramp with two lanes metered and one HOV lane
	1,350 – 1,720	<10%	Three-lane ramp with all lanes metered
	1,350 – 1,720	>10%	Three-lane ramp with all lanes metered, or three-lane ramp with two lanes metered and one HOV lane
	>1,720	-	Consider alternate metering strategies or no metering

Note: HOV = high occupancy vehicle; vph = vehicles per hour.

2.1.2 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 et al., 2013). NDOT considers ramp metering when the freeway operates at speeds lower than 50 mph for at least 30 minutes for more than 200 days a year (Jacobs Engineering Group Inc., 2013). TxDOT considers 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 speeds less than 30 mph during the peak periods (Arnold, 1998; Wilbur Smith Associates, 2006).

2.1.3 Occupancy

Occupancy, a traffic flow parameter, is commonly 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 (v/c) 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).

2.1.4 Level of Service (LOS)

Some agencies use level of service (LOS) when considering the time-of-day activation of ramp metering. NDOT warrants ramp metering on Nevada freeways when the LOS is E or worse during peak periods.

2.1.5 Summary

This section discussed the traffic-related warrants for deploying RMSs. Table 2-3 summarizes the traffic-related thresholds used by various agencies in the United States (U.S.) to warrant RMS deployment.

Table 2-3: Traffic-related Warrants for 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
	AZ	> 2,050	Ramp volume > 400 vph
	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	
LOS	NV, NY, VA	LOS E or LOS F	

Note: LOS = level of service; mph = miles per hour; vph = vehicles per hour; vphpl = vehicles per hour per lane.

2.2 Criteria for Activating RMSs during Non-recurrent Congestion

In addition to time-of-day scheduling, RMSs can be activated to alleviate non-recurrent congestion resulting from variations in traffic demand, traffic incidents, and adverse weather conditions. Parameters that can be considered to warrant RMSs during non-recurring congestion include: congestion level, traffic flow parameters, incident characteristics, and rainfall. These parameters are discussed in the following subsections.

2.2.1 Congestion Level

Freeway traffic conditions are monitored by the RMS 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; FDOT, 2020). Similarly, RMSs in Nevada can also be activated or 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) includes special afternoon hours in the ramp metering time-of-day scheduling to alleviate heavy traffic, and the time-of-day schedule also may 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 at all times of the day due to heavy traffic (Balke et al., 2009).

2.2.2 Traffic Flow Parameters

Traffic flow parameters, such as traffic volume, speed, and occupancy, are used as criteria for the activation and deactivation of RMSs during non-recurrent congestion. The use of these parameters is supported by the presence of detectors on freeways collecting real-time traffic data. In Florida, the RMS operator determines the time for activating RMSs by observing the average speed at a mainline detector. RMSs are activated when the average speed drops to 45 mph for a consistent 5-minute period and deactivated when the average speed reaches 50 mph (FDOT, 2020). RMS operation guidelines in Texas indicate that the general activation and deactivation times during peak periods can be adjusted based on traffic demand. In addition, for high traffic demand observed near high-volume ramps located in suburban areas, RMS activation can be considered when the traffic volume in the rightmost lane of the freeway reaches approximately 1,600 vphpl (Balke, 2009).

In some Caltrans districts, metering hours during off-peak periods are selected based on traffic speed and v/c ratio (Lu et al., 2019). A v/c threshold of between 0.6 and 0.8 and a speed less than 30 mph are considered as the criteria for activating the RMSs. The Oregon Department of Transportation (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. In Michigan, RMSs were activated during off-peak periods when traffic speed dropped to 35 – 45 mph and deactivated when traffic speed returned to 50 – 60 mph (Kostyniuk et al., 1988). Also, the RMSs were activated during off-peak periods when traffic occupancy increased to 10% – 13% and deactivated when traffic occupancy returned to 6% – 9% (Kostyniuk et al., 1988).

2.2.3 Incident Characteristics

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 (FDOT, 2020). The other adjacent RMSs are activated based on the queuing conditions, which are determined by the RMS operator by monitoring traffic conditions using CCTV and/or detectors. The downstream RMS during peak hours is required to remain operational. NDOT requires an operator to make changes to the RMS operation hours during emergencies or unique situations (Jacobs Engineering Group Inc., 2013). Conversely, operators in Minnesota TMCs use CCTV cameras to view crash locations and temporarily deactivate the RMSs until the incident is cleared (Athey Creek Consultants, 2019). This is specific for incidents that occur on the entrance ramps to allow vehicles to follow the directions of incident responders.

Lane blockages affect the capacity of freeways and interrupt the regular traffic flow. FDOT District Six established guidelines, shown in Table 2-4, 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 indicated 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. The need for activating the RMSs was derived from the predicted demand values in the next 15-minute period and the estimation of the forecasted D/C ratio for the next 15-minute period. Results indicated a need for activating all ten RMSs due to lane blockage incidents during peak hours. It is worth noting that depending on the number of lanes, incident lane blockage can evolve from all lanes blocked, > 2 lanes blocked, ≤ 2 lanes blocked, and no lanes blocked. Hence, the RMS operator has to determine the appropriate action (FDOT, 2020).

Table 2-4: Guidelines for Activating RMSs for Traffic Incidents in Florida

Event	Upstream RMS	Downstream RMS
All Lanes Blocked	Activate all RMS with a lower metering rate	Deactivate temporarily
		Activate immediately after blockage 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 blockage 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 when the blocked lane is open

2.2.4 Rainfall

Rainfall may also be considered as a factor for activating the RMSs due to its impact on freeway capacity. Fartash (2017) considered medium and heavy rains to activate the RMSs. The effect of rainfall was also considered to estimate the number of ramps to be activated and the metering rate. Since rain may affect the capacity and demand of the roadway, the capacity drop due to rainfall was included in the estimation of the D/C. However, it was assumed that rain did not affect the demand. The predicted D/C for the next 15-minute period indicated that all ten RMSs along the study corridor needed to be activated for heavy rains during peak hours.

2.2.5 Summary

This section discussed the criteria that can be used for activating and deactivating ramp meters during non-recurrent congestions. These parameters included congestion level, traffic flow parameters, incident characteristics, and rainfall. All the above-discussed parameters are crucial for activating and deactivating ramp meters during recurrent and non-recurrent congestion. This project used these parameters to develop the guidelines for activating and deactivating ramp meters during off-peak hours and on weekends. Table 2-5 summarizes the criteria used by different state DOTs in the U.S. for activating RMSs due to non-recurrent congestion.

Table 2-5: 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, due to an incident not causing lane blockage
		Lane blockage (e.g., all lanes, > 2 lanes, ≤ 2 lanes blocked)
	MN	Incident is cleared
Rainfall	FL	Heavy rain (> 0.25 in/hr)

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

2.3 Metrics for Quantifying the Benefits of Activating RMSs

Several metrics are used to assess the performance of RMSs activated due to recurrent and non-recurrent congestion. The metrics included, but are not limited to, travel time, travel time reliability, traffic speed, traffic delay, LOS, traffic volume, and traffic throughput. These performance metrics are discussed in detail in the following subsections.

2.3.1 Travel Time

Several studies used travel time as a metric of 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, KDOT and MoDOT (2011) analyzed the travel time on a ramp-metered corridor before and after the start of metering operations using the FCT. Results indicated significant improvements in travel time during morning peak hours with RMSs activated.

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. The study compared travel times when the RMSs were activated and deactivated during morning peak hours on weekdays. Using descriptive statistics, results indicated that activating the RMSs was associated with a 95-second average reduction in travel time. 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).

2.3.2 Travel Time Reliability

Travel time reliability is a measure of the consistency of travel time and reflects the road user's experience in commuting. Metrics used to indicate the travel time reliability of a segment 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, and travel time index (TTI) (Lomax et al., 2003). Lower TTIs and BIs indicate reliable travel times along a corridor.

Cohen et al. (2017) used the variance of travel times to determine 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 more variation in travel time along the corridor 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 activating 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 BI values when mainline traffic was at LOS E or 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.

2.3.3 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 metered segments, before and after the start of RMS operations, were compared. Results showed that speeds increased on most of the segments 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 benefits of using the fuzzy logic algorithm in ramp metering before implementation in Washington State. 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 show any improvement as a result of activating the RMSs on a corridor in Las Vegas, NV (Xie et al., 2012).

Travel speeds were also used to determine the benefits of activating the RMSs on arterials parallel to the metered freeways. Cambridge Systematics Inc. (2001) showed that changes in the travel speeds on parallel arterials were not significant when RMSs were activated. Results suggest that, without significant changes in arterial volumes that can cause gridlock at intersections, travel speeds along arterials are expected to not change because of ramp metering operations (Cambridge Systematics Inc., 2001).

2.3.4 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.

Drakopoulos et al. (2004) used delays on entrance ramps to assess the need for more RMSs along a corridor in Milwaukee, WI. Findings indicated that activating 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. Levinson and Zhang (2006) suggest that despite positive impacts on the freeways, ramp metering might increase traffic delays on entrance 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 RMS operations. Results indicated a reduction of the queue length for one of the adjacent arterials as a result of activating the RMSs (Neel & Gibbens, 2001).

2.3.5 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 as a result of activating the RMSs on Saturdays. Slight improvements in both VHT (1.8%) and VMT (1.0%) were observed as a result of 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 indicated significant traffic diversions between entrance ramps when RMSs were activated (Horowitz et al., 2004).

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 select 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 time periods. Horowitz et al. (2004) indicated that traffic diversion from the freeway to arterials when the RMSs were activated was less than 10%. However, the amount of traffic diverted from the freeway was not equal to the total increase in traffic on the parallel arterials. Using an analytic model, Zhang (2007) indicated that activating the RMSs does not worsen traffic conditions on all arterials in the network. Because of network equilibrium, some arterials might experience better traffic conditions, while others might be impacted negatively (Zhang, 2007).

2.3.6 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. 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.

2.3.7 Summary

This section discussed the metrics that can be used to quantify the benefits of activating RMSs. These metrics included travel time, travel time reliability, travel speed, traffic delays, traffic volume and throughput, and LOS. Table 2-6 summarizes the metrics used to evaluate the effect of activating RMSs and their focus location.

Table 2-6: Performance Metrics Used to Evaluate RMS Activation

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

2.4 Summary

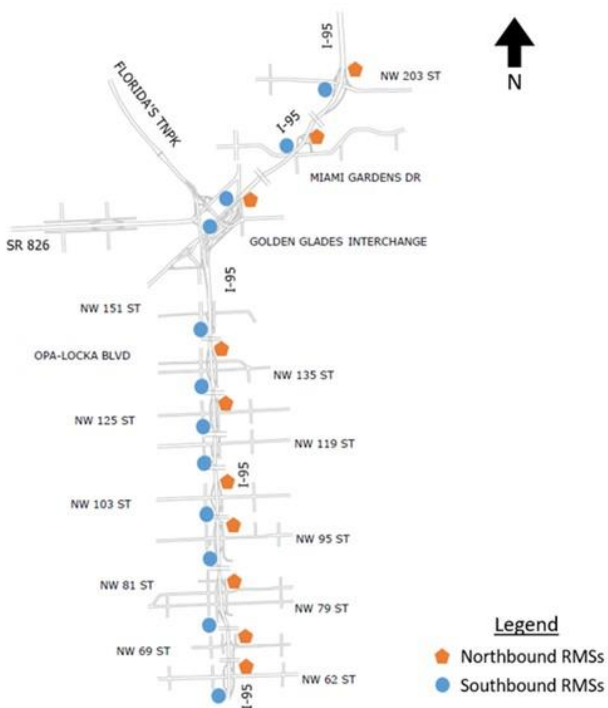
This chapter focused on identifying and reviewing the existing guidelines for activating RMSs in Florida and other states. The reviewed guidelines focused on RMS operations during peak hours and off-peak hours. The guidelines for considering RMS activation due to incidents and adverse weather conditions were also discussed. Finally, performance metrics that can be used to quantify the benefits of activating RMSs were identified and discussed.

CHAPTER 3
STUDY AREA AND DATA

This chapter discusses the study area used in this research and the data needed to develop guidelines for activating and deactivating RMSs during off-peak hours and on weekends. Data used in this research project include traffic data, incident data, rain data, and ramp metering operational data.

3.1 Study Area

A 10-mile section of I-95 between Ives Dairy Road and NW 62nd Street in Miami-Dade County, Florida, was selected to evaluate the performance and develop guidelines for RMS activation during off-peak hours and weekends. The section has 10 RMSs along I-95 in the northbound (NB) direction and 12 RMSs along I-95 in the southbound (SB) direction. Figure 3-1 shows the locations of the RMSs along the I-95 study section. Ramp metering operations began in 2009, and the RMSs are operated and managed by FDOT District Six. The RMSs are operational during the morning peak period for the SB direction and the afternoon peak period 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 every day. Also, the RMSs in the study area are sometimes used to manage traffic during non-recurring congestion due to incidents or special events (e.g., concert events).



Number	I-95 Direction	Location
1	Northbound	NW 62 Street
2		NW 69 Street
3		NW 79 Street
4		NW 95 Street
5		NW 103 Street
6		NW 125 Street
7		NW 135 Street
8		NW 2 Ave
9		Miami Gardens Drive
10		Ives Dairy Rd
11	Southbound	Ives Dairy Rd
12		Miami Gardens Drive
13		US 441
14		NW 167 Street
15		NW 151 Street
16		NW 135 Street
17		NW 125 Street
18		NW 119 Street
19		NW 103 Street
20		NW 95 Street
21		NW 79 Street
22		NW 62 Street

Figure 3-1: I-95 Study Corridor

3.2 Data

The following data were required to achieve the research goal: (1) traffic data; (2) incident data; (3) rain data; and (4) ramp metering operational data. The following subsections discuss each of these data types and their sources.

3.2.1 Traffic Data

Traffic data required in this research project include speed, volume, and occupancy. Traffic data were extracted from the Regional Integrated Transportation Information System (RITIS), an automated data sharing, dissemination, and archiving system that includes real-time data feeds and archive data analysis tools, such as probe, detector, and transit data analytics. RITIS stores and disseminates data from several sources, including data vendors (e.g., HERE Technologies, INRIX, and TomTom) and detectors maintained by transportation authorities (e.g., FDOT).

The traffic volume, speed, and occupancy data in RITIS were collected using detectors maintained by FDOT District Six. Traffic data can be extracted from RITIS in either a raw format or aggregated in 5-minute, 15-minute, 30-minute, and 1-hour intervals, depending on the scale of analysis. In this research project, data in 5-minute intervals were used. Figure 3-2 provides the location of detectors that collect data along the study corridor between NW 79th Street and NW 103rd Street.

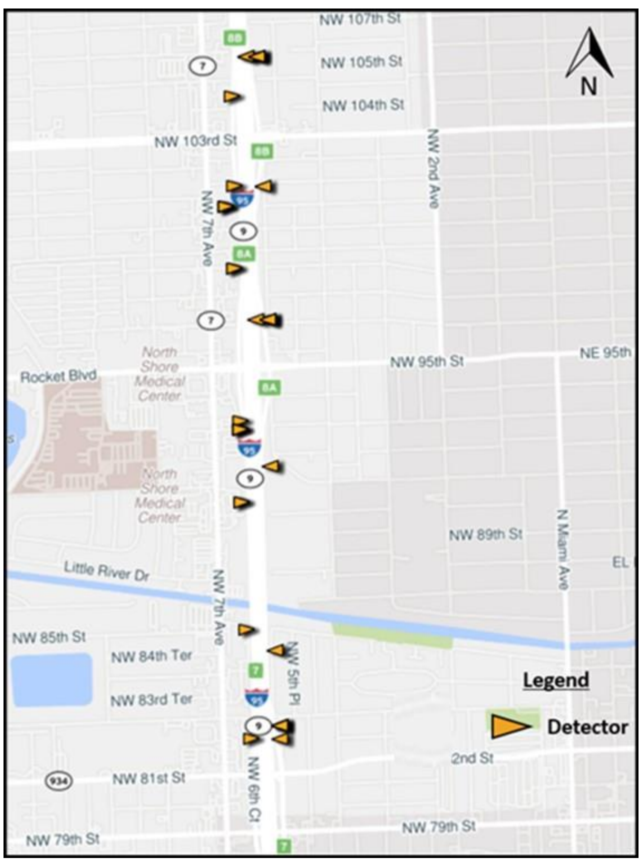


Figure 3-2: Location of Detectors along the Study Corridor

3.2.2 Incident Data

Traffic incident data was collected from SunGuide®, an Advanced Traffic Management System (ATMS) software used to process and archive incident data on Florida's transportation system. The SunGuide® incident database contains most of the relevant information related to incidents, including:

- Event ID
- Roadway, e.g., I-95, I-295, I-10, etc.
- Latitude and longitude of the event location
- Incident notification time
- Incident clearance duration
- Event type, i.e., crash, flooding, disabled vehicle, debris on the roadway, etc.
- Time of event
- Number and categories of responding agencies
- Lane closure information
- Incident severity
- Incident detection method

All of the above-listed variables are self-explanatory except event type and detection method. The SunGuide® database contains several types of incidents, including crashes, disabled vehicles, debris on the roadway, emergency vehicles, police activity, vehicle fire, flooding, pedestrian, abandoned vehicle, construction, and others. The database also identifies how an incident was detected, i.e., by Road Rangers, Florida Highway Patrol (FHP), FL511 Probe vehicle, CCTV, County Police, Waze, or by a motorist.

3.2.3 Rain Data

Rain data was extracted from the National Oceanic and Atmospheric Administration (NOAA) database. Specifically, the data was retrieved from the NOAA's Next Generation Weather Radar (NEXRAD), which detects precipitation and atmospheric movement using a network of 160 high-resolution Doppler radar sites at approximately 5-minute intervals from each site (Barr, 2015). The precipitation data are recorded as reflectivity, a measure of fractions of radiations reflected by a given surface expressed as a ratio of the radiant energy reflected and the total amount of energy incident on the surface (Andrew, 2019). The reflectivity data was extracted from a radar located in Miami, FL. The radar covers a 248.5-mile radius which includes the study corridor. The reflectivity data was retrieved at 5-minute intervals corresponding to the ramp metering operation hours of each RMS in the study corridor. The reflectivity values were converted to rainfall intensity using Equation 3-1 (Teegavarapu, 2012).

$$R = \left[\frac{10^{\frac{dBZ}{10}}}{250}\right]^{\frac{1}{1.2}} \tag{3-1}$$

where, R is the rainfall intensity expressed in millimeters per hour (mm/hr), and dBZ is an abbreviation for decibel relative to reflectivity. The dBZ measures the strength of the energy reflected to the radar by the target surface, in this case, the roadway segment.

3.2.4 Ramp Metering Operations Data

Ramp metering operations data are required to identify the days and times when the RMSs were activated and deactivated. These data were collected from the FDOT District Six TMC, which contains the following information:

- Operation date
- RMS ID
- Turn-on (activation) time
- Turn-off (deactivation) time
- Reasons for activation
- Event ID
- Comments

Since ramp metering along the study corridor only operates on typical weekdays, weekends and holidays are not included in the analysis. Reasons listed for activating the RMSs include recurrent congestion, non-recurrent congestion, incident, weather, central time of the day (CTOD), and local time of the day (LTOD). The CTOD is when the activation is set for a fixed time that is established in the central controller of the ramp metering system at the TMC. LTOD is when the controller in the field near the ramp meter activates the ramp metering system due to a lack of communication or malfunction in the central controller. While CTOD is a schedule that is maintained and operated through SunGuide®, LTOD is configured in the field ramp meter controller. Note that CTOD and LTOD typically have the same TOD operational window. The database contains the event identification that caused the activation and deactivation of the RMSs. The comments listed provide more details on the ramp metering activation and deactivation, including activation for inclement weather or special events.

3.3 Summary

This chapter discussed data required to assess the need for activating RMSs including traffic data, incident data, rain data, and ramp metering operations data. Table 3-1 summarizes the data used in this research.

Table 3-1: Data and Data Sources

Data	Data Sources
Traffic data	Regional Integrated Traffic Information System (RITIS)
Incident data	SunGuide®
Rain data	National Oceanic and Atmospheric Administration (NOAA)
RMS operations data	FDOT District Six TMC

CHAPTER 4
ACTIVATION AND DEACTIVATION GUIDELINES DURING OFF-PEAK HOURS

This chapter presents the guidelines for activating and deactivating RMSs in response to non-recurrent congestion during off-peak hours. Specifically, the guidelines were developed considering incidents and adverse weather conditions during off-peak hours on weekdays. The following sections discuss the data used, data processing procedures, methods, and the developed guidelines for RMSs activation and deactivation during off-peak hours on weekdays.

4.1 Data and Data Sources

The analysis was based on the 10-mile section of I-95 between Ives Dairy Road and NW 62nd Street in Miami-Dade County, Florida. This section has 10 RMSs in the NB direction and 12 RMSs in the SB direction. The ramp metering operations began in 2009. FDOT District Six operates and manages these RMSs. The RMSs 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 every day. Also, the RMSs in the study area are used to manage traffic during non-recurring congestion due to incidents or special events (e.g., concerts).

The following data were extracted from 2013 through 2019 to develop guidelines for activating and deactivating RMSs during the off-peak hours:

- *Incident data*: Seven years (2013 – 2019) of incident data along I-95 were extracted from SunGuide®, an ATMS software used to process and archive incident data on Florida's transportation system.

- *Ramp metering operations data:* These data were used to identify the days and times when the RMSs were activated and deactivated. The data were collected from the FDOT District Six TMC from 2013 through 2019.

- *Rain data:* Seven years (2013 – 2019) of rain data along I-95 were extracted from the NOAA database. Specifically, the data were retrieved from the NOAA's NEXRAD, which detects precipitation and atmospheric movement using a network of 160 high-resolution Doppler radar sites at approximately 5-minute intervals from each site.

- *Traffic data:* Traffic flow data, i.e., speed, volume, and occupancy, were extracted from the RITIS, an automated data sharing, dissemination, and archiving system that includes real-time data feeds and archives data analysis tools, such as probe, detector, and transit data analytics. These data were collected at 5-minute intervals for the years 2013 through 2019.

These data and their sources were discussed in detail in Chapter 3 of this report.

4.2 Data Processing

Data processing procedures included: extracting traffic flow parameters at 5-minute intervals during an incident clearance time and rainfall events. The following subsection discusses these procedures in detail.

4.2.1 Extract Traffic Flow Parameters during Incident Clearance Time

Traffic flow parameters at 5-minute intervals were extracted from traffic detectors at the nearest upstream, second nearest upstream, and downstream location of the incident. Figure 4-1 illustrates a typical incident location along the study corridor.

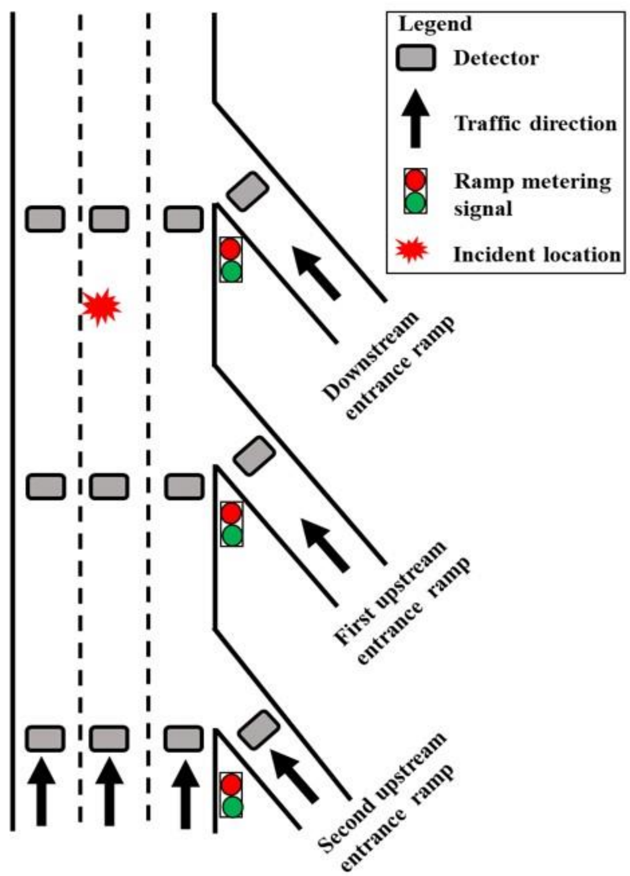


Figure 4-1: Typical Incident Location Scenario

For each incident, the following data were recorded: the time and date of occurrence, the duration of the incidents, and the time when the incidents were cleared. RMS operations data were used to check whether the incidents occurred when the upstream RMSs and the downstream RMS were turned ON or OFF. Incidents that occurred when the RMSs were turned ON and OFF were identified and recorded. The traffic flow parameters at every 5-minute interval during the incident clearance time were extracted from the detectors located upstream and downstream of the incident location. It is worth noting that all incidents that occurred on holidays, on weekends, and during

Hurricane Irma in 2017 and Hurricane Michael in 2018 were excluded from the analysis. Figure 4-2 summarizes the process of extracting traffic flow parameters during the incident clearance time.

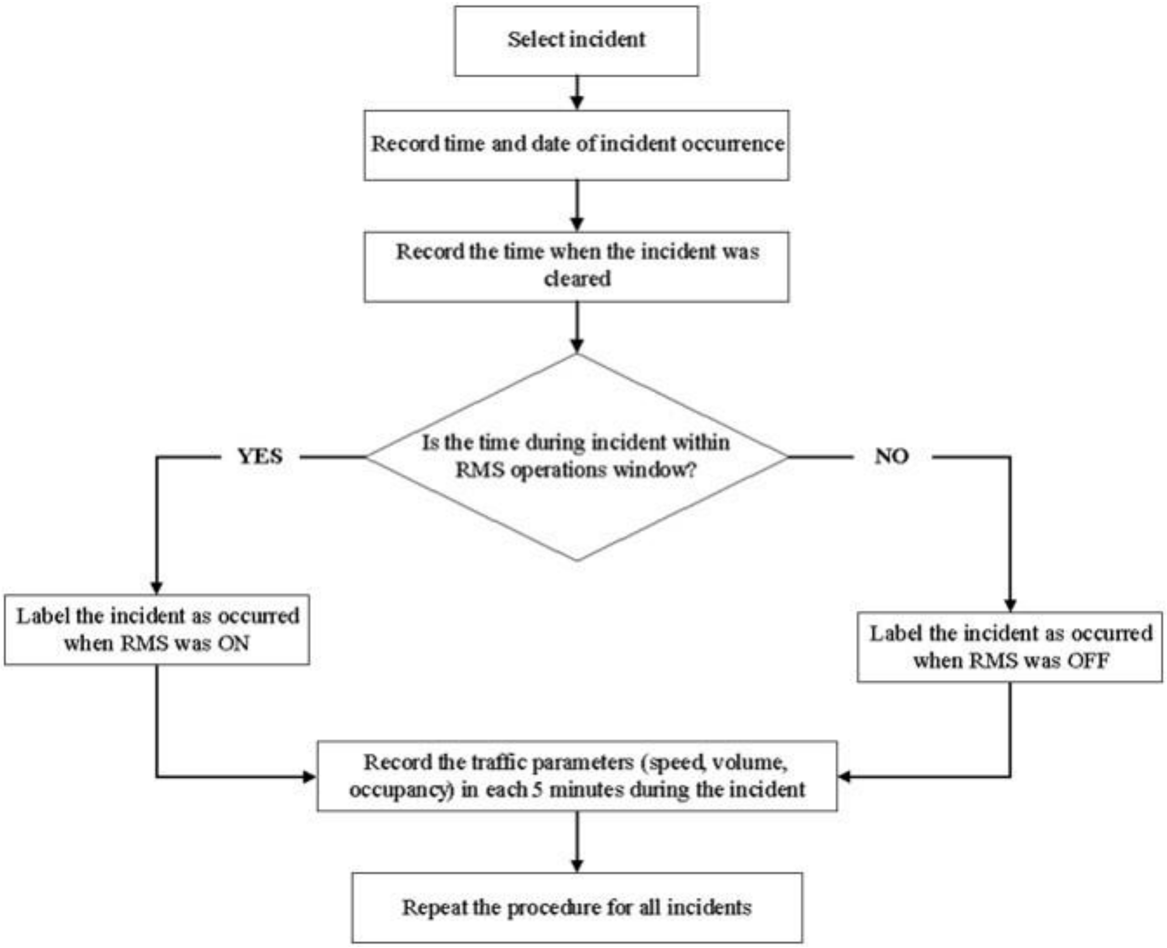


Figure 4-2: Incident Data Processing

4.2.2 Extract Traffic Flow Parameters during Rain

Given that the rain data was available in a raster format, three polygons were defined along the study corridor for data collection, as shown in Figure 4-3. The data were extracted from the polygons and then converted to rain intensity using Equation 4-1. The traffic flow parameters during rain events were extracted at every 5-minute interval. Whenever there was an incident during rainfall, the traffic flow data during that incident clearance duration were excluded from the analysis.

$$R = \left[\frac{10^{\frac{dBZ}{10}}}{250}\right]^{\frac{1}{1.2}} \qquad (4\text{-}1)$$

where, R is the rainfall intensity expressed in millimeters per hour (mm/hr), and dBZ is an abbreviation for decibel relative to reflectivity. The dBZ measures the strength of the energy reflected to the radar by the target surface, in this case, the roadway segment.

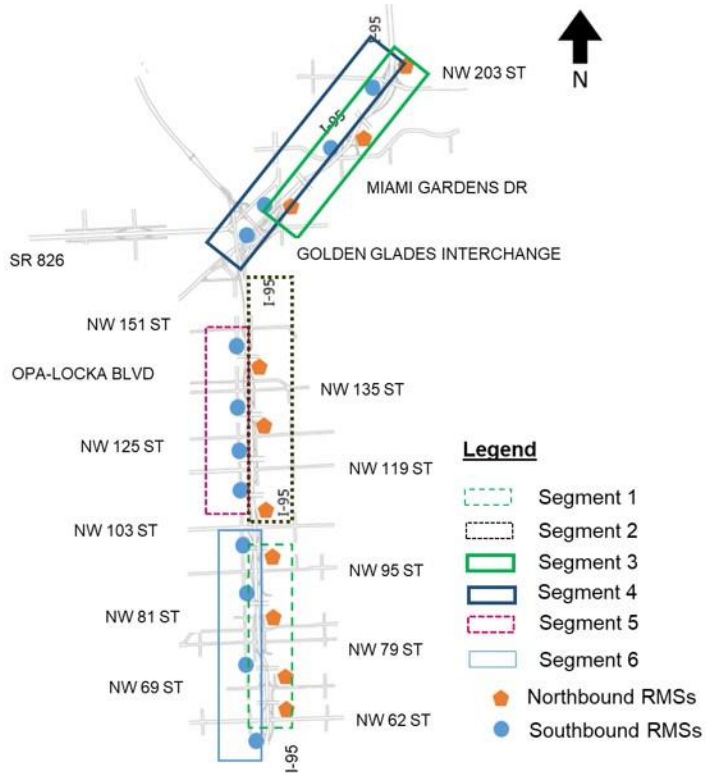


Figure 4-3: Rainfall Polygons along the Study Corridor

4.3 Methodology

This section discusses the method used to develop guidelines for activating and deactivating RMSs in response to non-recurrent congestion during off-peak hours on weekdays.

4.3.1 Clustering of the Traffic Flow Data

The *k*-means clustering analysis was used to categorize traffic flow data into groups based on fundamental traffic flow variables. Clustering techniques identify the similarities and dissimilarities between data and classify the data into groups with homogenous characteristics. Since the objective of clustering techniques is to classify a set of data into groups, this method is a common approach used to separate data into subgroups by reducing the within-group distances and maximizing the distances between groups (Xu et al., 2012). The *k*-means clustering allocates each observation to a cluster (*J*), with the nearest center point based on a pre-specified number (*k*) of clustering centers, as shown in Equation 4-2.

$$J = \sum_{j=1}^{k} \sum_{i \epsilon C_j} \left\| X_i - c_j \right\|^2 \tag{4-2}$$

where,

X_i = ith traffic flow observation,
c_j = jth cluster center,
k = number of clusters, and
C_j = object set of the jth cluster.

The symbol ‖.‖ denotes any vector form representing the distance between the traffic flow observation and the cluster center. The *k*-means technique is an iterative procedure involving the computation of cluster centroids. A cluster centroid is an arbitrary point in space that represents the average location of the particular cluster. Each data point is assigned to the closest centroid. The location of each centroid is updated in each iteration until no significant change is observed in the location of centroids (Kianfar & Edara, 2010). The *k*-means algorithm is applied using the following three steps. First, the algorithm chooses k objects as initial cluster centers. Then, each observation is assigned to the cluster with the nearest center. Finally, the centers of the new clusters are established after calculating the mean of all observations in each cluster.

This study used *k*-means clustering to classify the traffic flow datasets into three groups based on speed and occupancy. The clustering method was applied to two sets of speed and occupancy observations grouped according to the time of day: (1) daytime off-peak periods and (2) nighttime off-peak periods. The *k*-means clustering was conducted iteratively by setting the number of clusters from 3 to 15. The silhouette index, one of the indices used to determine the optimal number of clusters in a dataset, was used to determine the optimal number of clusters. The silhouette index combines information about within-cluster and between-cluster variation (Charrad et al., 2014; Rousseeuw, 1987). The three established traffic flow states were used to recommend when to activate and deactivate RMSs.

4.3.2 Establish Traffic Flow States with Respect to the Incident Location

The data collected using the procedure described in Section 4.2.1 included three traffic flow parameters: volume, speed, and occupancy. In this research, speed and occupancy were used to establish traffic flow states upstream and downstream of the incident location. Occupancy was used instead of density since density cannot be directly measured from the detectors.

The *k*-means clustering method was applied to the speed and occupancy data collected every five minutes within the incident clearance time to establish the traffic flow states. The *k*-means clustering approach described in Section 4.3.1 was used to categorize speed and occupancy. The *k*-means clustering was conducted iteratively by setting the number of clusters from 3 to 15. The minimum number of considered clusters was based on the assumption that traffic flow commonly consists of three states: free flow, transition flow, and congested flow. The silhouette index was used to select the optimum number of clusters.

4.3.3 Establish Traffic Flow States during Rain

The data collected using the procedure described in Section 4.2.2 included two traffic flow parameters: speed and occupancy. In this research, speed and occupancy were used to establish traffic flow states during rain. The procedure for establishing the traffic flow states was similar to that described in Section 4.3.2.

4.4 Analysis Results due to Incidents

This section discusses the analysis results for the activation and deactivation of RMSs in response to non-recurrent congestion due to incidents during off-peak hours on weekdays. During the seven-year study period (2013 – 2019), 25,911 incidents were recorded on weekdays. Of the 25,911 incidents, 16,945 incidents (65.4% of the incidents) did not require lane blockage and 8,966 (34.6% of the incidents) required lane blockage. Note that all incidents that occurred on holidays, peak hours, and those associated with missing traffic data were excluded from the analysis. Thus, a total of 5,837 incidents that resulted in at least one lane blockage and 10,570 incidents that did not require lane blockage were included in the analysis. Of the 5,837 incidents that resulted in at least one lane blockage, 64.6% occurred during daytime off-peak periods, and 35.4% occurred during nighttime off-peak periods. Of the 10,570 incidents that did not require lane blockage, 56.2% occurred during daytime off-peak periods, and 43.8% occurred during nighttime off-peak periods.

4.4.1 Traffic Flow States due to Incidents

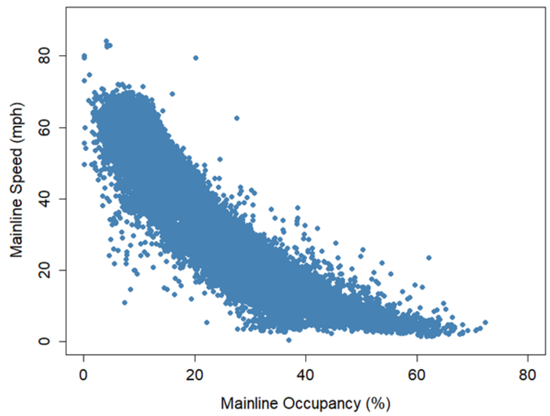
The *k*-means clustering was used to classify the traffic flow parameters (i.e., speed and occupancy) upstream and downstream of the incident locations into different traffic flow states. Three traffic flow states (i.e., *free flow state*, *transition flow state*, and *congested flow state*) were classified based on the speed and occupancy during the daytime off-peak and nighttime off-peak periods. These traffic flow states were established at the upstream on-ramp and downstream on-ramp of the incident location, as discussed in the following sections.

4.4.1.1 Traffic Flow States at the First Upstream On-ramp of the Incident Location

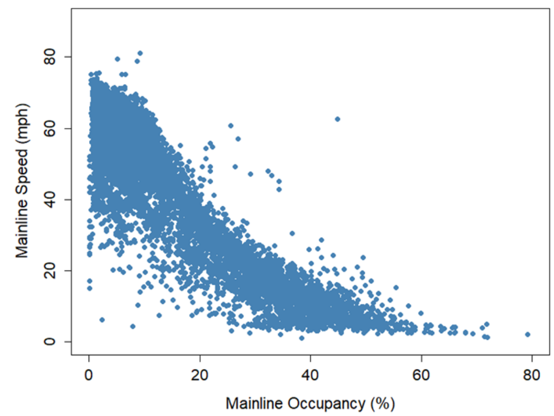
Figure 4-4 shows the traffic flow observations at the first upstream on-ramp of the incident location before clustering.

At least one lane blockage: The average speed and occupancy were approximately 40 mph and 20% during the daytime off-peak periods, respectively. On the other hand, the average speed was approximately 50 mph, and the average occupancy was approximately 11% during the nighttime off-peak periods.

No lane blockage: During daytime off-peak periods, the average speed and occupancy were approximately 52 mph and 13%, respectively. The average speed and occupancy were about 57 mph and 6% during the nighttime off-peak periods, respectively.

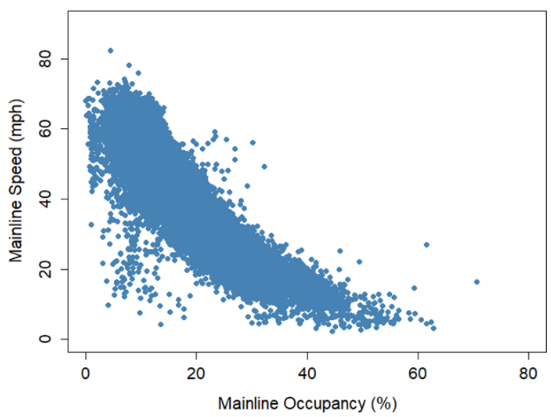


Daytime off-peak periods

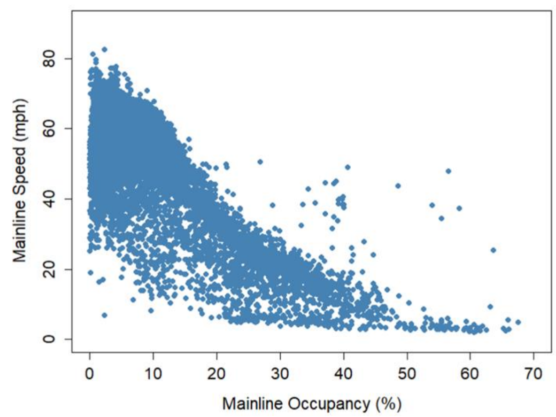


Nighttime off-peak periods

(a) At Least One Lane Blockage



Daytime off-peak periods



Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-4: Speed-Occupancy Diagram at the First Upstream On-ramp of the Incident Location

The silhouette index of the *k*-means clustering showed that three clusters were the optimal number of groups for traffic flow observations, as presented in Figure 4-5. Based on their speed-occupancy characteristics, the clusters were named *free flow state*, *transition flow state*, and *congested flow state*. The *free flow state* was characterized by higher travel speed and lower occupancy. The *transition flow state* was characterized by moderate travel speed and moderate occupancy. On the other hand, the *congested flow state* was characterized by lower travel speed and higher occupancy. Table 4-1 presents the summary statistics of the identified traffic flow states at the first upstream on-ramp of the incident location.

Table 4-1: Traffic Flow States at the First Upstream On-ramp of the Incident Location

Period	Traffic Flow States	At Least One Lane Blockage				No Lane Blockage			
		Number of Observations		Mean		Number of Observations		Mean	
		Count	%	Speed (mph)	Occupancy (%)	Count	%	Speed (mph)	Occupancy (%)
Daytime	Free flow	25,469	53.9	56.0	10.8	51,301	73.5	58.5	9.8
	Transition flow	10,964	23.2	29.7	23.5	9,773	14.0	43.8	15.2
	Congested flow	10,848	22.9	12.8	39.7	8,731	12.5	21.4	29.9
	Total	**47,281**				**69,805**			
Nighttime	Free flow	18,126	71.4	60.5	5.1	30,449	55.8	63.8	4.0
	Transition flow	3,322	13.1	37.0	14.1	20,392	37.4	54.1	6.6
	Congested flow	3,946	15.5	13.3	36.5	3,704	6.8	20.5	26.8
	Total	**25,394**				**54,545**			

Note: The number of observations presents the number of data points, i.e., speed and occupancy at every 5-minute interval within the incident clearance duration.

At least one lane blockage

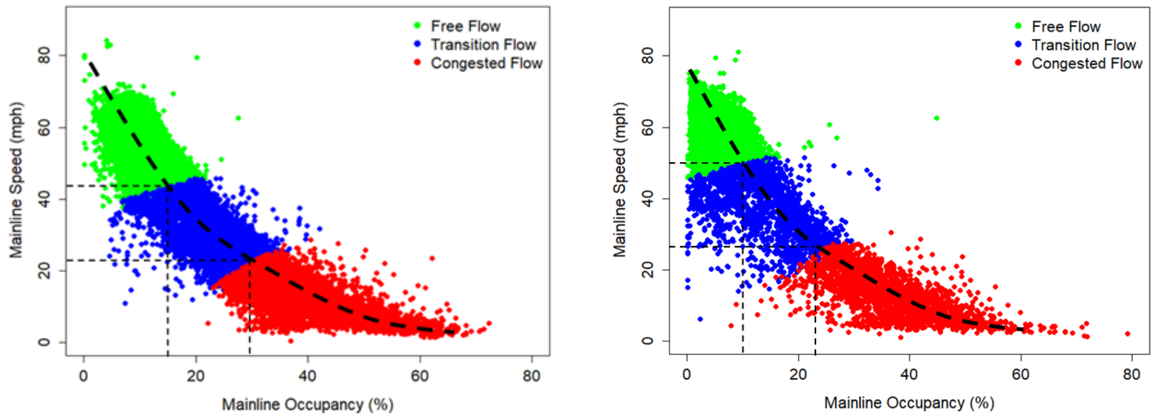
Daytime off-peak periods: As presented in Table 4-1, about 54%, 23%, and 23% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The *free flow state's* average speed and occupancy were approximately 56 mph and 11%, respectively. Also, the average speed and occupancy in the *transition flow state* were approximately 29 mph and 24%, respectively. Conversely, the average speed and occupancy in the *congested flow state* were approximately 13 mph and 40%, respectively.

Nighttime off-peak periods: Approximately 71%, 13%, and 16% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy were approximately 61 mph and 5%, respectively, in the *free flow states*. The average speed and occupancy in the *transition flow state* were about 37 mph and 14%, respectively. Also, the average speed and occupancy in the *congested flow state* were approximately 13 mph and 37%, respectively.

No lane blockage

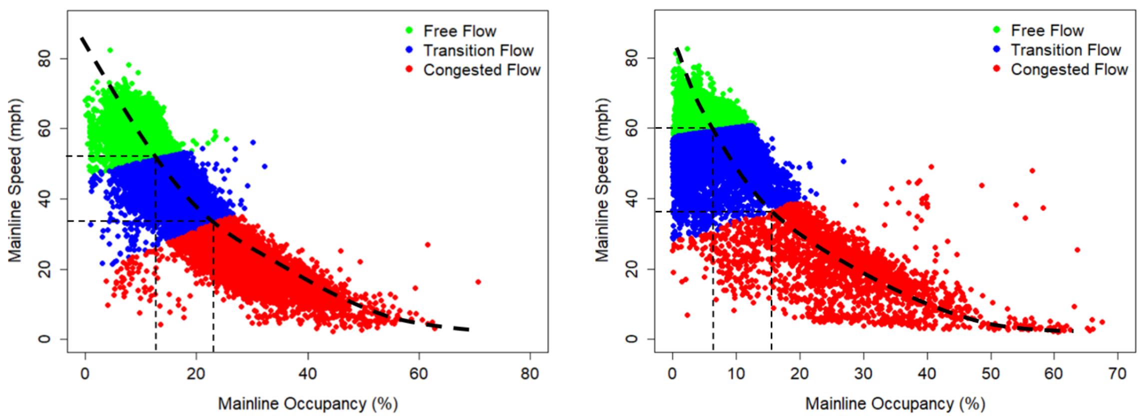
Daytime off-peak periods: As shown in Table 4-1, about 74%, 14%, and 13% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy were approximately 59 mph and 10%, respectively, in the *free flow state*. The average speed and occupancy in the *transition flow state* were about 44 mph and 15%, respectively. On the other hand, the average speed and occupancy in the *congested flow state* were approximately 21 mph and 30%, respectively.

Nighttime off-peak periods: Approximately 56%, 37%, and 7% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy were approximately 64 mph and 4%, respectively, in the *free flow state*. The average speed and occupancy in the *transition flow state* were about 54 mph and 7%, respectively. Also, the average speed and occupancy in the *congested flow state* were approximately 21 mph and 27%, respectively.



Daytime off-peak periods | Nighttime off-peak periods

(a) At Least One Lane Blockage



Daytime off-peak periods | Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-5: Traffic Flow States at the First Upstream On-ramp of the Incident Location

Based on the established traffic flow states shown in Figure 4-5, the first RMS upstream of the incident location may be activated and deactivated based on the following criteria:

Incidents resulting in at least one lane blockage

During daytime off-peak periods:

- Activate if the average speed drops below 45 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 45 mph for a consistent 5-minute period.

During nighttime off-peak periods:

- Activate if the average speed drops below 50 mph for a consistent 5-minute period.

- Deactivate if the incident has been cleared and when the average speed reaches 50 mph for a consistent 5-minute period.

Incidents with no lane blockage

During daytime off-peak periods:

- Activate if the average speed drops below 50 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 50 mph for a consistent 5-minute period.

During nighttime off-peak periods:

It is not necessary to activate the first RMS upstream of the incident location that occurred during the nighttime off-peak periods and did not require lane blockage. However, to prevent the congestion on the mainline freeway, the first RMS upstream of such incident characteristics may be activated and deactivated based on the following criteria:

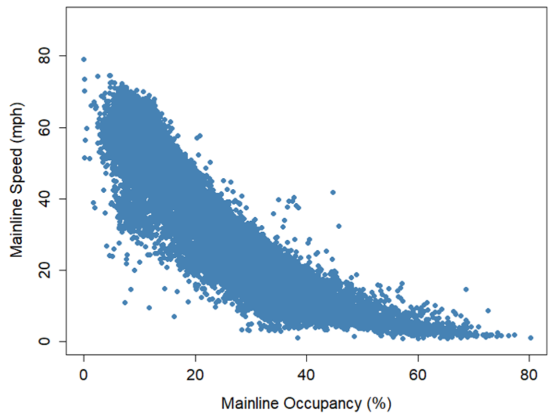
- Activate if the average speed drops below 35 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 35 mph for a consistent 5-minute period.

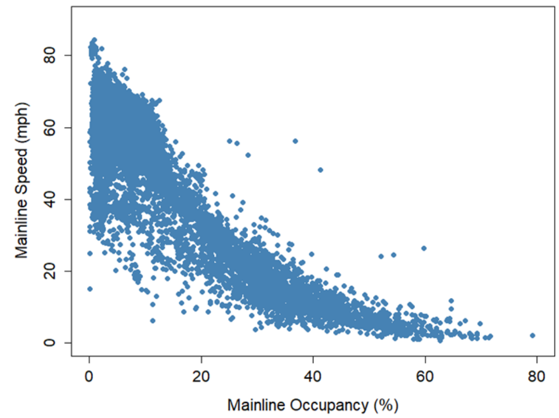
4.4.1.2 Traffic Flow States at the Second Upstream On-ramp of the Incident Location

Figure 4-6 presents the traffic flow observations at the second upstream on-ramp of the incident location before clustering.

At least one lane blockage: During the daytime off-peak periods, the average speed and occupancy were approximately 39 mph and 21%, respectively. Also, the average speed and occupancy were about 52 mph and 10% during the nighttime off-peak periods, respectively.

No lane blockage: The average speed and occupancy were approximately 51 mph and 13%, respectively, during the daytime off-peak periods. The average speed and occupancy were about 57 mph and 6% during the nighttime off-peak periods, respectively.

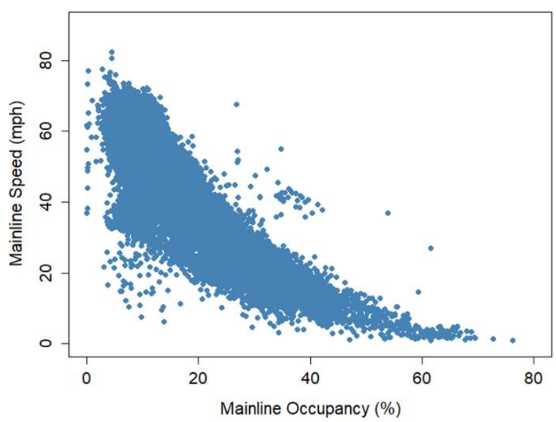


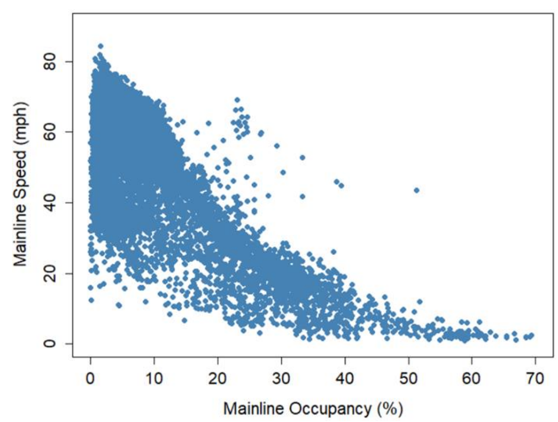


Daytime off-peak periods

Nighttime off-peak periods

(a) At Least One Lane Blockage





Daytime off-peak periods

Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-6: Speed-Occupancy Diagram at the Second Upstream On-ramp of the Incident Location

The silhouette index of the *k*-means clustering showed that three clusters were the optimal number of groups for traffic flow observations, as presented in Figure 4-7. The clusters were named *free flow state*, *transition flow state*, and *congested flow state*, based on their speed-occupancy characteristics. Table 4-2 shows the summary statistics of the identified traffic flow states at the second upstream on-ramp of the incident location.

Table 4-2: Traffic Flow States at the Second Upstream On-ramp of the Incident Location

Period	Traffic Flow States	At Least One Lane Blockage				No Lane Blockage			
		Number of Observations		Mean		Number of Observations		Mean	
		Count	%	Speed (mph)	Occupancy (%)	Count	%	Speed (mph)	Occupancy (%)
Daytime	Free flow	24,482	51.8	56.8	10.4	50,206	71.9	58.8	9.8
	Transition flow	10,975	23.2	29.5	23.0	11,803	16.9	39.1	14.2
	Congested flow	11,824	25.0	12.5	40.7	7,796	11.2	19.4	32.9
	Total	**47,281**				**69,805**			
Nighttime	Free flow	19,413	76.4	61.1	5.1	46,107	84.5	61.5	4.8
	Transition flow	2,704	10.6	34.5	14.5	5,782	10.6	38.5	7.3
	Congested flow	3,277	12.9	12.8	38.1	2,656	4.9	16.4	30.8
	Total	**25,394**				**54,545**			

Note: The number of observations presents the number of data points, i.e., speed and occupancy at every 5-minute interval within the incident clearance duration.

At least one lane blockage

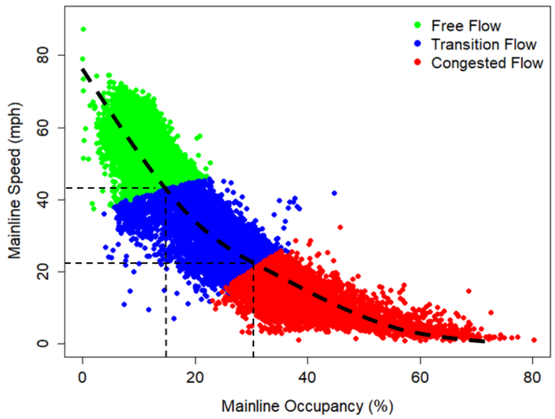
Daytime off-peak periods: Of the 47,482 observations, about 52% were classified in the *free flow state*, 23% were classified in the *transition flow state*, and 25% were classified in the *congested flow state*. The average speed and occupancy in the *free flow state* were approximately 57 mph and 10%, respectively. Also, the average speed and occupancy in the *transition flow state* were about 30 mph and 23%, respectively. Conversely, the average speed and occupancy in the *congested flow state* were approximately 13 mph and 41%, respectively.

Nighttime off-peak periods: Of the 25,394 observations, about 76%, 11%, and 13% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 61 mph and 5%, respectively. On the other hand, the average speed and occupancy in the *transition flow state* were about 35 mph and 15%, respectively. Also, the average speed and occupancy in the *congested flow state* were approximately 13 mph and 38%, respectively.

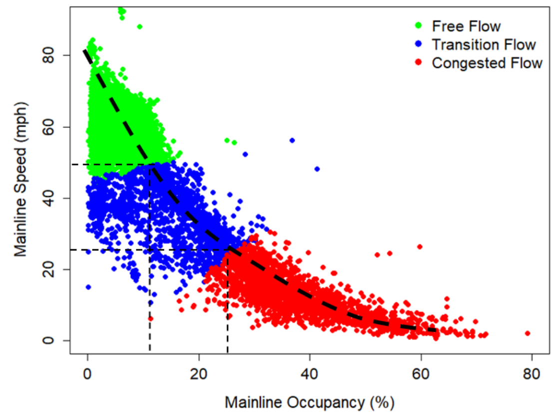
No lane blockage

Daytime off-peak periods: Approximately 72% were classified in the *free flow state*, 17% were classified in the *transition flow state*, and 11% were classified in the *congested flow state*. The average speed and occupancy were approximately 59 mph and 10% in the *free flow state*, respectively. The average speed and occupancy in the *transition flow state* were about 39 mph and 14%, respectively. The average speed and occupancy were approximately 19 mph and 33% in the *congested flow state*, respectively.

Nighttime off-peak periods: About 85%, 11%, and 5% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 62 mph and 5%, respectively. The average speed and occupancy in the *transition flow state* were about 39 mph and 7%, respectively. The average speed and occupancy in the *congested flow state* were approximately 16 mph and 31%, respectively.

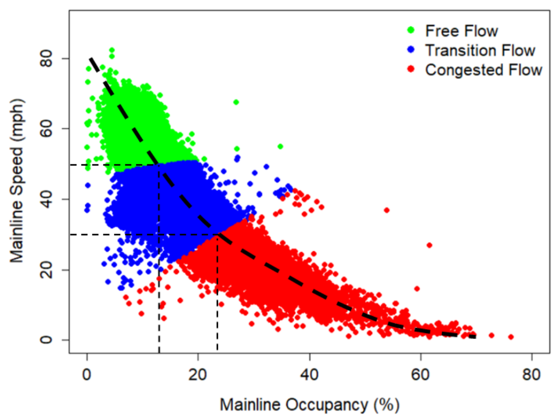


Daytime off-peak periods

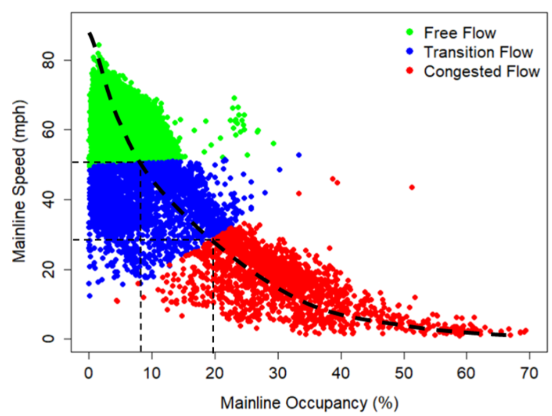


Nighttime off-peak periods

(a) At Least One Lane Blockage



Daytime off-peak periods



Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-7: Traffic Flow States at the Second Upstream On-ramp of the Incident Location

Based on the identified traffic flow states, as illustrated in Figure 4-7, the second RMS upstream of the incident location may be activated and deactivated based on the following criteria:

Incidents resulting in at least one lane blockage

During daytime off-peak periods:

- Activate if the average speed drops below 45 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared <u>and</u> when the average speed reaches 45 mph for a consistent 5-minute period.

During nighttime off-peak periods:

- Activate if the average speed drops below 50 mph for a consistent 5-minute period.

- Deactivate if the incident has been cleared and when the average speed reaches 50 mph for a consistent 5-minute period.

Incidents with no lane blockage

During daytime off-peak periods:

- Activate if the average speed drops below 50 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 50 mph for a consistent 5-minute period.

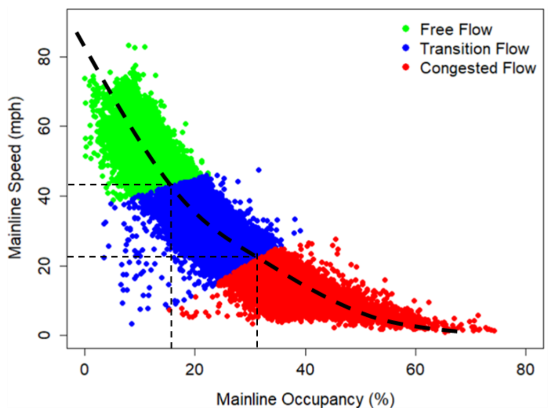
During nighttime off-peak periods:

It is not necessary to activate the second RMS upstream of the incident location that occurred during the nighttime off-peak periods and did not require lane blockage. However, to prevent the congestion on the mainline freeway, the second RMS upstream of such incident characteristics may be activated and deactivated based on the following criteria:

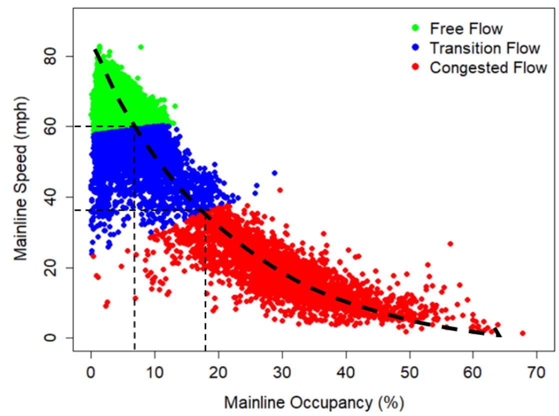
- Activate if the average speed drops below 35 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 35 mph for a consistent 5-minute period.

4.4.1.3 Traffic Flow States at Other Upstream On-ramps of the Incident Location

Similar trends were observed at the third, fourth, and fifth upstream on-ramps of the incident location. Figures 4-8 through 4-10 present the traffic flow states at the third, fourth, and fifth upstream on-ramps of the incident location. In this case, all RMSs upstream of the incident location may be activated and deactivated based on the above-stated criteria.

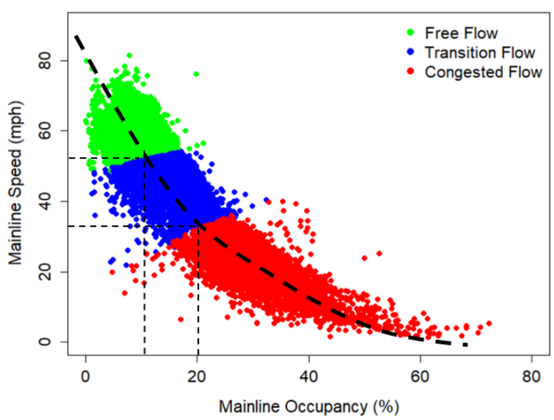


Daytime off-peak periods

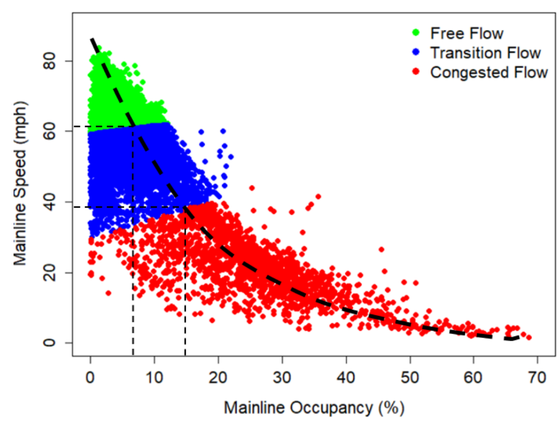


Nighttime off-peak periods

(a) At Least One Lane Blockage



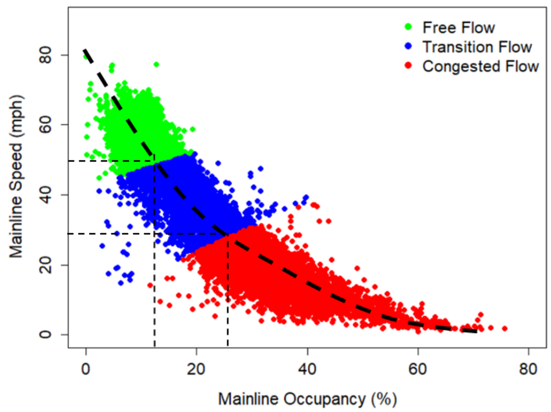
Daytime off-peak periods



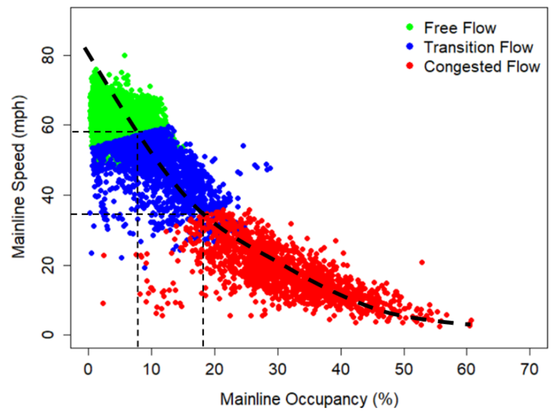
Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-8: Traffic States at the Third Upstream On-ramp of the Incident Location

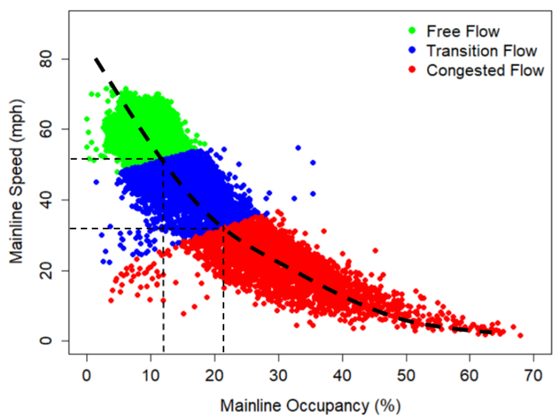


Daytime off-peak periods

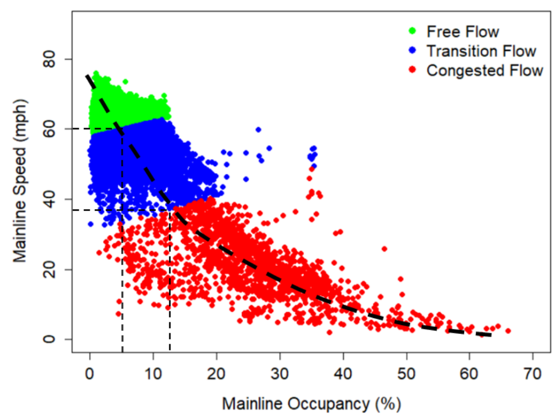


Nighttime off-peak periods

(a) At Least One Lane Blockage



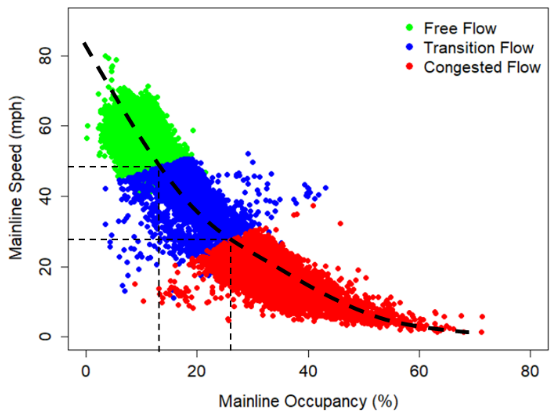
Daytime off-peak periods



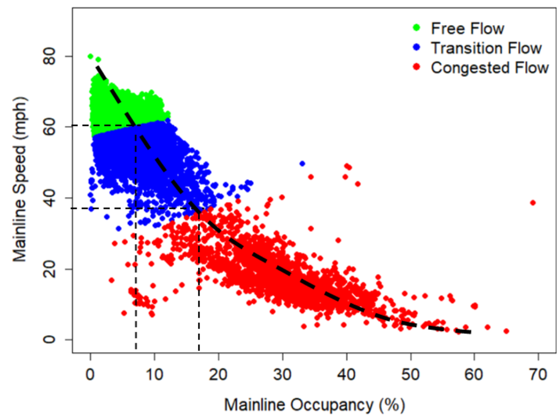
Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-9: Traffic States at the Fourth Upstream On-ramp of the Incident Location

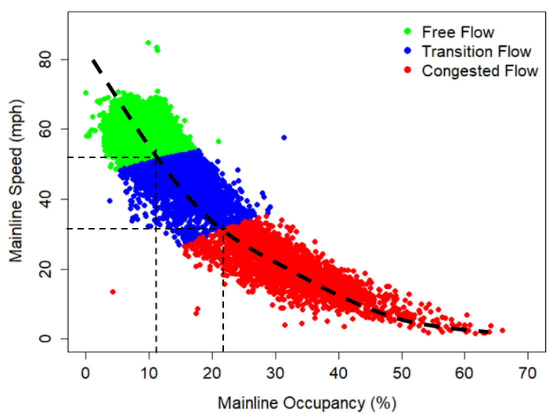


Daytime off-peak periods

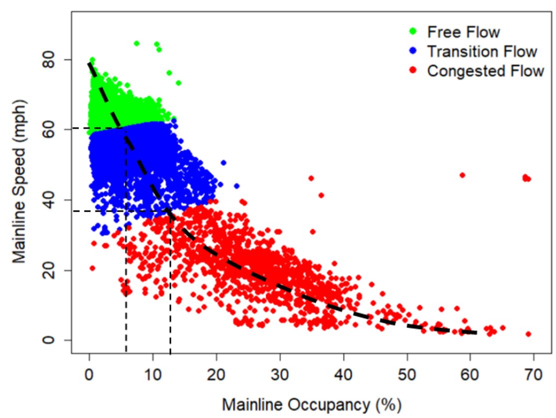


Nighttime off-peak periods

(a) At Least One Lane Blockage



Daytime off-peak periods



Nighttime off-peak periods

(b) No Lane Blockage

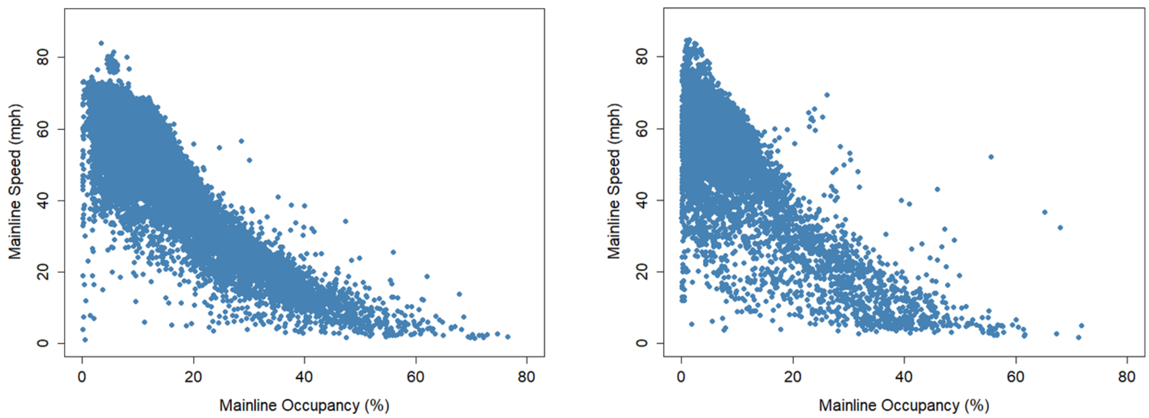
Figure 4-10: Traffic States at the Fifth Upstream On-ramp of the Incident Location

4.4.1.4 Traffic Flow States Downstream of the Incident Location

Figure 4-11 illustrates the traffic flow observations at the first downstream on-ramp of the incident location before clustering.

At least one lane blockage: The average speed and occupancy were approximately 52 mph and 13% during the daytime off-peak periods, respectively. During the nighttime off-peak periods, the average speed and occupancy were approximately 65 mph and 7%, respectively.

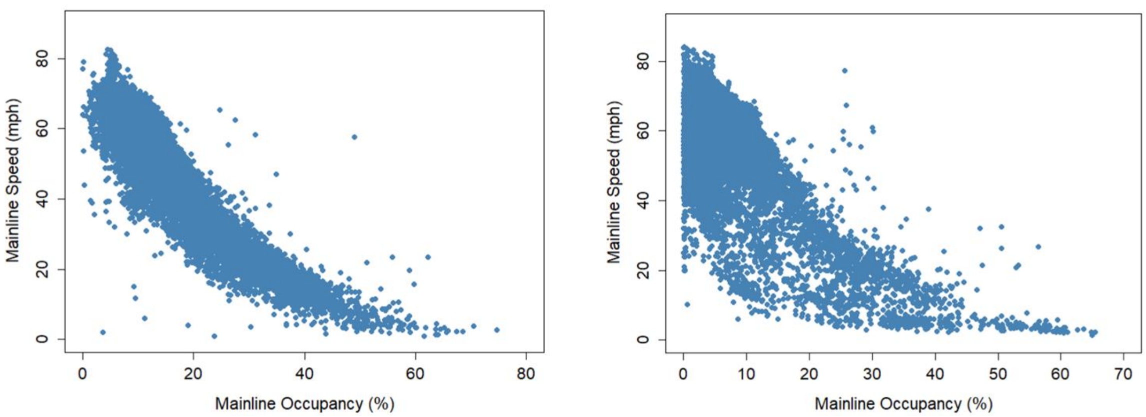
No lane blockage: The average speed and occupancy were approximately 55 mph and 12% during the daytime off-peak periods, respectively. During the nighttime off-peak periods, the average speed and occupancy were approximately 58 mph and 6%, respectively.



Daytime off-peak periods

Nighttime off-peak periods

(a) At Least One Lane Blockage



Daytime off-peak periods

Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-11: Speed-Occupancy Diagram at the First Downstream On-ramp of the Incident Location

The silhouette index of the *k*-means clustering showed that three clusters were the optimal number of groups for traffic flow observations, as presented in Figure 4-12. The clusters were identified as the *free flow state*, *transition flow state*, and *congested flow state* based on their speed-occupancy characteristics. Table 4-3 presents the summary statistics of the identified traffic flow states at the first downstream on-ramp of the incident location.

At least one lane blockage

Daytime off-peak periods: Approximately 66%, 23%, and 12% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The *free flow state* had an average speed and occupancy of approximately 60 mph and 9%, respectively. The *transition flow state* had an average speed and occupancy of approximately 45 mph and 14%, respectively. Also, the average speed and occupancy in the *congested flow state* were approximately 20 mph and 33%, respectively.

Nighttime off-peak periods: About 58%, 34%, and 9% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were about 64 mph and 4%, respectively. The average speed was approximately 51 mph, and the average occupancy was about 7% in the *transition flow state*. On the other hand, approximately 18 mph and 28% were the average speed and occupancy in the *congested flow state*, respectively.

Table 4-3: Traffic Flow States at the First Downstream On-ramp of the Incident Location

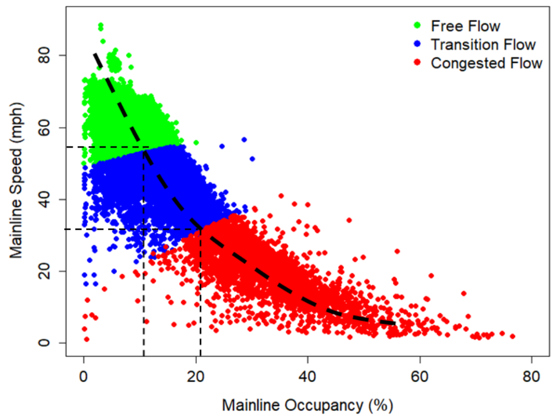
Period	Traffic Flow States	At Least One Lane Blockage				No Lane Blockage			
		Number of Observations		Mean		Number of Observations		Mean	
		Count	%	Speed (mph)	Occupancy (%)	Count	%	Speed (mph)	Occupancy (%)
Daytime	Free flow	31,084	65.7	59.8	8.8	45,499	65.2	61.0	9.3
	Transition flow	10,776	22.8	45.3	14.0	17,721	25.4	50.4	13.4
	Congested flow	5,429	11.5	19.8	32.9	6,585	9.4	21.6	31.8
	Total	**47,289**				**69,805**			
Nighttime	Free flow	14,607	57.5	63.8	4.3	27,834	51.0	65.3	3.7
	Transition flow	8,594	33.9	51.0	7.4	23,707	43.5	54.8	6.3
	Congested flow	2,186	8.6	18.1	27.8	3,004	5.5	19.5	24.7
	Total	**25,387**				**54,545**			

Note: The number of observations presents the number of data points, i.e., speed and occupancy at every 5-minute interval within the incident clearance duration.

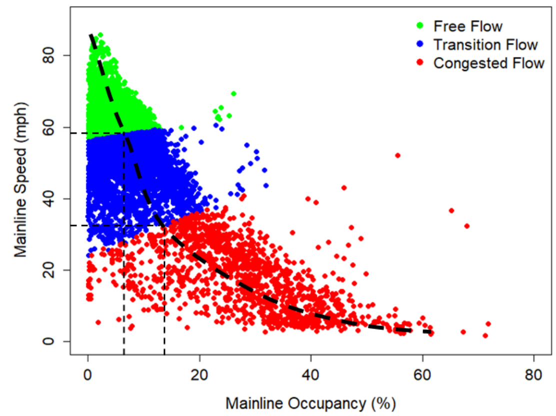
No lane blockage

Daytime off-peak periods: Approximately 65%, 25%, and 10% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 61 mph and 9%, respectively. The average speed and occupancy in the *transition flow state* were approximately 50 mph and 13%, respectively. Finally, the average speed and occupancy in the *congested flow state* were approximately 22 mph and 32%, respectively.

Nighttime off-peak periods: About 51%, 44%, and 6% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 65 mph and 4%, respectively. Also, the average speed and occupancy in the *transition flow state* were about 55 mph and 6%, respectively. On the other hand, approximately 20 mph and 25% were the average speed and occupancy in the *congested flow state*, respectively.

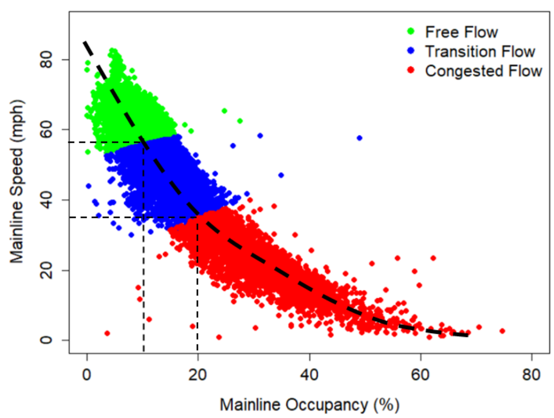


Daytime off-peak periods

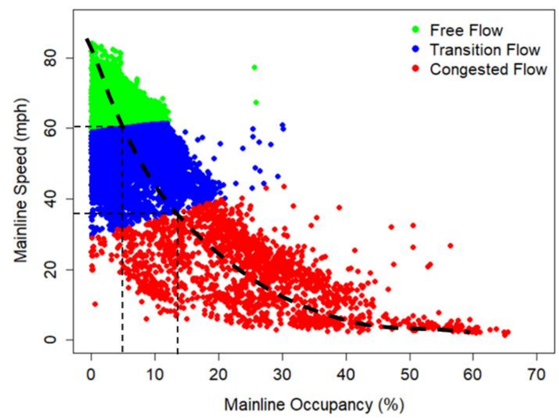


Nighttime off-peak periods

(a) At Least One Lane Blockage



Daytime off-peak periods



Nighttime off-peak periods

(b) No Lane Blockage

Figure 4-12: Traffic Flow States at the First Downstream On-ramp of the Incident Location

Based on the established traffic flow states, as shown in Figure 4-12, the first RMS downstream of the incident location may be activated and deactivated based on the following criteria:

Incidents resulting in at least one lane blockage

During daytime off-peak periods:

- Activate if the average speed drops below 35 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 35 mph for a consistent 5-minute period.

During nighttime off-peak periods:

- Activate if the average speed drops below 35 mph for a consistent 5-minute period.

- Deactivate if the incident has been cleared and when the average speed reaches 35 mph for a consistent 5-minute period.

Incidents with no lane blockage

During daytime off-peak periods:

- Activate if the average speed drops below 35 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the speed reaches 35 mph for a consistent 5-minute period.

During nighttime off-peak periods:

- Activate if the average speed drops below 35 mph for a consistent 5-minute period.
- Deactivate if the incident has been cleared and when the average speed reaches 35 mph for a consistent 5-minute period.

Note: The lower threshold for activating and deactivating the first adjacent RMSs downstream of the incident location allows the arterial adjacent to the entrance ramp to recover and provide an alternate route for the diverting traffic during the incident.

4.4.2 Guidelines for Off-peak Activation and Deactivation due to Incidents

The RMS activation and deactivation guidelines were developed based on the incidents that resulted in at least one lane blockage and those that did not require lane blockage. In both cases, the guidelines were developed separately for daytime off-peak periods and nighttime off-peak periods. The daytime off-peak periods included observations between 6:00 AM and 3:00 PM for the NB traffic and between 10:30 AM and 7:00 PM for the SB traffic. The nighttime off-peak periods included observations between 7:00 PM and 6:00 AM for both NB and SB traffic. Table 4-4 summarizes the RMS activation and deactivation guidelines due to incidents during weekday off-peak hours.

Table 4-4: Summary of Guidelines for RMS Activation and Deactivation due to Incidents

Period	RMS Location	Threshold: At Least One Lane Blockage		Threshold: No Lane Blockage	
		Activation	Deactivation	Activation	Deactivation
Daytime	Upstream	Speed ≤ 45 mph	Incident cleared & speed > 45 mph	Speed ≤ 50 mph	Incident cleared & speed > 50 mph
	Downstream	Speed ≤ 35 mph	Incident cleared & speed > 35 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph
Nighttime	Upstream	Speed ≤ 50 mph	Incident cleared & speed > 50 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph
	Downstream	Speed ≤ 35 mph	Incident cleared & speed > 35 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph

Incidents resulting in at least one lane blockage

Daytime off-peak periods: RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 45 mph and deactivated when the incident has been cleared and the average mainline speed reaches 45 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Nighttime off-peak periods: RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 50 mph and deactivated when the incident has been cleared and the average mainline speed reaches 50 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Incidents with no lane blockage

Daytime off-peak periods: RMSs upstream of the incident may be activated when the average speed on the mainline drops below 50 mph and deactivated when the incident has been cleared and the average mainline speed reaches 50 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Nighttime off-peak periods: RMSs upstream of the incident may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period. Conversely, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

4.5 Analysis Results during Rain

This section discusses the analysis results for the activation and deactivation of RMSs during rain events. The rain categories were defined according to the Highway Capacity Manual (HCM). The light rain had an intensity of > 0 in/hr but ≤ 0.10 in/hr. The medium rain had an intensity of > 0.10 in/hr and ≤ 0.25 in/hr, and heavy rain had an intensity of > 0.25 in/hr. Rain intensity was categorized into two categories: light rain and moderate or heavy rain.

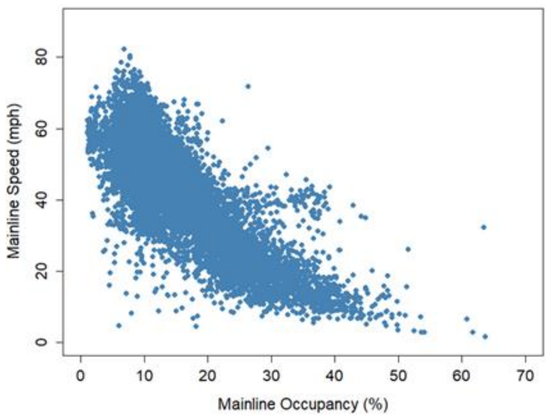
Rain events occurred on 1,106 weekdays along the study corridor during the 7-year study period (2013 – 2019). Approximately 922,284 traffic flow data observations at 5-minute intervals were extracted on the weekdays when it was raining. About 4% of the observations were excluded from the analysis because they were collected on holidays. In addition, whenever there was an incident during rainfall, the traffic flow data during that incident clearance duration were excluded from the analysis. The remaining 523,550 observations were divided based on time-of-day (i.e., daytime off-peak periods and nighttime off-peak periods) under different rain categories (i.e., light and moderate or heavy rain). The definition of the time-of-day categories was similar to that provided in Section 4.4.2. Approximately 35% and 65% of the observations were recorded during the daytime off-peak and nighttime off-peak periods, respectively.

4.5.1 Traffic Flow States during Rain

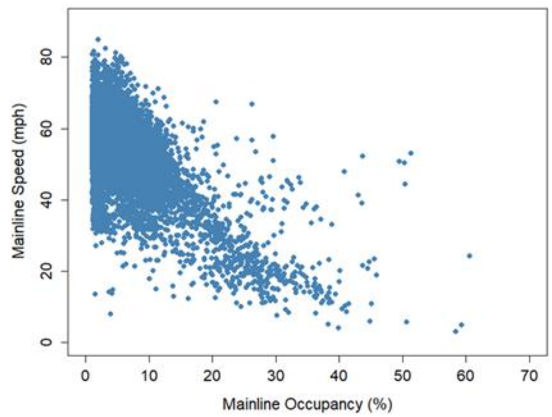
The *k*-means clustering was used to classify the traffic flow parameters (i.e., speed and occupancy) during rain into traffic flow states. The clustering method was applied to the sets of speed and occupancy recorded during daytime off-peak and nighttime off-peak periods for each rain category. Figure 4-13 shows the traffic flow observations during rain before clustering.

Light rain: During the daytime off-peak periods, the average speed was approximately 54 mph, and the average occupancy was approximately 12%. In contrast, during the nighttime off-peak periods, the average speed was around 60 mph, and the average occupancy was about 5%.

Moderate or heavy rain: The average speed and occupancy were approximately 46 mph and 14%, respectively, during the daytime off-peak periods. In contrast, during the nighttime off-peak periods, the average speed was 55 mph, and the average occupancy was 6%.

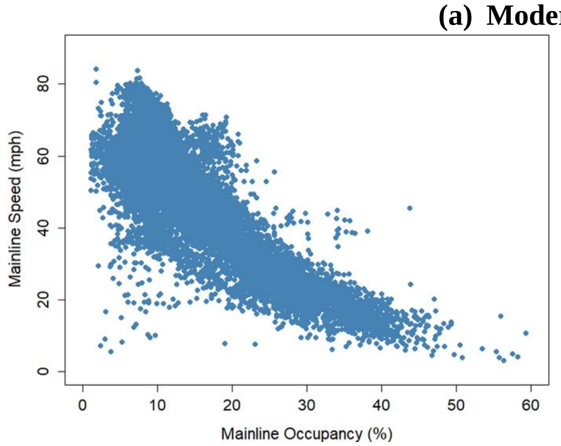


Daytime off-peak periods

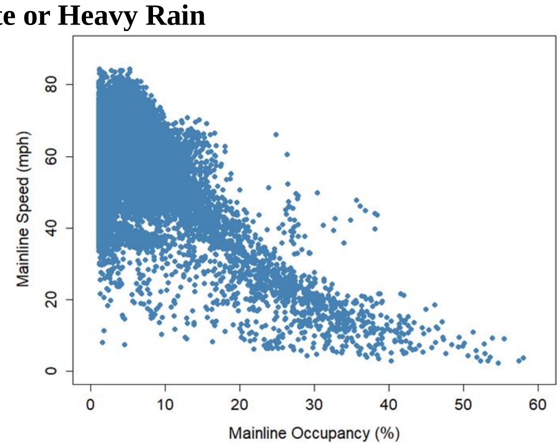


Nighttime off-peak periods

(a) Moderate or Heavy Rain



Daytime off-peak periods



Nighttime off-peak periods

(b) Light Rain

Figure 4-13: Speed-Occupancy Diagram during Rain

The silhouette index of the *k*-means clustering showed that three clusters were the optimal number of groups for traffic flow observations, as presented in Figure 4-14. The clusters were named *free flow state*, *transition flow state*, and *congested flow state* based on their speed-occupancy characteristics. Table 4-5 presents the summary statistics of the established traffic flow states during rain.

Table 4-5: Traffic Flow States during Rain

Period	Traffic Flow States	Moderate or Heavy Rain				Light Rain			
		Number of Observations		Mean		Number of Observations		Mean	
		Count	%	Speed (mph)	Occupancy (%)	Count	%	Speed (mph)	Occupancy (%)
Daytime	Free flow	10,280	53.1	55.3	9.7	45,149	69.8	59.9	9.9
	Transition flow	5,852	30.2	41.7	14.0	14,058	21.7	48.4	13.0
	Congested flow	3,214	16.6	21.2	27.9	5,452	8.4	23.9	27.9
	Total	**19,346**				**64,659**			
Nighttime	Free flow	9,715	46.6	61.9	3.9	58,275	49.1	65.9	3.1
	Transition flow	9,893	47.4	50.6	5.9	56,373	47.5	56.5	5.2
	Congested flow	1,262	6.0	28.2	20.2	3,999	3.4	30.0	16.3
	Total	**20,870**				**118,647**			

Note: The number of observations presents the number of data points, i.e., speed and occupancy at every 5-minute interval during rain.

Light rain

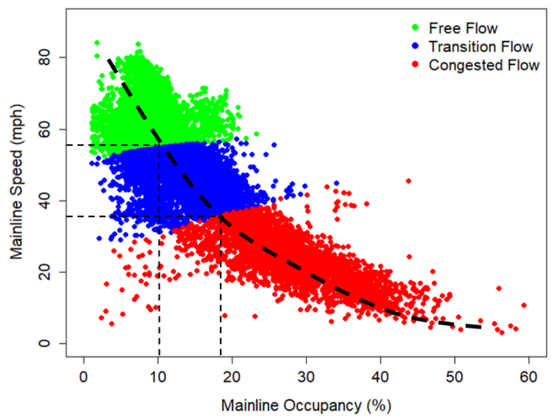
Daytime off-peak periods: Approximately 70%, 22%, and 8% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 60 mph and 10%, respectively. Also, the average speed and occupancy in the *transition flow state* were about 48 mph and 13%, respectively. Conversely, the average speed and occupancy in the *congested flow state* were approximately 24 mph and 28%, respectively.

Nighttime off-peak periods: About 49%, 48%, and 3% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 66 mph and 3%, respectively. Also, the average speed and occupancy in the *transition flow state* were approximately 57 mph and 5%, respectively. On the other hand, the average speed and occupancy in the *congested flow state* were approximately 30 mph and 16%, respectively.

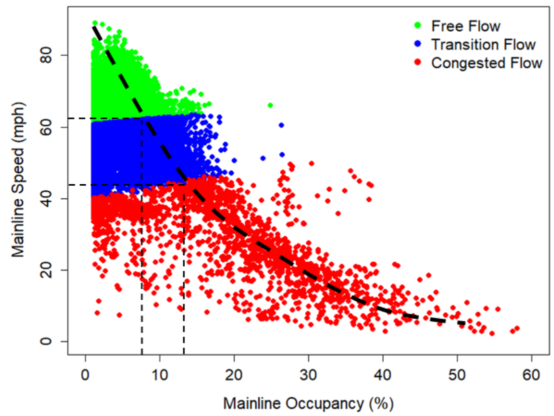
Moderate or heavy rain

Daytime off-peak periods: Of the 19,346 observations, approximately 53%, 30%, and 17% of the observations were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 55 mph and 10%, respectively. Also, the average speed and occupancy in the *transition flow state* were approximately 42 mph and 14%, respectively. The average speed and occupancy in the *congested flow state* were approximately 21 mph and 28%, respectively.

Nighttime off-peak periods: Of the 20,870 observations, about 47%, 47%, and 6% were classified in the *free flow state*, *transition flow state*, and *congested flow state*, respectively. The average speed and occupancy in the *free flow state* were approximately 62 mph and 4%, respectively. Also, the average speed and occupancy in the *transition flow state* were about 51 mph and 6%, respectively. The average speed and occupancy in the *congested flow state* were approximately 28 mph and 20%, respectively.

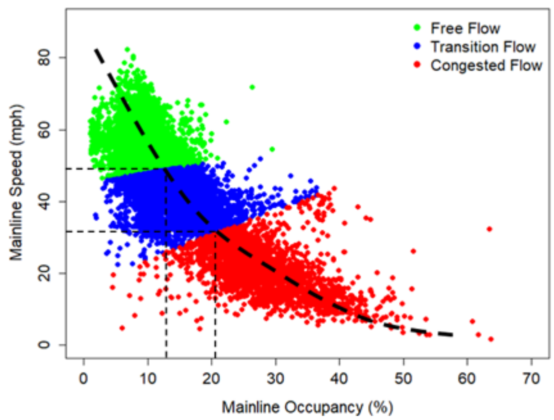


Daytime off-peak periods

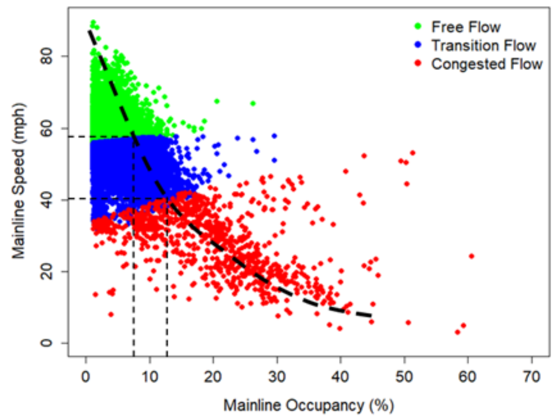


Nighttime off-peak periods

(a) Light Rain



Daytime off-peak periods



Nighttime off-peak periods

(b) Moderate or Heavy Rain

Figure 4-14: Traffic Flow States during Rain

Based on the established traffic flow states, as presented in Figure 4-14, the RMSs may be activated and deactivated during rain based on the following criteria:

Light rain

During daytime off-peak periods:

- Activate if the speed drops below 55 mph for a consistent 5-minute period.
- Deactivate if the rain stops and when the average speed reaches 55 mph for a consistent 5-minute period.

During nighttime off-peak periods:

It is not necessary to activate RMSs during light rain. However, to prevent congestion on the mainline freeway, the RMSs may be activated and deactivated based on the following criteria:

- Activate when the average speed drops below 45 mph for a consistent 5-minute period.
- Deactivate if the rain stops and when the average speed reaches 45 mph for a consistent 5-minute period.

Moderate or heavy rain

During daytime off-peak periods:

- Activate if the average speed drops below 50 mph for a consistent 5-minute period.
- Deactivate if the rain stops and when the average speed reaches 50 mph for a consistent 5-minute period.

During nighttime off-peak periods:

It is not necessary to activate RMSs during moderate or heavy rain. However, to prevent congestion on the mainline freeway, the RMSs may be activated and deactivated based on the following criteria:

- Activate when the average speed drops below 40 mph for a consistent 5-minute period.
- Deactivate if the rain stops and when the average speed reaches 40 mph for a consistent 5-minute period.

4.5.2 Guidelines for Off-peak Activation and Deactivation during Rain

Table 4-6 summarizes the activation and deactivation guidelines for RMSs during rain.

Table 4-6: Summary of Guidelines for RMS Activation and Deactivation during Rain

Period	Threshold: Light Rain		Threshold: Moderate or Heavy Rain	
	Activation	Deactivation	Activation	Deactivation
Daytime	Speed ≤ 55 mph	Rain stops & speed > 55 mph	Speed ≤ 50 mph	Rain stops & speed > 50 mph
Nighttime	Speed ≤ 45 mph	Rain stops & speed > 45 mph	Speed ≤ 40 mph	Rain stops & speed > 40 mph

Light rain

Daytime off-peak periods: The RMSs may be activated when the average speed drops below 55 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 55 mph for a consistent 5-minute period during light rain.

Nighttime off-peak periods: The RMSs may be activated when the average speed drops below 45 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 45 mph for a consistent 5-minute period during light rain.

Moderate or heavy rain

Daytime off-peak periods: As presented in Table 4-7, the RMSs may be activated when the average speed drops below 50 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 50 mph for a consistent 5-minute period during moderate or heavy rain.

Nighttime off-peak periods: The RMSs may be activated when the average speed drops below 40 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 40 mph for a consistent 5-minute period during moderate or heavy rain.

4.6 Summary

This chapter focused on developing the guidelines for activating and deactivating RMSs during off-peak hours. Real-time traffic data were used to develop the RMSs activation and deactivation guidelines in response to the incident and adverse weather conditions during the off-peak hours on weekdays.

Based on the established traffic flow states, Table 4-7 provides the guidelines for activating and deactivating RMSs during off-peak hours on weekdays due to incidents.

Table 4-7: RMS Activation and Deactivation Guidelines due to Incidents

Period	RMS	Threshold: At Least One Lane Blockage		Threshold: No Lane Blockage	
		Activation	Deactivation	Activation	Deactivation
Daytime	Upstream	Speed ≤ 45 mph	Incident cleared & speed > 45 mph	Speed ≤ 50 mph	Incident cleared & speed > 50 mph
	Downstream	Speed ≤ 35 mph	Incident cleared & speed > 35 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph
Nighttime	Upstream	Speed ≤ 50 mph	Incident cleared & speed > 50 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph
	Downstream	Speed ≤ 35 mph	Incident cleared & speed > 35 mph	Speed ≤ 35 mph	Incident cleared & speed > 35 mph

Based on the established traffic flow states, Table 4-8 summarizes the guidelines for activating and deactivating RMSs during off-peak hours on weekdays during rain.

Table 4-8: RMS Activation and Deactivation Guidelines during Rain

Period	Threshold: Light Rain		Threshold: Moderate or Heavy Rain	
	Activation	Deactivation	Activation	Deactivation
Daytime	Speed ≤ 55 mph	Rain stops & speed > 55 mph	Speed ≤ 50 mph	Rain stops & speed > 50 mph
Nighttime	Speed ≤ 45 mph	Rain stops & speed > 45 mph	Speed ≤ 40 mph	Rain stops & speed > 40 mph

CHAPTER 5
ACTIVATION AND DEACTIVATION GUIDELINES ON WEEKENDS

This chapter presents the guidelines for activating and deactivating RMSs in response to non-recurrent congestion on weekends. Specifically, the guidelines were developed in response to non-recurrent congestion due to incidents using a microscopic simulation approach. The following sections discuss the data needs, the VISSIM simulation model development, and the developed guidelines for RMSs activation and deactivation in response to non-recurrent congestion due to incidents that occurred on weekends.

5.1 Data Needs

The analysis was conducted along the I-95 section between NW 157th St and NW 62nd St in Miami, FL. This I-95 corridor consists of seven on-ramps and six off-ramps in the NB direction, and six on-ramps and seven off-ramps in the SB direction. The traffic flow data on weekends were collected from the RITIS. All the traffic flow data were extracted in aggregated one-hour intervals for one year from January 2019 to December 2019. Details of the data sources and data collection procedures were presented in Chapter 3 of this report.

5.2 VISSIM Model Development

A simulation approach was used to develop the guidelines for activating and deactivating RMSs in response to non-recurrent congestion on weekends using PTV Vissim® traffic flow simulation software. The VISSIM model developed by the FDOT was used in this research. The FDOT's base model was already calibrated following the FDOT Traffic Analysis Handbook guidelines (FDOT, 2014).

5.2.1 Model Verification

Model verification was done to ensure the base model was free from errors. The model verification process was performed following the FDOT Traffic Analysis Handbook guidelines (FDOT, 2014). The following parameters were verified:

(a) *Software:* The errors due to the tolling script for the express lanes were 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 were checked. Link geometrics were checked to ensure they matched the lane schematics.

(d) *Traffic control:* Vehicles entering the freeway from entrance ramps were checked to see whether they correctly followed the RMSs.

(e) *Vehicle characteristics:* Vehicles were checked and ensured there were no lane changes at unrealistic locations, and all the lane changes were done upstream at the appropriate location.

(f) *Number of simulation runs:* The preliminary number of runs (10 runs) was assumed adequate by the FDOT Traffic Analysis Handbook (FDOT, 2014). Thus, ten preliminary simulation runs were carried out and found efficient based on the standard deviation values.

5.2.2 Traffic Volume Input

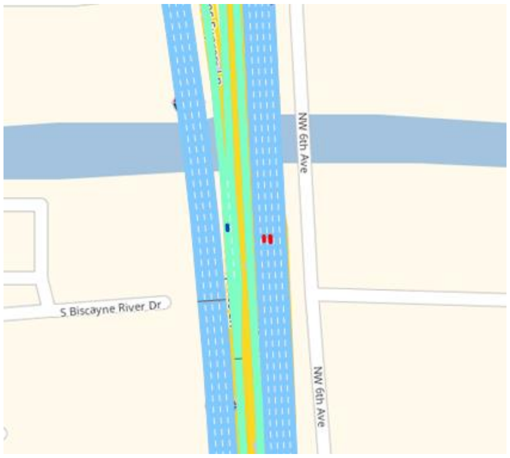
Since the calibrated VISSIM model from FDOT contained AM and PM peak traffic volume, the traffic volume input was changed to reflect the weekend traffic pattern. The traffic volume extracted from RITIS on weekends was used as the input in the calibrated VISSIM model. The dynamic traffic assignment (DTA) was used to assign the input traffic volume on the weekend in the calibrated VISSIM model. Note that the same method was used by FDOT for AM and PM peak periods traffic input. 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. The route selection was based on a logit model where the paths with the highest utilities were chosen. A similar process was repeated for other OD matrices for different times of the day on the weekend, making a total of three simulation hours.

5.2.3 Incident Scenarios

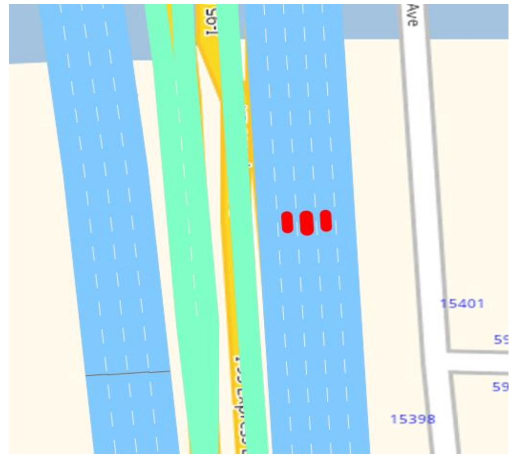
The pairwise simulation was conducted for the following incident scenarios.

- Incidents with 60-minute incident clearance duration and 2-lane blockage
- Incidents with 60-minute incident clearance duration and 3-lane blockage
- Incidents with 90-minute incident clearance duration and 2-lane blockage
- Incidents with 90-minute incident clearance duration and 3-lane blockage

These incident scenarios were modeled using the Component Object Model (COM) Application Programming Interface (API). 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 not possible to simulate the actual incidents in the VISSIM model, the disabled vehicle was created to reflect the incident scenarios. As illustrated in Figure 5-1, incidents with 2-lane and 3-lane blockage were simulated.



2-lane blockage incident



3-lane blockage incident

Figure 5-1: VISSIM Incident Scenarios

5.2.3.1 Two-lane Blockage

Two vehicles were programmed to stop on the freeway mainline to represent an incident at the chosen location for an allocated time interval. The vehicles were also programmed to depart following the end of the allocated time. The study simulated two incident clearance durations (60 minutes and 90 minutes). The incident clearance 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), as shown in Table 5-1.

5.2.3.2 Three-lane Blockage

Three vehicles were programmed to stop on the freeway mainline to represent an incident at the chosen location where the three-lane blockage incident occurred. The vehicles were also programmed to depart following the end of the allocated time. The study simulated two incident clearance durations (60 minutes and 90 minutes). The incident clearance durations selected were according to Exhibit 11-22 of the 2016 Highway Capacity Manual (HCM, 2016), as shown in Table 5-1.

Table 5-1: Mean Duration of Freeway Incidents (HCM, 2016)

Incident Severity Type	Distribution (%)	Duration (Minutes)			
		Mean	Minimum	Maximum	Standard Deviation
Shoulder closed	75.4	34	8.7	58	15.1
1 lane closed	19.6	34.6	16	58.2	13.8
2 lanes closed	3.1	53.6	30.5	66.9	13.9
3 lanes closed	1.9	67.9	36	93.3	21.9
4+ lanes closed	0	67.9	36	93.3	21.9

5.2.4 Simulation with and without RMS Activation

A sensitivity analysis was conducted on the VISSIM traffic volume inputs in developing the guidelines for RMS activation. By systematically varying the traffic volume on the freeway and the entrance ramp for various incident scenarios discussed in Section 5.2.3, the study determined the traffic conditions at which RMS activation significantly improved operations on the mainline and 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 5-2 lists all the cases considered as part of the sensitivity analysis.

Table 5-2: List of Cases Considered in the Sensitivity Analysis

Scenario	Case #	Ramp Volume (veh/hr/ln)	Freeway Mainline Volume (veh/hr/ln)
Incidents with 60-minute incident clearance duration	1	150	300
	2	650	850
	3	850	1,150
	4	1,000	1,350
Incidents with 90-minute incident clearance duration	5	150	300
	6	650	850
	7	850	1,150
	8	1,000	1,350

For activation, three entrance ramps upstream of the incident location were activated using the Washington fuzzy logic algorithm (Trinh, 2000). This 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. For the mainline, the detectors used for RMSs activation were the mainline detectors both upstream and downstream of the entrance ramp. On the other hand, for the entrance ramp, the queue detector was used for RMSs activation. For each simulation run, the metering rate was provided accordingly based on these prevailing traffic conditions.

The travel speed on the freeway mainline, recorded with RMSs and without RMSs, was used to determine the effects of activating RMSs on the freeway operations. 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 is no difference between the mean travel speed with and without RMSs. On the other hand, the alternative hypothesis states that there is a difference in travel speed with and without RMSs, whereby travel speed with RMSs is greater than travel speed without RMSs at a 95% confidence level. Equation 5-1 presents the formulated hypothesis tests.

Hypothesis on mean travel speeds:

$$\text{Null hypothesis } (H_0): \mu_1 - \mu_2 = 0 \qquad (5\text{-}1)$$
$$\text{Alternative hypothesis } (H_1): \mu_1 - \mu_2 > 0$$

where,

μ_1 = average travel speed with RMS, and
μ_2 = average travel speed without RMS.

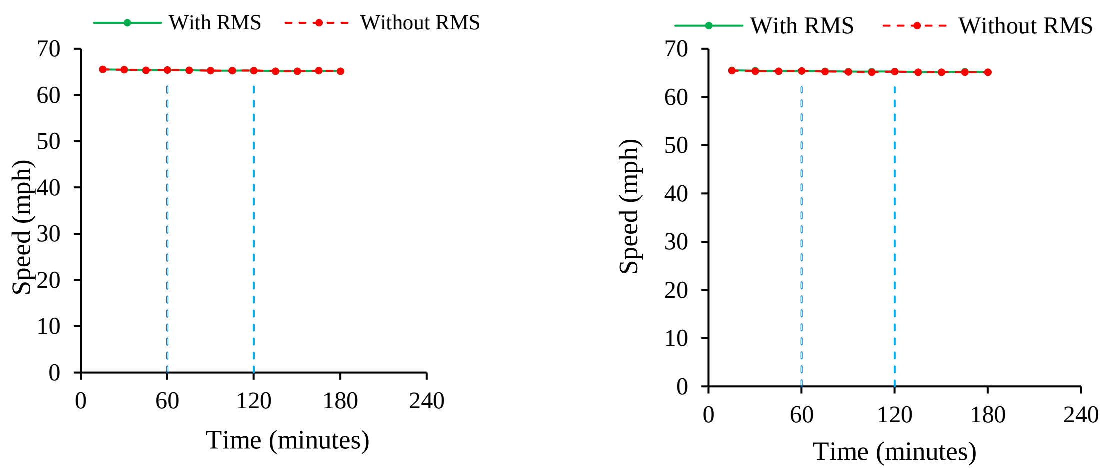
5.3 Guidelines for Activating and Deactivating RMSs on Weekends

This section discusses the guidelines for activating and deactivating RMSs in response to non-recurrent congestion on weekends. Specifically, the guidelines were developed using VISSIM microscopic simulation. The two incident scenarios with 2-lane and 3-lane blockage were modeled in VISSIM to represent the actual incident scenarios. The guidelines were based on the traffic volume and speed recorded from the detectors located upstream of the incident location.

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 on the freeway upstream and downstream of an on-ramp and on the on-ramp. These detectors were then used to measure the freeway speed for different freeway and ramp demand volumes, both with and without RMS activation.

5.3.1 Incidents with 60-Minute Incident Clearance Duration

The speed profiles for a 60-minute incident clearance duration were developed at various freeway mainline and on-ramp traffic volumes. Figure 5-2 presents the speed profiles at lower traffic volumes (i.e., ramp volume 150 veh/hr/ln and mainline volume 300 veh/hr/ln) for both cases (i.e., 2-lane blockage and 3-lane blockage). No changes were observed in travel speed with and without RMSs activation at lower traffic volume on the freeway mainline and on-ramp. This implies that at lower traffic volume on the mainline and on-ramp, there is no need to activate RMSs due to incidents.

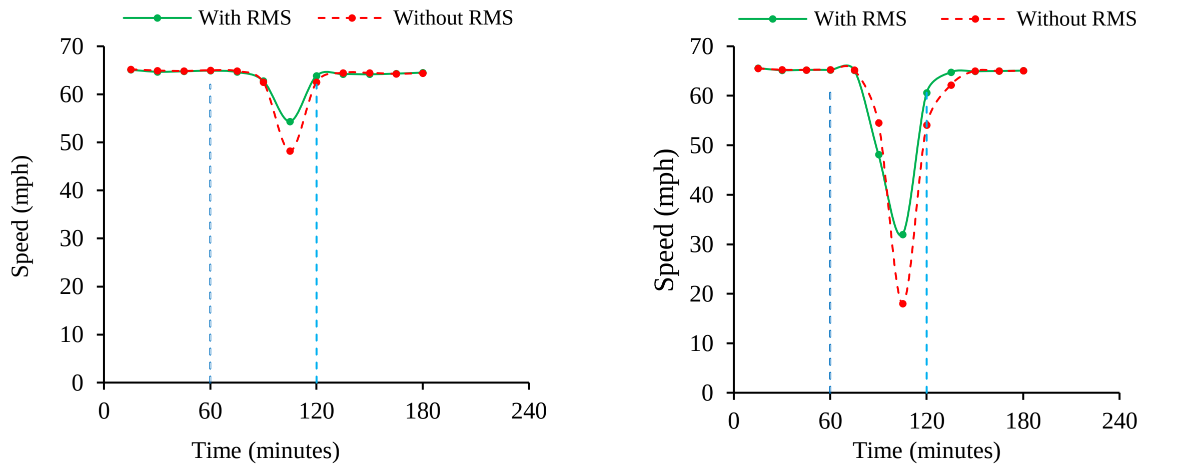


(a) 2-lane blockage, Ramp volume 150 veh/hr/ln, Freeway mainline volume 300 veh/hr/ln

(b) 3-lane blockage, Ramp volume 150 veh/hr/ln, Freeway mainline volume 300 veh/hr/ln

Figure 5-2: Speed Profiles Case I

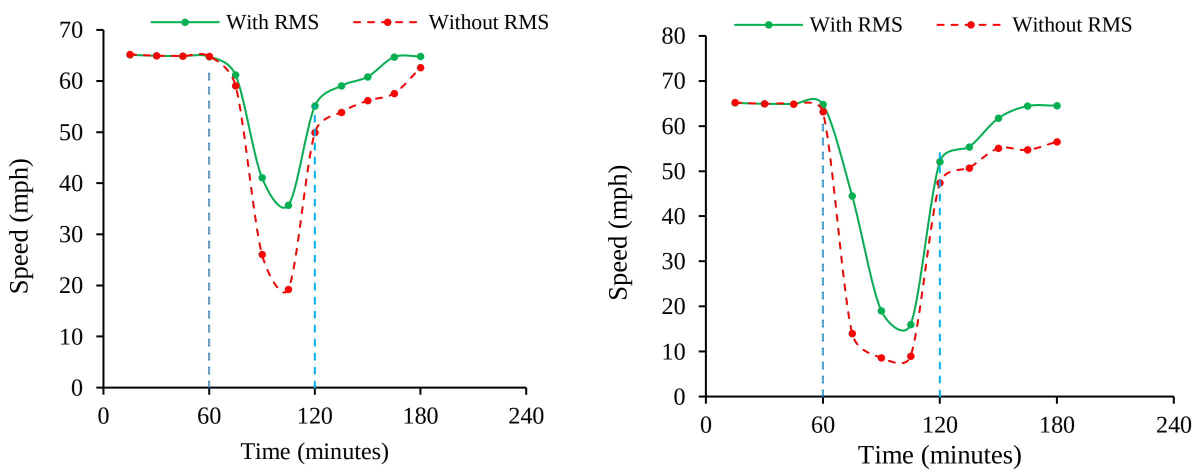
At higher traffic volumes, the lines presenting the travel speed with RMSs were above the line showing the travel speed without RMSs during the incident clearance time. This implies that the travel speed with RMSs activation was higher than without RMSs activation during the incident clearance time. Figures 5-3 through 5-5 present the speed profiles at higher traffic volumes (i.e., ramp volume greater than 650 veh/hr/ln and mainline volume greater than 850 veh/hr/ln) for both cases (i.e., 2-lane blockage and 3-lane blockage), respectively. The travel speed was observed to decrease at the beginning of an incident, i.e., one hour after the simulation began. Eventually, it returned to normal after the incident was cleared, i.e., 60 minutes later. Also, the travel speed decreases as the traffic volume increase within the incident clearance duration. As expected, an incident with a 3-lane blockage caused a much higher drop in speed than an incident with a 2-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 on-ramp. This implies that at these traffic volume ranges on the mainline and the on-ramp, the activation of RMSs due to incidents will significantly increase travel speed.



(a) 2-lane blockage, Ramp volume 650 veh/hr/ln, Freeway mainline volume 850 veh/hr/ln

(b) 3-lane blockage, Ramp volume 650 veh/hr/ln, Freeway mainline volume 850 veh/hr/ln

Figure 5-3: Speed Profiles Case II



(a) 2-lane blockage, Ramp volume 850 veh/hr/ln, Freeway mainline volume 1,150 veh/hr/ln

(b) 3-lane blockage, Ramp volume 850 veh/hr/ln, Freeway mainline volume 1,150 veh/hr/ln

Figure 5-4: Speed Profiles Case III

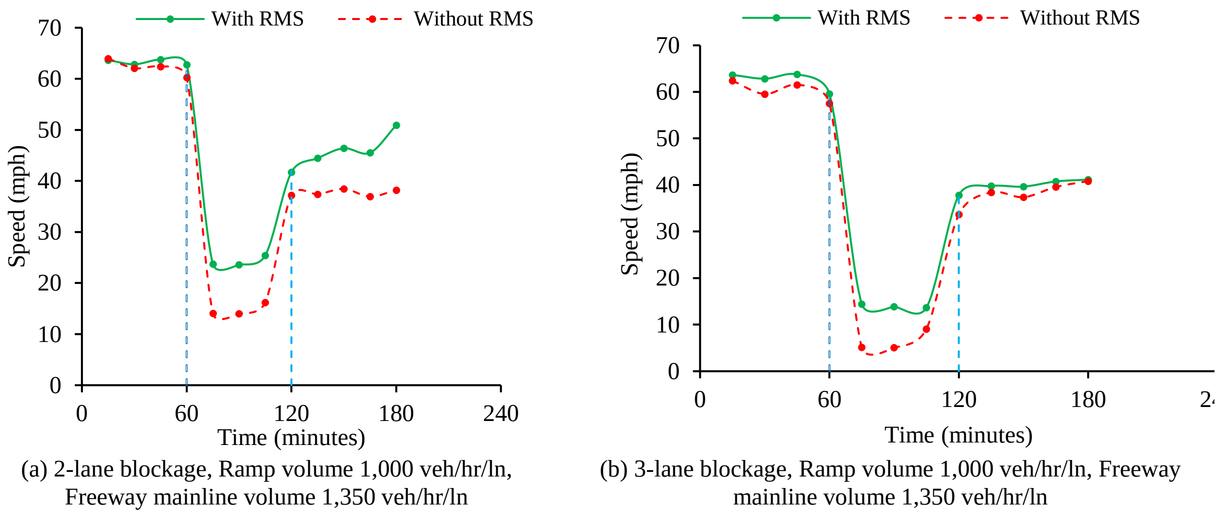


Figure 5-5: Speed Profiles Case IV

For all incident scenarios (i.e., incidents with 2-lane and 3-lane blockage), it is noted that travel speed on the mainline freeway was higher when RMSs were activated. This suggests that the RMSs improved freeway operations by resulting in smoother traffic flow on the freeway mainline. Moreover, as expected, the drop in travel speed was much higher for the incident with 3-lane blockage than the incident with 2-lane blockage.

Based on the sensitivity analysis, different speed profiles were used to determine the threshold for RMS activation and deactivation. These thresholds were tested for significance for each incident scenario. Table 5-3 presents the results of a *t*-test performed to determine the freeway and the ramp demand traffic volume that will significantly change travel speed with RMSs and without RMSs for a 60-minute incident clearance time.

Table 5-3: RMS Activation Guidelines for a 60-Minute Incident Clearance Duration

Scenario	Ramp Volume (veh/hr/ln)	Freeway Mainline Volume (veh/hr/ln)																
		300	350	400	650	700	750	800	850	950	1000	1050	1100	1150	1200	1250	1350	1800
2-lane blockage	150	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	200	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	300	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	450	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	500	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	600	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	700	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	800	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	950	×	×	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓
	1000	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
3-lane blockage	150	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	200	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	300	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	450	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	500	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	600	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	750	×	×	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓
	800	×	×	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓
	950	×	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓
	1000	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓

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

As presented in Table 5-3, a significant change in speed when RMSs were activated for a 60-minute incident clearance duration for a 2-lane blockage scenario was observed when the ramp traffic volume exceeds 950 veh/hr/ln, and freeway mainline traffic volume exceeds 1,100 veh/hr/ln. Also, for a 3-lane blockage, a significant change in travel speed when RMSs were activated was observed when the ramp traffic volume exceeds 750 veh/hr/ln, and the freeway mainline traffic volume exceeds 1,100 veh/hr/ln.

Therefore, based on the *t*-test results presented in Table 5-3 and the speed profiles presented in Figures 5-2 through 5-5, the RMSs upstream of the incident location may be activated and deactivated based on the following criteria:

Incidents with 2-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 950 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,100 veh/hr/ln, and
    c. Average speed on the mainline drops below 50 mph.

- Deactivate if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

Incidents with 3-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 750 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,100 veh/hr/ln, and
    c. Average speed on the mainline drops below 50 mph.

- Deactivate if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

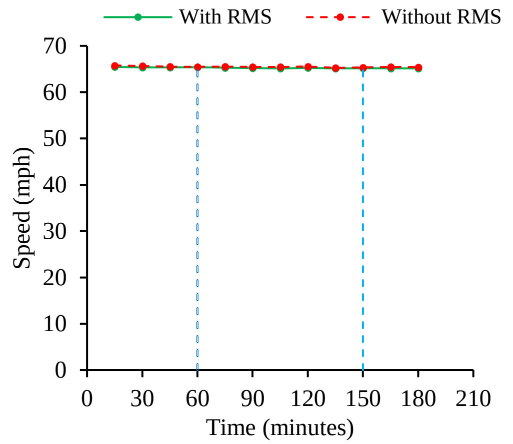
Table 5-4 summarizes the guidelines for activating and deactivating RMSs upstream of the incident location for a 60-minute incident clearance duration.

Table 5-4: RMS Activation and Deactivation Guidelines for a 60-Minute Incident Clearance Duration

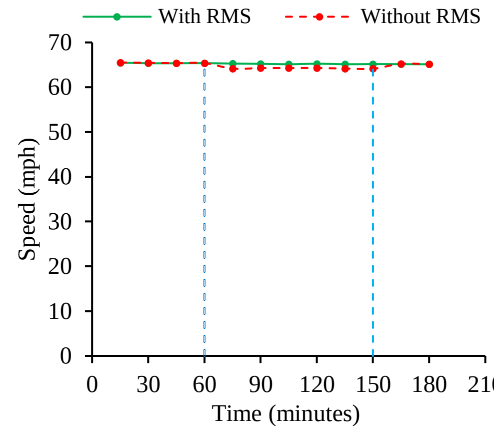
Incident Scenario	Thresholds	
	Activation	Deactivation
2-lane blockage	Ramp volume > 950 veh/h/ln & Mainline volume > 1,100 veh/h/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph
3-lane blockage	Ramp volume > 750 veh/h/ln & Mainline volume > 1,100 veh/h/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph

5.3.2 Incidents with 90-Minute Incident Clearance Duration

The speed profiles for a 90-minute incident clearance duration were developed at various freeway and on-ramp traffic volumes. Similar to the 60-minute incident clearance 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. Figure 5-6 presents the speed profile at lower traffic volumes (i.e., ramp volume 150 veh/hr/ln and mainline volume 300 veh/hr/ln) for both cases (i.e., 2-lane blockage and 3-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 on-ramp. This implies that at lower traffic volume on the mainline and on the on-ramp, there is no need to activate RMSs due to incidents.



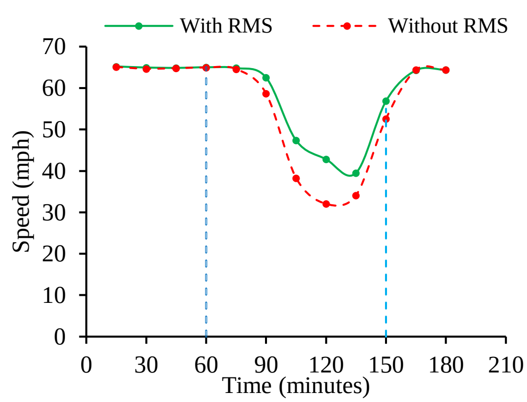
(a) 2-lane blockage, Ramp volume 150 veh/hr/ln, Freeway mainline volume 300 veh/hr/ln



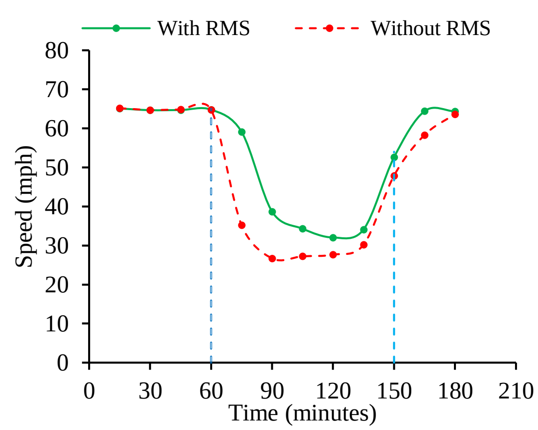
(b) 3-lane blockage, Ramp volume 150 veh/hr/ln, Freeway mainline volume 300 veh/hr/ln

Figure 5-6: Speed Profiles Case V

Figures 5-7 through 5-9 present the speed profiles at higher traffic volumes (i.e., ramp traffic volume greater than 650 veh/hr/ln and mainline traffic volume greater than 850 veh/hr/ln) for both cases (i.e., 2-lanes blockage and 3-lanes blockage). The travel speed was observed to decrease at the beginning of an incident, i.e., one hour after the simulation began. Eventually, it returned to normal after the incident was cleared, i.e., 90 minutes later. Also, the travel speed decreases as the traffic volume increase during the incident clearance time. Moreover, as expected, the drop in travel speed was much higher for the incident with 3-lane blockage than the incident with 2-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 on-ramp. This implies that at these traffic volume ranges on the mainline and the on-ramp, the activation of RMSs due to incidents will significantly increase travel speed.

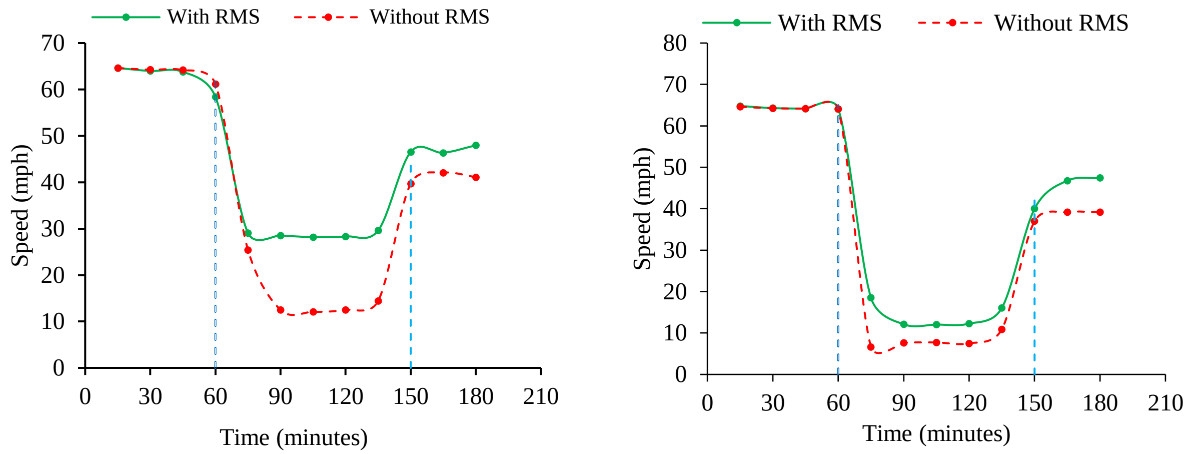


(a) 2-lane blockage, Ramp volume 650 veh/hr/ln, Freeway mainline volume 850 veh/hr/ln



(b) 3-lane blockage, Ramp volume 650 veh/hr/ln, Freeway mainline volume 850 veh/hr/ln

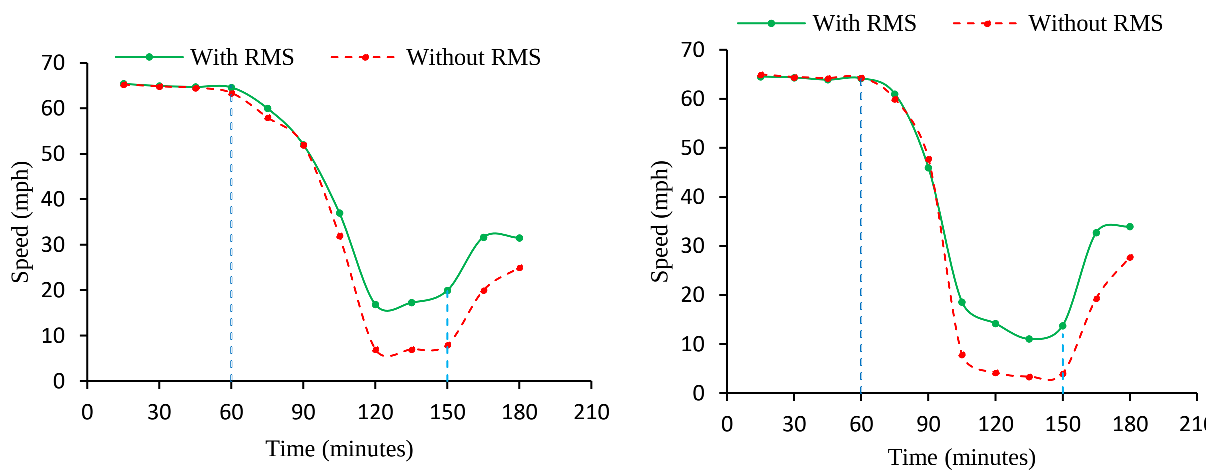
Figure 5-7: Speed Profiles Case VI



(a) 2-lane blockage, Ramp volume 850 veh/hr/ln, Freeway mainline volume 1,150 veh/hr/ln

(b) 3-lane blockage, Ramp Volume 850 veh/hr/ln, Freeway mainline volume 1,150 veh/hr/ln

Figure 5-8: Speed Profiles Case VII



(a) 2-lane blockage, Ramp volume 1,000 veh/hr/ln, Freeway mainline volume 1,350 veh/hr/ln

(b) (b) 3-lane blockage, Ramp volume 1,000 veh/hr/ln, Freeway mainline volume 1,350 veh/hr/ln

Figure 5-9: Speed Profiles Case VIII

For all incident scenarios (i.e., incident with 2-lane and 3-lane blockage), it is noted that travel speed on the mainline freeway was higher when RMSs were activated. This suggests that the RMSs improved freeway operations by producing smoother traffic flow on the freeway mainline. Moreover, for an incident with a 3-lane blockage, the drop in travel speed was much higher than for an incident with a 2-lane blockage.

Based on the sensitivity analysis, different speed profiles were used to determine the threshold for RMSs activation and deactivation. These thresholds were tested for significance for each incident scenario. Table 5-5 presents the results of a *t*-test performed to determine the freeway and the ramp demand traffic volume that will significantly change travel speed with RMSs and without RMSs for a 90-minute incident clearance time.

Table 5-5: RMS Activation Guidelines for a 90-Minute Incident Clearance Duration

Scenario	Ramp Volume (Veh/hr/ln)	Freeway Mainline Volume (veh/hr/ln)																
		300	350	400	650	700	750	800	850	950	1000	1050	1100	1150	1200	1250	1350	1800
2-lane blockage	150	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	200	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	300	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	450	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	500	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	600	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	700	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	800	×	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓
	950	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
	1000	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
3-lane blockage	150	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	300	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	450	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	500	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	600	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	650	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	700	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
	800	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓
	950	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	1000	×	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

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

As presented in Table 5-5, a significant change in speed when RMSs were activated for a 90-minute incident clearance duration for a 2-lane blockage scenario was observed when the ramp traffic volume exceeds 800 veh/hr/ln, and freeway mainline traffic volume exceeds 1,050 veh/hr/ln. Also, for a 3-lane blockage, a significant change in travel speed was observed when the ramp traffic volume exceeds 800 veh/hr /ln, and the freeway mainline traffic volume exceeds 1,000 veh/hr/ln.

Therefore, based on the *t*-test results presented in Table 5-5 and the speed profiles presented in Figures 5-6 through 5-9, the RMSs upstream of the incident location may be activated and deactivated based on the following criteria:

Incidents with 2-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 800 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,050 veh/hr/ln, and
    c. Average speed on the mainline drops below 50 mph.

- Deactivate if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

Incidents with 3-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 800 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,000 veh/hr/ln, and
    c. Average speed on the mainline drops below 50 mph.

- Deactivate if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

Table 5-6 presents the guidelines for activating and deactivating RMSs upstream of the incident location for a 90-minute incident clearance duration.

Table 5-6: RMS Activation and Deactivation Guidelines for a 90-Minute Incident Clearance Duration

Incident Scenario	Thresholds	
	Activation	Deactivation
2-lane blockage	Ramp volume > 800 veh/hr/ln & Mainline volume > 1050 veh/hr/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph
3-lane blockage	Ramp volume > 800 veh/hr/ln & Mainline volume > 1000 veh/hr/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph

5.4 Summary

This chapter focused on developing the guidelines for activating and deactivating RMSs on weekends. A simulation approach was used to develop RMSs activation and deactivation guidelines due to incidents on weekends. Based on the sensitivity analysis and speed profiles, Table 5-7 summarizes the guidelines for activating and deactivating RMSs on weekends due to incidents. Note that the analysis was conducted for two incident clearance durations, 60-minute and 90-minute. However, since the incident duration is not available at the time of the incident, the most conservative thresholds between the two scenarios (i.e., 60-min and 90-min) were identified and recommended as the thresholds for activating and deactivating RMSs on weekends.

Table 5-7: RMS Activation and Deactivation Guidelines on Weekends

Incident Clearance Duration	Thresholds	
	Activation	Deactivation
2-lane blockage	Ramp volume > 800 veh/h/ln & Mainline volume > 1,050 veh/h/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph
3-lane blockage	Ramp volume > 750 veh/hr/ln & Mainline volume > 1,000 veh/hr/ln & Speed ≤ 50 mph	Incident cleared & speed > 50 mph

CHAPTER 6
BENEFITS OF ACTIVATING RAMP METERS

This chapter presents the potential benefits of activating RMSs in response to non-recurring congestion during off-peak hours and on weekends. The potential benefits were quantified based on the developed guidelines presented in Chapters 4 and 5 of this report.

6.1 Benefits of Activating RMSs during Off-peak Hours

This section discusses the potential benefits of activating RMSs in response to non-recurrent congestion due to incidents and adverse weather conditions (i.e., rain) during off-peak hours on weekdays. Specifically, the potential benefits were quantified based on the developed guidelines presented in Chapter 4 of this report.

6.1.1 Benefits of Activating RMSs in Response to Incidents

The potential benefits of activating RMSs due to incidents were estimated based on the developed RMS activation guidelines. The following steps were adopted to quantify the benefits of activating RMSs in response to incidents:

- Step 1: Establish traffic flow states upstream of the incident location.
- Step 2: Identify variables affecting traffic flow states upstream of the incident location.
- Step 3: Identify factors influencing traffic flow states upstream of the incident location.
- Step 4: Determine the impact of RMSs on traffic flow states upstream of the incident location.

6.1.1.1 Establish Traffic Flow States Upstream of the Incident Location

As discussed in Chapter 4, the *k*-means clustering was used to classify the traffic flow datasets into three groups based on speed and occupancy. The established traffic flow states, i.e., *free flow state*, *transition flow state*, and *congested flow state*, were used to quantify the potential benefits of activating RMSs due to incidents.

6.1.1.2 Identify Variables Affecting Traffic Flow States Upstream of the Incident Location

Tables 6-1 and 6-2 provide the descriptive statistics of the variables included in the analysis of daytime off-peak and nighttime off-peak periods, respectively. The main variables of the models were related to the operations of RMSs upstream and downstream of the incident location. During daytime off-peak periods, the *free flow state* had fewer observations (1.2% and 1.4%) when the first and second RMSs upstream of the incident location were *activated*. Also, the *free flow state* had only 0.9% of the observations when the first RMS downstream of the incident location was *activated*.

Similarly, during nighttime off-peak periods, the *free flow state* had fewer observations (1.0% and 1.1%) when the first and second RMS upstream of the incident location were *activated*. Also, the *free flow state* had only 0.5% of the observations when the first RMS downstream of the incident location was *activated*. Since the *free flow state* had a lower proportion of observations when RMSs were activated, the *free flow state* was not included in the analysis. Moreover, based on the developed guidelines, RMS activation was not recommended in the *free flow state*. Therefore, the *transition flow state* and *congested flow state* were analyzed to quantify the potential benefits of activating RMSs due to incidents. Other model variables included incident type (i.e., crashes and vehicle problems), fire rescue, towing involved, and lane blockage.

Daytime Off-peak Periods

Table 6-1 presents the descriptive statistics of the analysis variables according to the traffic state during the daytime off-peak periods. The following variables were analyzed: RMSs, incident type, fire rescue, towing, and lane blockage.

Table 6-1: Summary of Variables Based on Traffic States during Daytime Off-peak Periods

Categorical Variable	Factor	Free Flow State	Transition Flow State	Congested Flow State
First upstream RMS	Deactivated	66,379	16,521	14,651
	Activated	795	1,811	2,780
Second upstream RMS	Deactivated	66,249	16,430	14,716
	Activated	925	1,902	2,715
Downstream RMS	Deactivated	66,576	17,256	15,905
	Activated	598	1,076	1,526
Incident type	Vehicle problems	46,547	9,372	7,969
	Crash	20,627	8,960	9,462
Fire rescue present	No	63,128	15,782	13,675
	Yes	4,046	2,550	3,756
Towing involved	No	65,586	18,182	17,089
	Yes	1,588	465	555
Lane blockage	No	50,004	9,614	8,526
	Yes	17,170	8,718	8,905

Note: Values represent the number of data points, i.e., speed and occupancy, at every 5-minute interval within the incident clearance duration.

RMS: This variable indicated whether the RMSs were turned ON or OFF during the incident clearance duration. This variable was categorized into two categories, i.e., whether RMSs were *activated* or *deactivated*. As presented in Table 6-1, the *transition flow state* and the *congested flow state* had similar observations when the first and second RMS upstream of the incident location were *activated*. A similar proportion of observations was observed in the *transition flow state* and the *congested flow state* when the first RMS downstream of the incident location was *activated*.

Incident type: This variable was categorized into crashes and vehicle problems (disabled or abandoned vehicles, emergency vehicles, and police activity). As indicated in Table 6-1, the proportion of observations involving vehicle problems was higher in the *transition flow state* (51.1%) than in the *congested flow state* (45.7%). On the other hand, the proportion of observations involving crashes was lower in the *transition flow state* (48.9%) than in the *congested flow state* (54.3%).

Fire rescue: This variable indicated whether or not fire rescue was involved to clear the incident. Both the *transition flow state* and the *congested flow states* had relatively fewer observations when fire rescue was involved to clear the incident than when fire rescue was not involved.

Towing: This variable indicated whether or not towing was involved to clear the incident. As presented in Table 6-1, the *transition flow state* and the *congested flow state* had relatively fewer observations when towing was involved to clear the incident than when towing was not involved.

Lane blockage: This variable referred to whether or not an incident resulted in travel lane blockage. In this study, the lane blockage variable had two groups: whether an incident resulted in at least one lane blockage or no lane blockage. The proportion of observations associated with lane blockage was lower in the *transition flow state* (47.6%) than in the *congested flow state* (51.1%).

Nighttime Off-peak Periods

Table 6-2 presents the descriptive statistics of the analysis variables according to the traffic state during the nighttime off-peak periods. The following variables were analyzed: RMSs, incident type, fire rescue, towing, and lane blockage.

Table 6-2: Summary of Variables Based on Traffic States During Nighttime Off-peak Periods

Categorical Variable	Factor	Free Flow State	Transition Flow State	Congested Flow State
First upstream RMS	Deactivated	40,325	21,323	4,707
	Activated	427	1,094	1,865
Second upstream RMS	Deactivated	40,313	21,322	4,826
	Activated	439	1,095	1,746
Downstream RMS	Deactivated	40,548	21,665	5,250
	Activated	204	752	1,322
Incident type	Vehicle problems	30,105	16,479	3,440
	Crash	10,647	5,938	3,132
Fire rescue present	No	37,222	21,541	5,134
	Yes	3,530	876	1,438
Towing involved	No	39,453	22,035	6,407
	Yes	1,299	382	165
Lane blockage	No	29,639	19,839	3,508
	Yes	11,113	2,578	3,064

Note: The values represent the number of data points, i.e., speed and occupancy, at every 5-minute interval within the incident clearance duration.

RMS: As can be observed from Table 6-2, the *transition flow state* and the *congested flow state* had almost similar proportions of observations when the first and second RMS upstream of the incident location were *activated*. A similar proportion of observations was observed in the *transition flow state* and the *congested flow state* when the first RMS downstream of the incident location was *activated*.

Incident type: The proportion of observations involving vehicle problems was higher in the *transition flow state* (73.5%) than in the *congested flow state* (52.3%). On the other hand, the proportion of observations involving crashes was lower in the *transition flow state* (26.5%) than in the *congested flow state* (47.7%).

Fire rescue: Both the *transition flow state* and the *congested flow state* had relatively fewer observations when fire rescue was involved to clear the incident than when fire rescue was not involved.

Towing: Similar to fire rescue, both the *transition flow state* and the *congested flow state* had relatively fewer observations when towing was involved to clear the incident than when towing was not involved.

Lane blockage: As indicated in Table 6-2, the proportion of observations associated with lane blockage was lower in the *transition flow state* (11.5%) than in the *congested flow state* (46.6%).

6.1.1.3 Factors Influencing Traffic Conditions Upstream of the Incident Location

Based on the number of observations in the clusters (i.e., established traffic flow states), the logistic regression model was developed to analyze the effect of variables between two traffic states, i.e., *transition flow state* and *congested flow state*. Logistic regression is a widely applied method for analyzing binary classification problems (Kitali et al., 2019; Xu et al., 2013). The response variable of the logistic regression has two classes: 0 or 1. The probability of classifying the observation *i* in class 1 is estimated using Equation 6-1:

$$\pi_i = \frac{\exp(x_i^T\beta)}{1+\exp(x_i^T\beta)} \tag{6-1}$$

where,

x_i^T = ith explanatory variable vector-matrix transpose,
β = vector of unknown coefficients.

The parameters of Equation 6-1 were estimated using the log-likelihood function shown in Equation 6-2.

$$\ell(\beta) = \sum_{i=1}^{n}\{y_i\log(\pi_i) + (1-y_i)\log(1-\pi_i)\} \tag{6-2}$$

where,

n = number of observations,
y_i = response variable for observation i, and
π_i = probability of classifying the observation i in class 1.

Other variables are as defined in Equation 6-1.

Results of the logistic regression were interpreted using the odds ratio (OR). An odds ratio was calculated as the exponential of the estimated mean β, i.e., exp (β). An odds ratio of 1.0 indicates a variable with no influence on changing the traffic flow condition from the *transition flow state* to the *congested flow state*. An odds ratio greater than 1.0 indicates that a change from the base level to another for the studied categorical variable would increase the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 100(OR – 1) %. An odds ratio less than 1.0 indicates that a change from the base level to another for the studied categorical variable would decrease the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 100(OR – 1) %.

6.1.1.4 Impact of RMSs on Traffic Conditions Upstream of the Incident Location

The impact of RMSs on traffic conditions in the *transition flow state* and the *congested flow state* was analyzed. As stated earlier, the *free flow state* was excluded in the analysis due to fewer observations when RMSs were activated. Also, based on the developed guidelines presented in Chapter 4, RMS activation was not recommended in the *free flow state*. The potential benefits of activating RMSs due to incidents are discussed in the following subsection.

Impact of Activating RMSs on Traffic Conditions Affected by Incidents during Daytime Off-peak Periods

Table 6-3 presents the logistic regression results of the traffic states (i.e., *transition flow state* and *congested flow state*) during daytime off-peak periods. The result showed that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 45%. Conversely, activating the second RMS upstream of the incident location did not significantly affect the traffic conditions. Similarly, activating the first RMS downstream of the incident location did not significantly affect the traffic conditions. These findings suggested that activating the first RMS upstream of the incident location could help improve traffic flow conditions. Also, results indicated that it might not be necessary to activate the RMSs further upstream and the first RMS downstream of the incident location to improve traffic flow conditions.

Table 6-3: Model Results in Response to Incidents during Daytime Off-peak Periods

Variables	Category	Transition Flow Vs. Congested Flow				
		Coeff.	S. E.	95% CI		OR
				2.5%	97.5%	
First upstream RMS	Deactivated*					
	Activated	**-0.590**	**0.076**	**-0.740**	**-0.441**	**0.55**
Second upstream RMS	Deactivated*					
	Activated	0.085	0.068	-0.048	0.219	1.09
Downstream RMS	Deactivated*					
	Activated	0.021	0.058	-0.092	0.133	1.02
Incident type	Vehicle problems*					
	Crash	**-0.115**	**0.023**	**-0.160**	**-0.069**	**0.89**
Fire rescue present	No*					
	Yes	**-0.509**	**0.032**	**-0.572**	**-0.447**	**0.60**
Towing involved	No*					
	Yes	**-0.189**	**0.065**	**-0.317**	**-0.063**	**0.83**
Lane blockage	No*					
	Yes	**0.109**	**0.025**	**0.061**	**0.158**	**1.12**
Constant		0.213	0.017	0.179	0.246	1.24

Note: Bold numbers show significant variables at 95% confidence interval (CI); Coeff. = coefficient; S.E. = standard error; OR = odds ratio; * refers to base category.

Other variables, such as crashes, fire rescue, and towing, reduced the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 11%, 40%, and 17%, respectively. As expected, lane blockage increased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 12%.

Impact of Activating RMSs on Traffic Conditions Affected by Incidents during Nighttime Off-peak Periods

Table 6-4 provides the logistic regression results of the traffic states (i.e., *transition flow state* and *congested flow state*) during nighttime off-peak periods. All variables included in the analysis were significant at a 95% confidence interval (CI). The result showed that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 82%. The effect of activating the second RMS upstream of the incident location was not directly analyzed because it was highly correlated with the first RMS upstream of the incident location. Activating the first RMS downstream of the incident location decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 35%. These findings suggest that activating the first RMS upstream and downstream of the incident location could help improve traffic flow conditions.

Other variables, such as crashes, fire rescue, and lane blockage, decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 28%, 64%, and 74%, respectively.

Table 6-4: Model Results in Response to Incidents During Nighttime Off-peak Periods

Variables	Category	Transition Flow Vs. Congested Flow				
		Coeff.	S. E.	95% CI		OR
				2.5%	97.5%	
First upstream RMS	Deactivated* Activated	-1.698	0.071	-1.837	-1.560	0.18
Downstream RMS	Deactivated* Activated	-0.426	0.082	-0.588	-0.264	0.65
Incident type	Vehicle problems* Crash	-0.334	0.035	-0.403	-0.265	0.72
Fire rescue present	No* Yes	-1.021	0.056	-1.131	-0.910	0.36
Towing involved	No* Yes	0.404	0.118	0.174	0.637	1.50
Lane blockage	No* Yes	-1.354	0.040	-1.433	-1.276	0.26
Constant		2.085	0.023	2.041	2.130	8.05

Note: Coeff. = coefficient; S.E. = standard error; OR = odds ratio; * refers to base category.

6.1.1.5 Summary

This section focused on quantifying the potential benefits of activating RMSs in response to non-recurrent congestion due to incidents. The benefits were determined based on the developed RMS activation guidelines. Similar to the developed guidelines, the benefits were also estimated based on the time of day, i.e., daytime off-peak periods and nighttime off-peak periods.

Daytime off-peak periods: The results showed that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 45%. Conversely, activating the second RMS upstream of the incident location did not significantly affect the traffic flow conditions. Similarly, activating the first RMS downstream of the incident location did not significantly affect the traffic flow conditions. These findings suggest that activating the first RMS upstream of the incident location could help improve traffic flow conditions. Also, the results indicated that it might not be necessary to activate the RMSs further upstream and the first RMS downstream of the incident location to improve traffic flow conditions.

Nighttime off-peak periods: The results showed that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 82%. Similarly, activating the first RMS downstream of the incident location decreased the likelihood of traffic flow changing from the *transition flow state* to the *congested flow state* by 35%. These findings suggest that activating the first RMS upstream and downstream of the incident location could help improve traffic conditions upstream of the incident location.

6.1.2 Benefits of Activating RMSs during Rain

This section discusses the potential benefits of activating RMSs during rain. The benefits were estimated based on the developed guidelines for activating RMSs during rain. The following steps were used to quantify the benefits of activating RMSs during rain:

- Step 1: Establish traffic flow states during rain.
- Step 2: Identify variables affecting traffic flow states during rain.
- Step 3: Identify factors influencing traffic flow states during rain.
- Step 4: Determine the impact of RMSs on traffic flow states during rain.

6.1.2.1 Establish Traffic Flow States during Rain

As discussed in Chapter 4, the *k*-means clustering was used to classify the traffic flow datasets into three groups based on speed and occupancy. The established traffic flow states (i.e., *free flow state*, *transition flow state*, and *congested flow state*) were used to quantify the potential benefits of activating RMSs in response to non-recurrent congestion caused by rain.

6.1.2.2 Identify Variables Affecting Traffic States during Rain

The variables included in the analysis were the RMSs and rain intensity. The RMS variable had two categories: whether the RMSs were *activated* or *deactivated* during rain. The rain intensity categories were defined according to the HCM. The light rain had an intensity of > 0 in/hr but ≤ 0.10 in/hr. The moderate rain had an intensity of > 0.10 in/hr and ≤ 0.25 in/hr, and the heavy rain had an intensity of > 0.25 in/hr. In this research, the rain intensity variable was divided into two main categories: light rain and moderate or heavy rain.

Table 6-5 describes the variables affecting the traffic conditions during rain according to the traffic state. As presented in Table 6-5, more observations were classified in the *congested flow state* than in the *transition flow state* and *free flow state* when the RMSs were *activated* during rain. Also, based on the developed guidelines presented in Chapter 4, RMS activation was not recommended when the traffic is in the *free flow state*. Therefore, the *transition flow state* and the *congested flow state* were analyzed to quantify the potential benefits of activating RMSs during rain.

Furthermore, relatively more observations were categorized in the *congested flow state* than the *transition flow state* when the RMSs were *activated* during rain. The proportion of observations associated with moderate and heavy rain was higher in the *transition flow state* than in the *congested flow state*.

Table 6-5: Variables Affecting Traffic Conditions during Rainfall

Period	Variable	Factor	Free Flow State	Transition Flow State	Congested Flow State
Daytime	RMSs	Deactivated	55,135	19,407	7,498
		Activated	294	503	1,168
	Rain intensity	Light	45,149	14,058	5,452
		Moderate or heavy	10,280	5,852	3,214
Nighttime	RMSs	Deactivated	67,946	65,701	3,981
		Activated	44	565	1,280
	Rain intensity	Light	58,275	56,373	3,999
		Moderate or heavy	9,715	9,893	1,262

Note: The values represent the number of data points, i.e., speed and occupancy at every 5-minute interval during rain.

6.1.2.3 Factors Influencing Traffic Conditions during Rain

Based on the number of observations in clusters (i.e., established traffic flow states), the logistic regression model described in Section 6.1.1.3 was developed to analyze the effect of variables between two traffic flow states, i.e., the *transition flow state* and the *congested flow state.* The model results were interpreted using the odds ratio (OR), as described in Section 6.1.1.3.

6.1.2.4 Impact of RMSs on Traffic Conditions during Rain

This research analyzed the impact of RMSs on traffic conditions in the *transition flow state* and the *congested flow state*. The *free flow state* was excluded in the analysis due to fewer observations when RMSs were activated. Moreover, based on the developed guidelines presented in Chapter 4, RMS activation was not recommended when the traffic is in the *free flow state.* Table 6-6 presents the logistic regression results of the traffic states, i.e., *transition flow state* and *congested flow state*, during rain.

Table 6-6: Logistic Regression Results during Rainfall

Period	Variables	Category	Transition Flow Vs. Congested Flow				
			Coeff.	S. E.	95% CI		OR
					2.5%	97.5%	
Daytime	RMS	Deactivated* Activated	-1.773	0.055	-1.882	-1.666	0.17
	Rain intensity	Light* Moderate or heavy	-0.316	0.028	-0.371	-0.262	0.73
	Constant		1.054	0.017	1.022	1.087	2.87
Nighttime	RMS	Deactivated* Activated	-3.571	0.053	-3.676	-3.467	0.03
	Rain intensity	Light* Moderate or heavy	-0.396	0.038	-0.471	-0.321	0.67
	Constant		2.873	0.018	2.838	2.909	17.69

Note: Coeff. = coefficient; CI = confidence interval; S.E. = standard error; OR = odds ratio; * refers to base category.

As shown in Table 6-6, all variables included in the analysis were significant at the 95% CI. The results indicated that activating RMSs during rain significantly influenced the change from the *transition flow state* to the *congested flow state*. Specifically, activating RMSs decreased the likelihood of traffic conditions changing from the *transition flow state* to the *congested flow state* by 83% during daytime off-peak periods. Similarly, activating RMSs reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 97% during nighttime off-peak periods. These findings suggest that activating the RMSs during rain could help improve traffic flow conditions. Results also indicated that moderate or heavy rain was associated with a 27% and 33% reduced likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* during daytime off-peak and nighttime off-peak periods, respectively.

6.1.2.5 Summary

This section discussed the potential benefits of activating RMSs during rain. The benefits were determined based on the developed RMS activation guidelines. Similar to the developed guidelines, the benefits were also estimated based on the time of day, i.e., daytime off-peak periods and nighttime off-peak periods.

Daytime off-peak periods: The results showed that activating RMSs decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 83%. These findings suggest that activating the RMSs could help improve traffic flow conditions during moderate or heavy rain.

Nighttime off-peak periods: The results indicated that activating RMSs reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 97%. These findings suggest that activating the RMSs could help improve traffic flow conditions during moderate or heavy rain.

6.2 Benefits of Activating RMSs on Weekends

Real-world data for RMS activation on weekends were not available because ramp meters in Florida are not operational during the weekends. Thus, a microscopic simulation approach was used to quantify the potential benefits of activating RMSs on weekends. The benefits were estimated based on the developed guidelines for activating RMSs on weekends, as presented in Chapter 5 of this report.

6.2.1 Performance Metrics

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

Lane blockage: In this study, 2-lane and 3-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 (60 minutes and 90 minutes).

Ramp volume: This variable represents the number of vehicles on the freeway on-ramp. The selection of the ramp volume was based on the sensitivity analysis discussed in Section 5.2.4. The developed guidelines showed that for a 2-lane blockage, RMS activation was recommended when the ramp volume exceeds 950 veh/hr/ln for an incident with a 60-minute incident clearance duration. Also, for an incident with a 90-minute incident clearance duration, RMS activation was necessary when the ramp volume exceeds 800 veh/hr/ln. The worst-case scenario (i.e., ramp volume exceeding 800 veh/hr/ln) was selected to quantify the potential benefits of activating the RMSs in response to an incident requiring a 2-lane blockage. On the other hand, RMS activation was recommended for a 3-lane blockage when the ramp volume exceeds 750 veh/hr/ln for an incident with a 60-minute incident clearance duration. Also, for an incident with a 90-minute incident clearance duration, RMS activation was necessary when the ramp volume exceeds 800 veh/hr/ln. In this case, ramp volume exceeding 750 veh/hr/ln was selected to quantify the potential benefits of activating the RMSs in response to an incident requiring a 3-lane blockage.

Freeway mainline volume: This variable represents the traffic volume on the freeway mainline. Similar to the ramp volume variable, the selection of the freeway mainline volume was based on the sensitivity analysis discussed in Section 5.2.4. The developed guidelines showed that for a 2-lane blockage, RMS activation was recommended when the freeway mainline volume exceeds 1100 veh/hr/ln for an incident with a 60-minute incident clearance duration. Also, for an incident with a 90-minute incident clearance duration, RMS activation was recommended when the freeway mainline volume exceeds 1050 veh/hr/ln. The worst-case scenario (i.e., mainline freeway volume above 1050 veh/hr/ln) was selected to quantify the potential benefits of activating the RMSs in response to the incident requiring a 2-lane blockage. On the other hand, RMS activation was recommended for a 3-lane blockage when the freeway mainline volume exceeds 1100 veh/hr/ln for an incident with a 60-minute incident clearance duration. Also, for an incident with a 90-minute incident clearance duration, RMS activation was necessary when the freeway mainline volume exceeds 1000 veh/hr/ln. In this case, the mainline freeway volume exceeding 1000 veh/hr/ln was selected to quantify the potential benefits of activating the RMSs in response to an incident requiring a 3-lane blockage. Table 6-7 summarizes the ramp and freeway mainline volume used to quantify the potential benefits of activating RMSs in response to incidents on weekends.

Table 6-7: Traffic Volume Activation Thresholds

Incident Type	Incident Clearance Duration (minutes)	Activation Threshold	
		Ramp Volume (veh/h/ln)	Freeway Mainline Volume (veh/h/ln)
2-lane blockage (40%)	60	> 950	>1100
	90	**>800**	**>1050**
3-lane blockage (60%)	60	>750	>1100
	90	**>750**	**>1000**

Note: Bolded values were selected as traffic input to quantify the potential benefits of activating RMSs on weekends; 40% and 60% are the percentages of lane blockage based on general-purpose lanes only.

Ramp metering rate: The metering rate was continuously computed using fuzzy logic algorithms based on the traffic conditions. The minimum metering rate was conditioned not to fall below five veh/minute to avoid a zero-metering rate and ensure that the signal was metering at all times. Table 6-8 provides the summary of the computed metering rates.

Table 6-8: Computed Metering Rates

Incident Type	Incident Clearance Duration (minutes)	Metering Rates (veh/min)		
		Minimum	**Mean**	**Maximum**
2-lane blockage (40%)	60	5	10	18
	90	5	8	18
3-lane blockage (60%)	60	5	8	18
	90	5	7	18

Note: 40% and 60% are the percentages of lane blockage based on general-purpose lanes only.

6.2.2 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. In VISSIM, the average speed is estimated using Equation 6-3. The average speed with and without RMS activation was analyzed to quantify the potential benefits of RMSs on weekends.

$$Average\ speed = \frac{d}{t} \quad (6\text{-}3)$$

where,

d = total distance,

t = total travel time.

Table 6-9 summarizes the simulation results for the average speed in the simulated scenarios.

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 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 of the freeway 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 of the freeway network.

Table 6-9: Simulation Results for Average Speed

Incident Type	Incident Clearance Duration (minutes)	Activation Scenario	Average Speed (mph)	Increase in Speed (%)
2-lane blockage (40%)	60	Without RMSs	46.00	11
		With RMSs	51.29	
	90	Without RMSs	38.45	15
		With RMSs	44.2	
3-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 based on general-purpose lanes only.

6.2.3 Impacts of RMSs on Average Delay

As discussed earlier, the average delay was used as one of the performance measures to examine the impacts of activating RMSs on weekends. The average delay represents the delay that a vehicle experiences on a roadway network over a given time period. 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 for both with and without RMS activation was analyzed to quantify the potential benefits of RMSs. In VISSIM, the average delay per vehicle is computed using Equation 6-4.

$$Average\ delay = \frac{D}{N_{netw} + N_{arriv}} \quad (6\text{-}4)$$

where,

D = total delay of all vehicles in the network at the end of evaluation time,
N_{netw} = number of vehicles in the network at the end of evaluation time, and
N_{arriv} = number of vehicles that have arrived at the end of evaluation time.

Table 6-10 summarizes the simulation results for the average vehicle delay of the simulated scenarios.

Two-lane blockage: 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 reduced 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 of the incident location could improve traffic flow conditions of the freeway network.

Three-lane blockage: 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 of the incident location could improve traffic flow conditions of the freeway network.

Table 6-10: Simulation Results for Average Delay

Incident Type	Incident Clearance Duration (minutes)	Activation Scenario	Average Delay (s/veh)	Decrease in Delay (%)
2-lane blockage (40%)	60	Without RMSs	76.94	22
		With RMSs	60.24	
	90	Without RMSs	142.60	25
		With RMSs	106.01	
3-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 based on general-purpose lanes only.

6.2.4 Summary

This section focused on quantifying the potential benefits of activating RMSs on weekends using a microscopic simulation approach. Average speed and average delay were used as the performance metrics to evaluate the benefits of activating RMSs on weekends. Table 6-11 summarizes the potential benefits of activating RMSs on weekends.

Table 6-11: Benefits of Activating RMSs on Weekends

Incident Type	Incident Clearance Duration (minutes)	Increase in Speed (%)	Decrease in Delay (%)
2-lane blockage (40%)	60	11	22
	90	15	25
3-lane blockage (60%)	60	7	15
	90	10	18

Note: 40% and 60% are the percentages of lane blockage based on general-purpose lanes only.

Average speed: For a 2-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 3-lane blockage, activating RMSs improved the average speed by 7% and 10% for an incident with a 60-minute and 90-minute incident clearance duration, respectively. These findings imply that activating RMSs in response to incidents on weekends improves the average speed by at least 7%.

Average delay: For a 2-lane blockage, results showed that activating RMSs reduced the average delay of vehicles on the freeway network by 22% and 25% for an incident with a 60-minute and 90-minute incident clearance duration, respectively. For a 3-lane blockage, activating RMSs decreased the average delay of vehicles on the freeway network by 15% and 18% for an incident with a 60-minute and 90-minute incident clearance duration, respectively. These findings suggest that activating RMSs in response to incidents on weekends decreases the average delay of vehicles on the freeway network by at least 15%.

6.3 Summary

This chapter focused on quantifying the potential benefits of activating RMSs during off-peak hours and weekends. The potential benefits of activating RMSs during off-peak hours and weekends are as follows:

Benefits of Activating RMSs in Response to Incidents during Daytime Off-peak Hours
Overall, the results suggested that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 45%. This implies that activating the first RMS upstream of the incident location could help improve traffic flow conditions. However, based on the analysis, the results suggested that it might not be necessary to activate the RMSs further upstream and the first RMS downstream of the incident location to improve traffic flow conditions.

Benefits of Activating RMSs in Response to Incidents during Nighttime Off-peak Hours
Overall, the findings suggest that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 82%. Similarly, activating the first RMS downstream of the incident location reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 35%. These findings suggest that activating the first RMS upstream and downstream of the incident location could help improve traffic flow conditions.

Benefits of Activating RMSs during Rain
Overall, activating RMSs decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 83% during daytime off-peak periods. Similarly, findings showed that activating RMSs reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 97% during nighttime off-peak periods. These findings imply that activating the RMSs could help improve traffic flow conditions during rain.

Benefits of Activating RMSs in Response to Incidents on Weekends
The analysis results suggested that activating RMSs in response to an incident on weekends increased the average speed by at least 7%. Also, RMSs activation was found to reduce the average delay of vehicles in the roadway network by at least 15%.

CHAPTER 7
USER MANUAL FOR RAMP METER ACTIVATION AND DEACTIVATION TOOL

This chapter presents the user manual for the RMS activation and deactivation tool. The Tool is intended to provide support and guidance to ramp metering operators in FDOT District Six to identify the need for activating and deactivating RMSs during off-peak hours and on weekends. This Tool is based on the developed guidelines presented in Chapters 4 and 5 of this report.

7.1 Getting Started

This section describes the basic interactions needed to use the Tool. It consists of the following subsections.

- Navigation: guidance for selecting and using the worksheets.
- Instructions Worksheet: a brief overview of RMSs and descriptions of the inputs required for activation and deactivation of the RMSs.
- Entering Data: guidance for entering data in the worksheets, as well as reviewing, saving, and printing results.

7.1.1 Navigation

The Tool contains a total of six (6) worksheets. To navigate among the worksheets, click on the worksheet tabs at the bottom of the workbook window. Worksheets consist of the following contents:

- Preface – includes a foreword, acknowledgments, and a disclaimer.
- Instructions – provides a brief overview of RMS and descriptions of the input variables required for activation and deactivation of the RMS.
- Worksheets for RMS activation and deactivation guidelines – includes a separate worksheet for RMS activation due to incidents, rain, and on weekends.
- Info worksheet – includes a summary of the RMS activation and deactivation guidelines.

7.1.2 Instructions Worksheet

The "INSTRUCTIONS" worksheet provides details of the input variables required for activating and deactivating RMSs during off-peak hours and on weekends. This information should be read prior to first using the Tool. Descriptions of the input variables are provided in the following subsections.

7.1.2.1 Activation and Deactivation of RMSs in Response to Incidents during Off-peak Hours

To determine when to activate RMSs in response to incidents during off-peak hours, the Operator is required to determine the incident characteristics, the speed along the freeway mainline during the incident clearance duration, and the time of the incident. Table 7-1 provides the descriptions of the input data needed for activating RMSs in response to incidents during off-peak hours on weekdays.

Table 7-1: Required Input Data to Determine When to Activate RMSs in Response to Incidents

Variable		Description
Speed (mph)		Speed along the freeway mainline
Lane blockage	Yes	An incident resulting in at least one lane blockage
	No	No lane blockage due to incident
Time of day	Daytime	6:00 AM-3:00 PM (NB) and 10:30 AM-7:00 PM (SB)
	Nighttime	7:00 PM-6:00 AM

Note: NB = Northbound; SB = Southbound.

If the conditions warrant activation of the RMS, the Operator is required to follow up on the attributes presented in Table 7-2 to determine whether to deactivate the RMS or continue with activation. These attributes must be reviewed each time any changes occur in the incident characteristics and speed along the mainline.

Table 7-2: Required Input Data to Determine When to Deactivate RMSs in Response to Incidents

Variable		Description
Speed (mph)		Speed along the freeway mainline
Incident cleared	Yes	Event closed in the SunGuide® application
	No	Event still active in the SunGuide® application
Lane blockage	Yes	An incident resulting in at least one lane blockage
	No	No lane blockage due to incident
Time of day	Daytime	6:00 AM-3:00 PM (NB) and 10:30 AM-7:00 PM (SB)
	Nighttime	7:00 PM-6:00 AM

Note: NB = Northbound; SB = Southbound.

7.1.2.2 Activation and Deactivation of RMSs in Response to Rain during Off-peak Hours

To determine when to activate RMSs in response to rain during off-peak hours on weekdays, the Operator must determine the rain intensity, speed along the freeway mainline, and the time when it is raining. Table 7-3 presents the descriptions of the input data required for activating RMSs in response to rain during off-peak hours on weekdays.

Table 7-3: Required Input Data to Determine When to Activate RMSs during Rain

Variable		Description
Speed (mph)		Speed along the freeway mainline
Rain intensity	Light	Rainfall intensity > 0 in/hr but ≤ 0.10 in/hr
	Moderate or heavy	Rainfall intensity > 0.10 in/hr
Time of day	Daytime	6:00 AM-3:00 PM (NB) and 10:30 AM-7:00 PM (SB)
	Nighttime	7:00 PM-6:00 AM

Note: NB = Northbound; SB = Southbound.

If the conditions warrant activation of RMSs, the Operator must review the attributes presented in Table 7-4 to determine whether to deactivate the RMSs or continue with activation. These attributes must be reviewed each time any changes occur in the rain characteristics and speed along the mainline.

Table 7-4: Required Input Data to Determine When to Deactivate RMSs during Rain

Variable		Description
Speed (mph)		Speed along the freeway mainline
Rain stopped	Yes	Weather is clear (rain stopped)
	No	Rain continues
Rain intensity	Light	Rainfall intensity > 0 in/hr but ≤ 0.10 in/hr
	Moderate or heavy	Rainfall intensity > 0.10 in/hr
Time of day	Daytime	6:00 AM-3:00 PM (NB) and 10:30 AM-7:00 PM (SB)
	Nighttime	7:00 PM-6:00 AM

Note: NB = Northbound; SB = Southbound.

7.1.2.3 Activation and Deactivation of RMSs in Response to Incidents on Weekends

To determine when to activate RMSs in response to incidents on weekends, the Operator must identify the incident characteristics, speed along the freeway mainline, and the traffic flow on the mainline and on-ramps. Table 7-5 describes the input data needed for activating RMSs in response to incidents on weekends.

Table 7-5: Required Input Data to Determine When to Activate RMSs in Response to Incidents on Weekends

Variable		Descriptions
Speed (mph)		Speed along the freeway mainline
Ramp volume (veh/hr/ln)		Traffic flow along the on-ramp
Mainline volume (veh/hr/ln)		Traffic flow along freeway mainline
Lane blockage	2-lane blockage	An incident resulting in two-lane blockages
	3-lane blockage	An incident resulting in three-lane blockages

Note: mph = miles-per-hour; veh/hr/ln = Vehicles-per-hour-per-lane.

If the conditions warrant activation of RMSs, the Operator must review the attributes presented in Table 7-6 to determine whether to deactivate the RMSs or continue with activation. These attributes must be reviewed each time any changes occur in the incident characteristics and speed along the mainline.

Table 7-6: Required Input Data to Determine When to Deactivate RMSs in Response to Incidents on Weekends

Variable		Descriptions
Speed (mph)		Travel speed along the freeway mainline
Incident cleared	Yes	Event closed in the SunGuide® application
	No	Event still active in the SunGuide® application
Lane blockage	2-lane blockage	An incident resulting in two-lane blockages
	3-lane blockage	An incident resulting in three-lane blockages

Note: mph = miles-per-hour.

7.2 Entering Data

The cells with the white background are for user input. Other cells are locked to prevent accidental changes. Key-in the speed values in the input message box as shown in Figure 7-1.

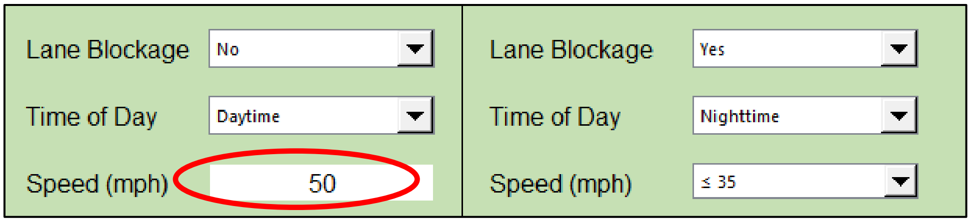


Figure 7-1: Sample Interactive Input Message Box for Continuous Variable

A drop-down list is provided for some cells with a drop-down combo box, as shown in Figure 7-2. Left-click on the drop-down arrow to see the list of input choices. Use the mouse pointer to select the desired option.

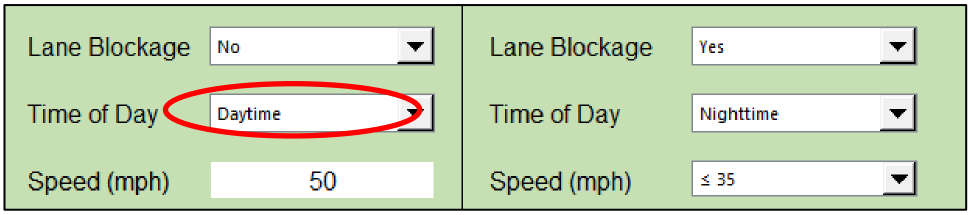


Figure 7-2: Sample Drop-down List for Categorical Variables

The data entered into the worksheets can be saved by saving the entire workbook as a separate file. On the main menu, select *File > Save As* and enter a new file name when prompted. To print the results, select *File > Print* on the main menu. Click on *Print Preview* to see and print the one-page printout of the results. If the information shown is acceptable, click on *Print* at the top of the window to print the results page. Ensure that the printer is turned on prior to clicking the *Print* button. The following sections explain the input data and the decision when to activate or deactivate RMSs.

7.2.1 Activation of RMSs in Response to Incidents during Off-peak Hours

Upstream Input Variables: The speed variable is added by filling in the Tool cells with the white background. Other input variables are categorical and are added by selecting categories that represent the best possible condition from their respective drop-down lists.

Categorical variables

- Lane Blockage: Please select from the respective drop-down list.
- Time of Day: Please select from the respective drop-down list.

Downstream Input Variables: All variables are categorical. Categorical input variables are added by selecting categories representing the best possible condition from their respective drop-down lists.

Categorical variables

- Lane Blockage: Please select from the respective drop-down list.
- Time of Day: Please select from the respective drop-down list.
- Speed: Please select from the respective drop-down list.

Figure 7-3 provides an example of the input-output scenario for activating RMSs upstream and downstream of the incident location.

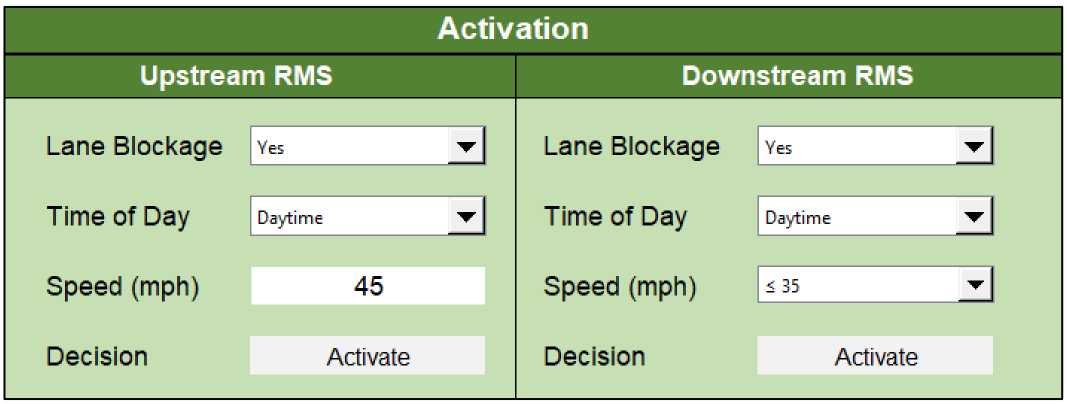


Figure 7-3: Sample Input-Output for Upstream and Downstream RMS Activation

Error Checks

All inputs must be entered to obtain the results. The worksheet will return an error message if one or more input attribute(s) is not selected or keyed-in, as shown in Figure 7-4.

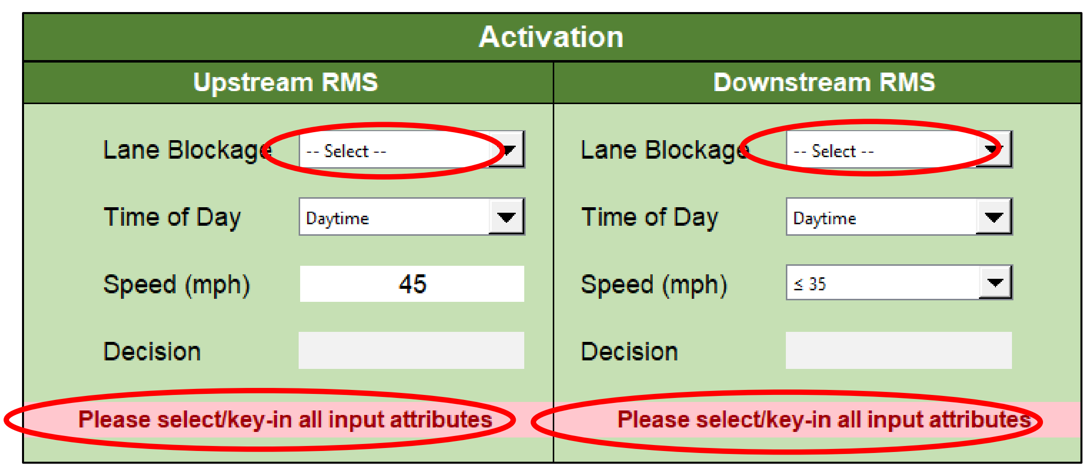


Figure 7-4: Sample Input Error Check for Upstream and Downstream RMS Activation

7.2.2 Deactivation of RMSs in Response to Incidents during Off-peak Hours

Upstream Input Variables: The speed variable is added by filling in the Tool cells with the white background. Other input variables are categorical and are added by selecting categories representing the best possible situation from their respective drop-down lists.

Categorical variables

- Incident Cleared: Please select from the respective drop-down list.
- Lane Blockage: Please select from the respective drop-down list.
- Time of Day: Please select from the respective drop-down list.

Downstream Input Variables: All variables are categorical. Categorical input variables are added by selecting categories that represent the best possible condition from their respective drop-down lists.

Categorical variables

- Incident Cleared: Please select from the respective drop-down list.
- Lane Blockage: Please select from the respective drop-down list.
- Time of Day: Please select from the respective drop-down list.
- Speed: Please select from the respective drop-down list.

Figure 7-5 illustrates an example of the input-output scenario for deactivating RMSs upstream and downstream of the incident location.

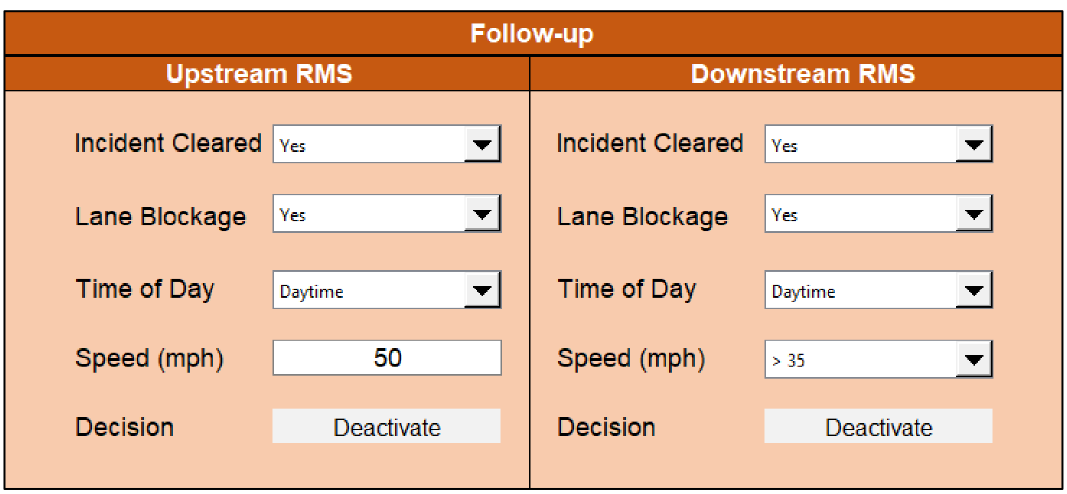


Figure 7-5: Sample Input-Output for Upstream and Downstream RMS Deactivation

Error Checks

All inputs must be entered to obtain the results. The worksheet will return an error message if one or more input attribute(s) is not selected or keyed-in, as shown in Figure 7-6.

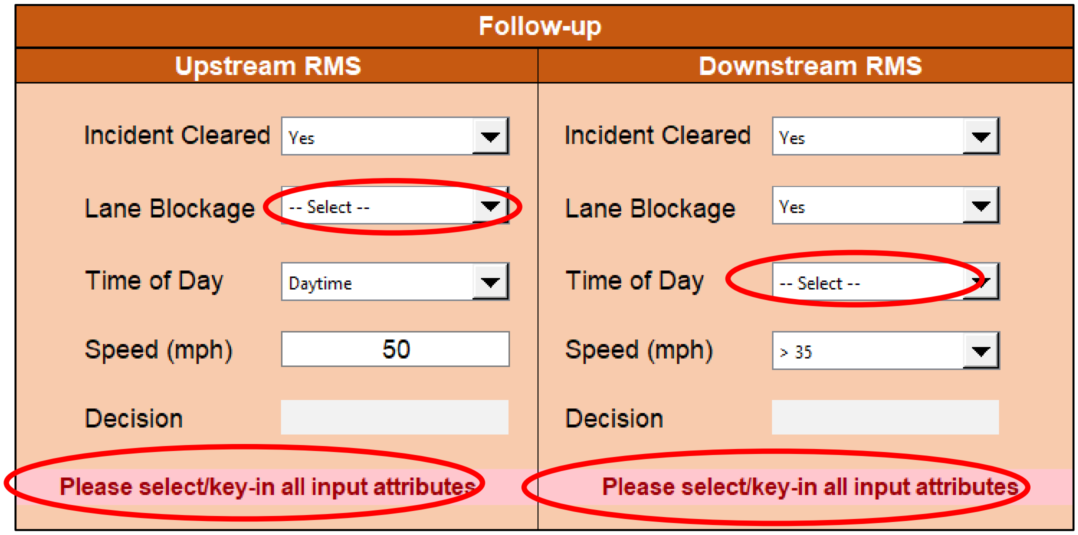


Figure 7-6: Sample Input Error Check for Upstream and Downstream RMS Deactivation

7.2.3 Activation of RMSs in Response to Rain during Off-peak Hours

Input Variables: The speed variable is added by filling in the Tool cells with the white background. Other input variables are categorical and are added by selecting categories that represent the best possible condition from their respective drop-down lists.

Categorical variables

- Rain Category: Please select from the respective drop-down list.
- Time of Day: Please select from the respective drop-down list.

Figure 7-7 provides an example of the input-output scenario for activating RMSs in response to rain during off-peak hours.

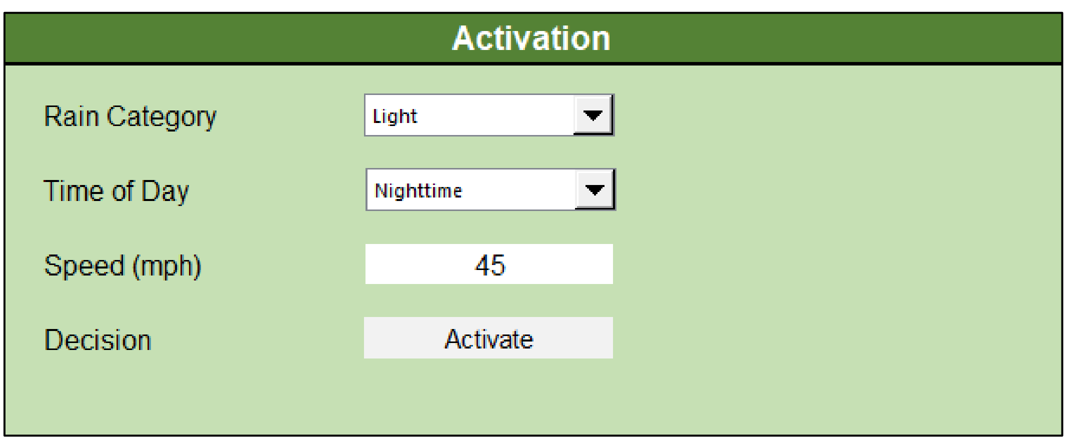


Figure 7-7: Sample Input-Output for RMS Activation during Rain

Error Checks
All inputs must be entered to obtain the results. The worksheet will return an error message if one or more input attribute(s) is not selected or keyed-in, as shown in Figure 7-8.

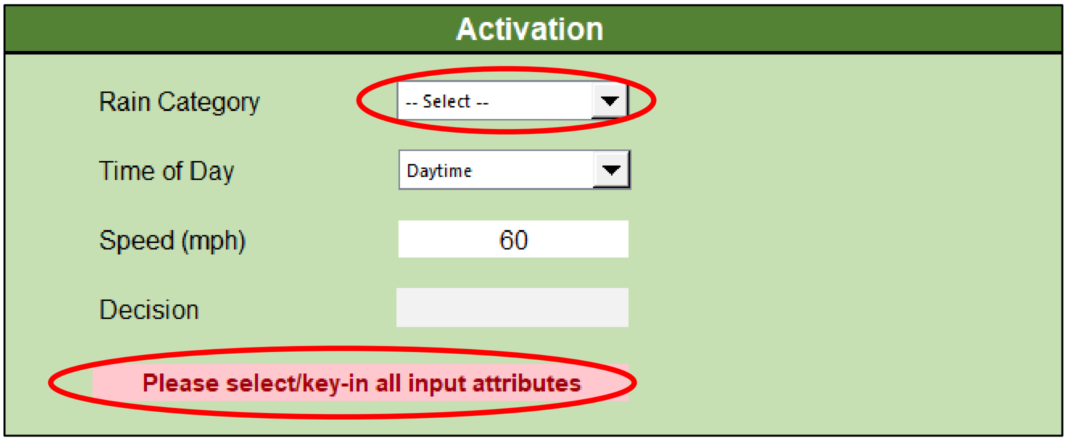


Figure 7-8: Sample Input Error Check for RMS Activation during Rain

7.2.4 Deactivation of RMSs in Response to Rain during Off-peak Hours

Input Variables: The speed variable is added by filling in the Tool cells with the white background. Other input variables are categorical and are added by selecting categories that represent the best possible condition from their respective drop-down lists.

Categorical variables

- Rain Stopped: Please select from the respective drop-down list.
- Rain Category: Please select from the respective drop-down list.
- Time of Day: Please select from the respective drop-down list.

Figure 7-9 provides an example of the input-output scenario for deactivating RMSs in response to rain during off-peak hours.

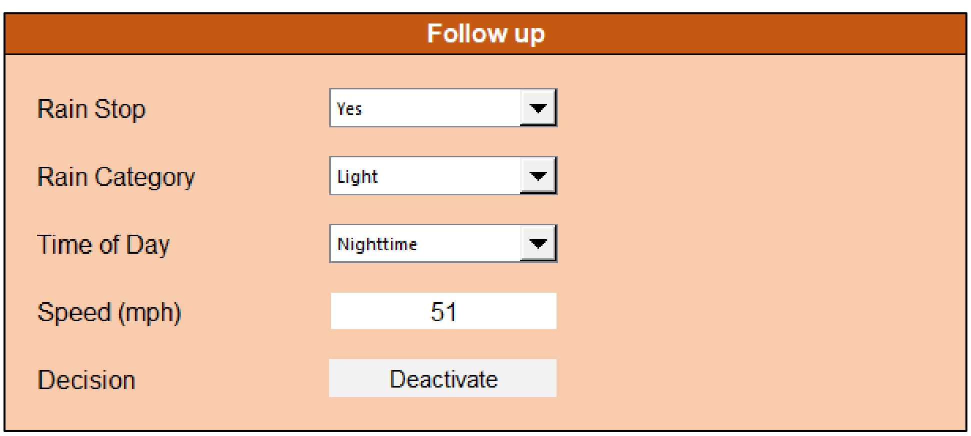


Figure 7-9: Sample Input-Output for RMS Deactivation during Rain

Error Checks

All inputs must be entered to obtain the results. The worksheet will return an error message if one or more input attribute(s) is not selected or keyed-in, as shown in Figure 7-10.

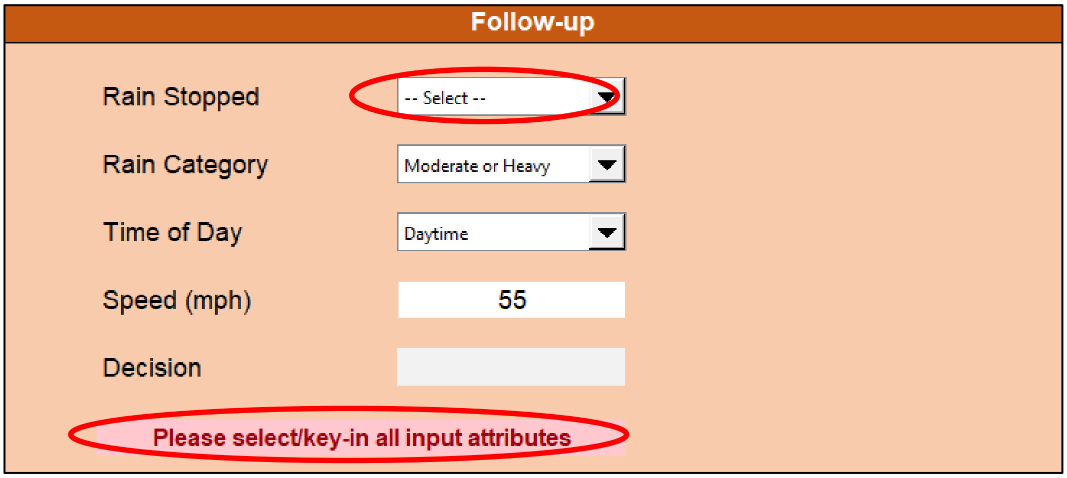


Figure 7-10: Sample Input Error Check for RMS Deactivation during Rain

7.2.5 Activation of RMSs in Response to Incidents on Weekends

Input Variables: All variables are categorical. Categorical input variables are added by selecting categories that represent the best possible condition from their respective drop-down lists.

Categorical variables

- Lane Blockage: Please select from the respective drop-down list.
- Ramp Volume: Please select from the respective drop-down list.
- Mainline Volume: Please select from the respective drop-down list.
- Speed: Please select from the respective drop-down list.

Figure 7-11 provides an example of the input-output scenario for activating RMSs in response to incidents on weekends.

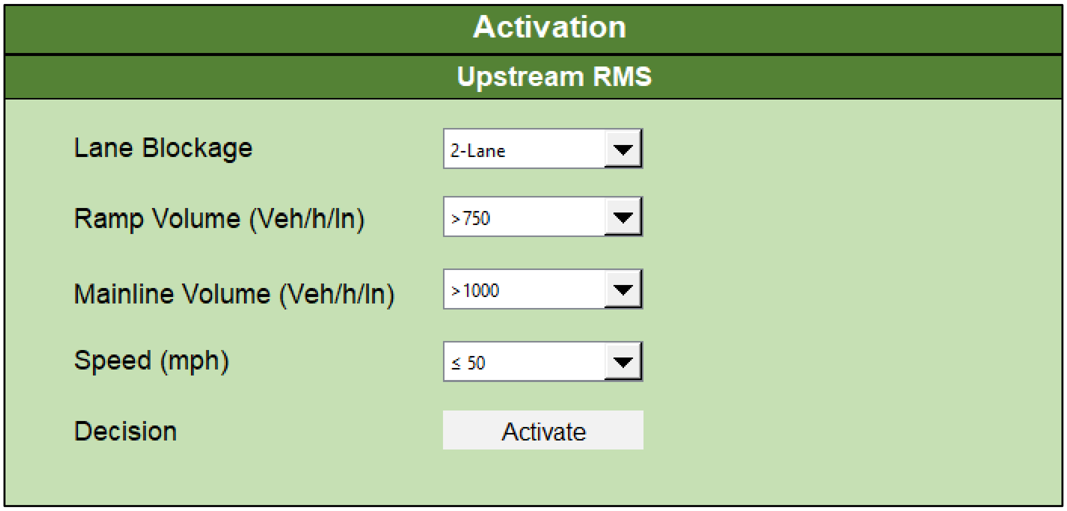


Figure 7-11: Sample Input-Output for RMS Activation on Weekends

Error Checks

All inputs must be entered to obtain the results. The worksheet will return an error message if one or more input attribute(s) is not selected or keyed-in, as shown in Figure 7-12.

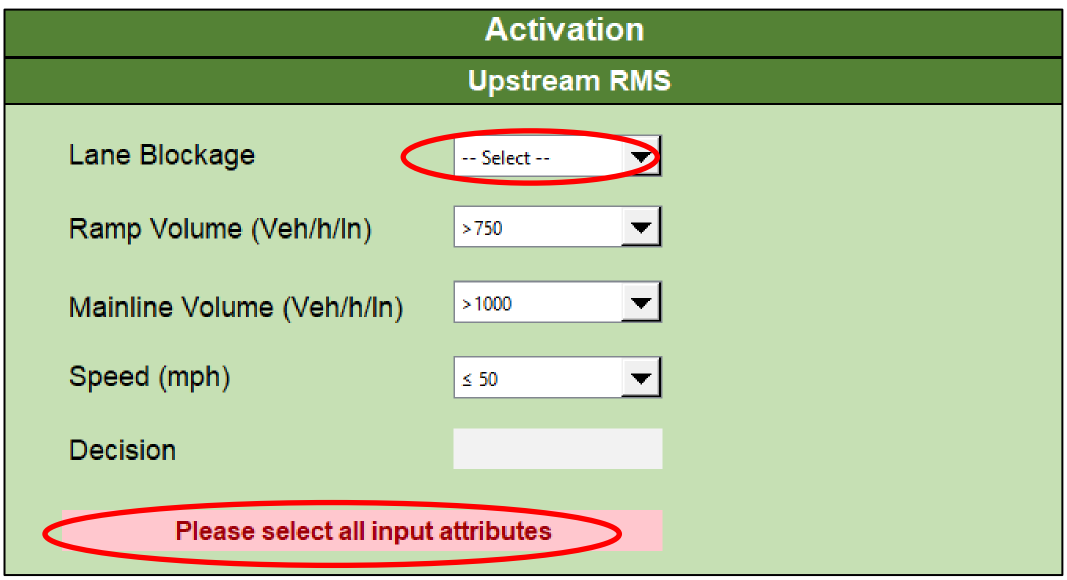


Figure 7-12: Sample Input Error Check for RMS Activation on Weekends

7.2.6 Deactivation of RMSs in Response to Incidents on Weekends

Input Variables: All variables are categorical. Categorical input variables are added by selecting categories that represent the best possible condition from their respective drop-down lists.

Categorical variables

- Incident Cleared: Please select from the respective drop-down list.

- Lane Blockage: Please select from the respective drop-down list.
- Speed: Please select from the respective drop-down list.

Figure 7-13 provides an example of the input-output scenario for activating RMSs on weekends.

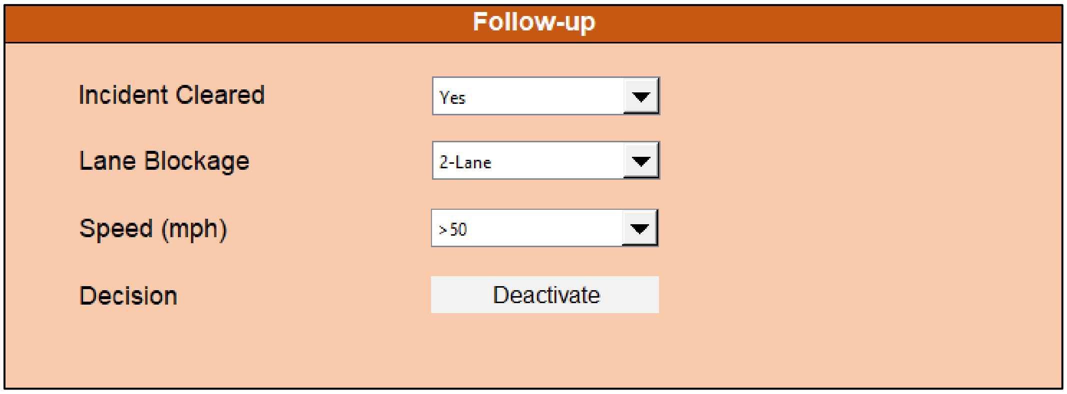


Figure 7-13: Sample Input-Output for RMS Deactivation on Weekends

Error Checks

All inputs must be entered to obtain the results. The worksheet will return an error message if one or more input attribute(s) is not selected or keyed-in, as shown in Figure 7-14.

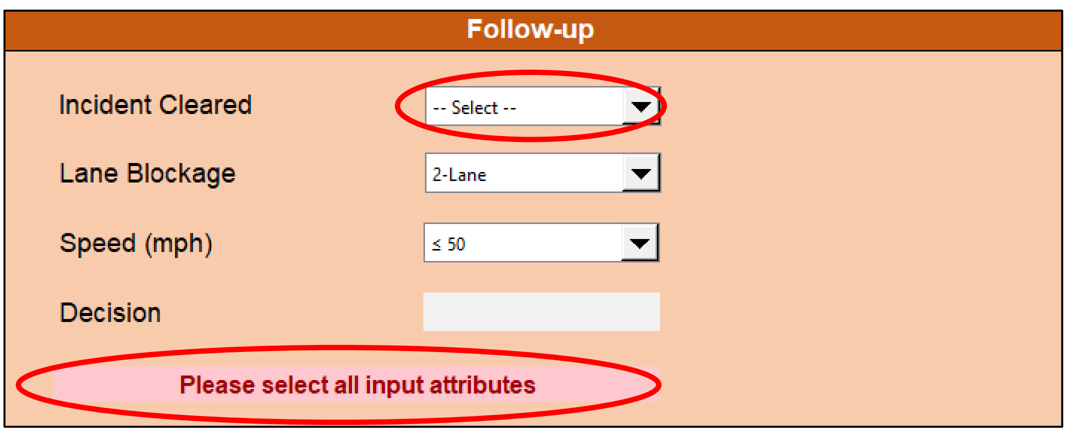


Figure 7-14: Sample Input Error Check for RMS Deactivation on Weekends

CHAPTER 8
RECOMMENDED ACTIVATION AND DEACTIVATION GUIDELINES

This chapter presents the recommended guidelines pertaining to activating and deactivating RMSs in response to incidents and adverse weather during off-peak hours and on weekends. These guidelines are recommended to be included in the FDOT District Six Standard Operating Guidelines (SOGs). The recommended guidelines are based on the analysis conducted in Chapters 4 and 5 of this report.

8.1 System Turn-on

The system turn-on was described in Section 6.7.3 of the SOGs. The section explains the guidelines used to turn on ramp signals during daily operation. In addition to these guidelines, the following guidelines could be included for consideration for activating RMSs during off-peak hours and on weekends. As described in the existing SOGs, the RMS Operator shall closely monitor traffic conditions on the freeway via the appropriate CCTVs and express lane module (ELM) and use the following criteria to turn on ramp signals.

8.1.1 Incidents Resulting in at Least One Lane Blockage

During daytime off-peak periods: If the average speed of the detector upstream of the incident location drops below 45 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned on. The RMS downstream of the incident location should be turned on if the average speed of the detector downstream of the incident location drops below 35 mph for a consistent 5-minute period.

During nighttime off-peak periods: If the average speed of the detector upstream of the incident location drops below 50 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned on. The RMS downstream of the incident location should be turned on if the average speed of the detector downstream of the incident location drops below 35 mph for a consistent 5-minute period.

Weekends: If the average speed of the detector upstream of the incident location drops below 50 mph, freeway mainline traffic volume is above 1000 veh/hr/ln, and the ramp volume is above 750 veh/hr/ln, the RMS that is upstream of the incident location should be turned on. Note that the SOGs for weekends are applicable only for incidents where at least two lanes are blocked.

8.1.2 Incidents with no Lane Blockage

During daytime off-peak periods: If the average speed of the detector upstream of the incident location drops below 50 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned on. The RMS downstream of the incident location should be turned on if the average speed of the detector downstream of the incident location drops below 35 mph for a consistent 5-minute period.

During nighttime off-peak periods: If the average speed of the detector upstream of the incident location drops below 35 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned on. The RMS downstream of the incident location should be turned on if the average speed of the detector downstream of the incident location drops below 35 mph for a consistent 5-minute period.

8.1.3 Light Rain

During daytime off-peak periods: The RMS should be turned on if the average speed drops below 55 mph for a consistent 5-minute period.

During nighttime off-peak periods: The RMS should be turned on if the average speed drops below 45 mph for a consistent 5-minute period.

8.1.4 Moderate or Heavy Rain

During daytime off-peak periods: The RMS should be turned on if the average speed drops below 50 mph for a consistent 5-minute period.

During nighttime off-peak periods: The RMS should be turned on if the average speed drops below 40 mph for a consistent 5-minute period.

8.2 System Turn-off

The system turn-off was described in Section 6.7.7 of the SOGs. The section explains the guidelines used to turn off ramp signals during daily operations. In addition to the existing guidelines as presented in the SOGs, the following guidelines could be included for consideration for deactivating RMSs during off-peak hours and on weekends. As described in the existing SOGs, the RMS Operator shall closely monitor traffic conditions on the freeway via the appropriate CCTVs and ELM and use the following criteria to turn off ramp signals.

8.2.1 Incidents Resulting in at Least One Lane Blockage

During daytime off-peak periods: Once the incident is cleared and the average speed of the detector upstream of the incident location exceeds 45 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned off. The RMS downstream of the incident location should be turned off once the average speed of the detector downstream of the incident location exceeds 35 mph for a consistent 5-minute period.

During nighttime off-peak periods: Once the incident is cleared and the average speed of the detector upstream of the incident location exceeds 50 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned off. The RMS downstream of the incident location should be turned on once the average speed of the detector downstream of the incident location exceeds 35 mph for a consistent 5-minute period.

Weekends: Once the incident is cleared and the average speed of the detector upstream of the incident location exceeds 50 mph, the RMS that is upstream of the incident location should be turned off.

8.2.2 Incidents with no Lane Blockage

During daytime off-peak periods: Once the incident is cleared and the average speed of the detector upstream of the incident location exceeds 50 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned off. The RMS downstream of the incident location should be turned off once the average speed of the detector downstream of the incident location exceeds 35 mph for a consistent 5-minute period.

During nighttime off-peak periods: Once the incident is cleared and the average speed of the detector upstream of the incident location exceeds 35 mph for a consistent 5-minute period, the RMS that is upstream of the incident location should be turned off. The RMS downstream of the incident location should be turned off once the average speed of the detector downstream of the incident location exceeds 35 mph for a consistent 5-minute period.

8.2.3 Light Rain

During daytime off-peak periods: The RMS should be turned off once the rain stops and the average speed exceeds 55 mph for a consistent 5-minute period.

During nighttime off-peak periods: The RMS should be turned off once the rain stops and the average speed exceeds 45 mph for a consistent 5-minute period.

8.2.4 Moderate or Heavy Rain

During daytime off-peak periods: The RMS should be turned off once the rain stops and the average speed exceeds 50 mph for a consistent 5-minute period.

During nighttime off-peak periods: The RMS should be turned off once the rain stops and the average speed exceeds 40 mph for a consistent 5-minute period.

CHAPTER 9
SUMMARY AND CONCLUSIONS

To address growing congestion on U.S. freeways, transportation agencies are implementing TSM&O strategies to optimize the capacity of the existing and planned transportation infrastructure for all modes of transportation to improve safety and reduce congestion. Ramp metering is a TSM&O strategy that utilizes signals installed at freeway on-ramps to dynamically manage traffic entering the freeway. RMSs are usually activated during peak hours to alleviate recurring congestion. However, the recurrent congestion during peak hours constitutes less than half of all congestion.

The primary goal of this research was to develop specific guidelines and criteria to activate ramp meters in response to non-recurring congestion during off-peak hours and on weekends. The proposed guidelines will enable FDOT District Six to use ramp metering to improve traffic operations and safety during off-peak hours and on weekends. The study results and the developed Microsoft Excel® application could also be leveraged across Florida, where ramp metering will be employed.

Specific objectives of this research included:

- Develop specific procedures to identify operational conditions that justify activating ramp meters during off-peak hours and on weekends.
- Quantify the potential benefits of activating ramp meters in response to non-recurring congestion during off-peak hours and on weekends.

9.1 Guidelines for Activating and Deactivating RMSs during Off-peak Hours

Real-time traffic data were used to develop the guidelines for activating and deactivating RMSs in response to incidents and adverse weather conditions (i.e., rain) during off-peak hours on weekdays.

9.1.1 Guidelines for Activating and Deactivating RMSs in Response to Incidents during Off-peak Hours

The RMS activation and deactivation guidelines were developed based on the incidents that resulted in at least one lane blockage and those that did not require lane blockage. In both cases, the guidelines were developed separately for daytime off-peak periods and nighttime off-peak periods. The developed guidelines are as follows:

Incidents resulting in at least one lane blockage

Daytime off-peak periods: The RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 45 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 45 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs upstream of the incident location may be activated when the average speed on the mainline drops below 50 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 50 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Incidents with no lane blockage

Daytime off-peak periods: The RMSs upstream of the incident may be activated when the average speed on the mainline drops below 50 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 50 mph for a consistent 5-minute period. In contrast, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs upstream of the incident may be activated when the average speed on the mainline drops below 35 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period. Conversely, the first adjacent RMS downstream of the incident location may be activated when the average speed on the mainline drops below 35 mph for a consistent 5-minute period and deactivated when the incident has been cleared and the average mainline speed reaches 35 mph for a consistent 5-minute period.

9.1.2 Guidelines for Activating and Deactivating RMSs in Response to Rain during Off-peak Hours

The RMS activation and deactivation guidelines were developed based on two rain categories. The first category consisted of light rain, and the second category comprised moderate or heavy rain. In both cases, the guidelines were developed separately for daytime off-peak periods and nighttime off-peak periods. The developed guidelines are as follows:

Light rain

Daytime off-peak periods: The RMSs may be activated when the average speed drops below 55 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 55 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs may be activated when the average speed drops below 45 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 45 mph for a consistent 5-minute period.

Moderate or heavy rain
Daytime off-peak periods: The RMSs may be activated when the average speed drops below 50 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 50 mph for a consistent 5-minute period.

Nighttime off-peak periods: The RMSs may be activated when the average speed drops below 40 mph for a consistent 5-minute period and deactivated when the rain stops and the average speed reaches 40 mph for a consistent 5-minute.

9.2 Guidelines for Activating and Deactivating RMSs in Response to Incidents on Weekends

A microscopic simulation approach was used to develop the guidelines for activating and deactivating RMSs in response to incidents on weekends. The two incident scenarios, i.e., with 2-lane and 3-lane blockage, were modeled in VISSIM to represent the actual incident scenarios. These developed guidelines will enable FDOT District Six to use ramp metering to improve traffic operations and safety on weekends. The developed guidelines are as follows:

Incidents with 2-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 800 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,050 veh/hr/ln, and
    c. Average speed on the mainline drops below 50 mph.

- Deactivate if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

Incidents with 3-lane blockage

- Activate the RMSs upstream of the incident location if all of the following three conditions are met:
    a. Ramp traffic volume exceeds 750 veh/hr/ln,
    b. Freeway mainline traffic volume exceeds 1,000 veh/hr/ln, and
    c. Average speed on the mainline drops below 50 mph.

- Deactivate if the incident has been cleared and when the average speed on the mainline reaches 50 mph.

9.3 Potential Benefits of Activating RMSs in Response to Non-recurring Congestion

The potential benefits of activating RMSs in response to non-recurring congestion during off-peak hours and on weekends were quantified based on the developed guidelines. The potential benefits of activating RMSs during off-peak hours and weekends are discussed in the following subsections.

9.3.1 Benefits of Activating RMSs in Response to Incidents during Daytime Off-peak Hours

Overall, the results suggested that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 45%. This implies that activating the first RMS upstream of the incident location could help improve traffic flow conditions. However, based on the analysis, the results suggested that it might not be necessary to activate the RMSs further upstream and the first RMS downstream of the incident location to improve traffic flow conditions.

9.3.2 Benefits of Activating RMSs in Response to Incidents during Nighttime Off-peak Hours

Overall, the findings suggest that activating the first RMS upstream of the incident location decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 82%. Similarly, activating the first RMS downstream of the incident location reduced the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 35%. These findings suggest that activating the first RMS upstream and downstream of the incident location could help improve traffic flow conditions.

9.3.3 Benefits of Activating RMSs during Rain

Overall, activating RMSs decreased the likelihood of traffic flow conditions changing from the *transition flow state* to the *congested flow state* by 83% during daytime off-peak periods. On the other hand, findings showed that activating RMSs reduced the likelihood of traffic flow conditions changing from the *transition flow states* to the *congested flow state* by 97% during nighttime off-peak periods. These findings imply that activating the RMSs could help improve traffic flow conditions during moderate or heavy rain.

9.3.4 Benefits of Activating RMSs in Response to Incidents on Weekends

The analysis results suggested that activation of RMSs in response to an incident on weekends increased the average speed by at least 7%. Also, activation of RMSs was found to reduce the average delay of vehicles on the freeway network by at least 15%.

9.4 Tool for the RMS Activation and Deactivation Guidelines during Off-peak Hours and Weekends

In addition, a tool for the RMS activation and deactivation guidelines during off-peak hours and on weekends was developed in Microsoft Excel®. A user manual for the tool is included in this report. The tool is intended to provide support and guidance to ramp metering operators in FDOT District Six to identify the need for activating or deactivating the RMSs during off-peak hours and on weekends.

The Tool contains a total of six worksheets:

- Preface – includes a foreword, acknowledgments, and a disclaimer.

- Instructions – provides a brief overview of RMS and descriptions of the input variables required for activation and deactivation of the RMS.
- Worksheets for RMS activation and deactivation guidelines – includes a separate worksheet for RMS activation due to incidents, rain, and on weekends.
- Info worksheet – includes a summary of the RMS activation and deactivation guidelines.

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