BEST PRACTICES FOR WORK ZONE SAFETY DURING TRAFFIC CONTROL PLACEMENT, REMOVAL, AND MODIFICATION – PHASE II

Final Report

PROJECT SPR 839

Oregon Department of Transportation

BEST PRACTICES FOR WORK ZONE SAFETY DURING TRAFFIC CONTROL PLACEMENT, REMOVAL, AND MODIFICATION – PHASE II

Final Report

PROJECT SPR 839

by

John Gambatese, PhD, PE(CA), Serey Raksa Moeung, Wei-Hsuen Lee, and Qichang Dai

School of Civil and Construction Engineering
Oregon State University
101 Kearney Hall
Corvallis, OR 97331

for

Oregon Department of Transportation
Research Section
555 13th Street NE, Suite 1
Salem OR 97301

and

Federal Highway Administration
1200 New Jersey Avenue SE
Washington, DC 20590

August 2023

Technical Report Documentation Page

1. Report No. FHWA-OR-RD-24-04	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Best Practices for Work Zone Safety during Traffic Control Placement, Removal, and Modification		5. Report Date February 2024 6. Performing Org. Code
7. Author(s) John A. Gambatese, 0000-0003-3540-6441 Serey Raksa Moeung, 0000-0003-1729-6146		8. Performing Organization Report No.
9. Performing Organization Name and Address Oregon Department of Transportation Research Section 555 13th Street NE, Suite 1 Salem, OR 97301		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Oregon Dept. of Transportation Research Section 555 13th Street NE, Suite 1 Salem, OR 97301	Federal Highway Admin. 1200 New Jersey Avenue SE Washington, DC 20590	13. Type of Report and Period Covered Final – Phase II 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract:

The set-up, removal, and modification of temporary work zone traffic control on multi-lane, high-speed roadways can create hazardous exposures for workers and motorists. A comprehensive literature review on the topic reveals a lack of a standard process and detailed guidance for setting up and removing traffic control. This study aimed to investigate the safety hazards and risk present during set-up, removal, and modification of temporary traffic control, and identify practices for improving safety during traffic control deployment and removal. Based on a survey of state DOT and roadway contractor personnel, the traffic control activities that present the highest risk are placement of the initial signs and merging taper, retrieval of knocked over cones and barrels in a live traffic lane, and set-up and removal of traffic control near an open on-ramp. Case study investigations were conducted of three recommended treatments – electronic roadway flares, a PCMS, and a radar speed sign – placed in the shoulder upstream of the Road Work Ahead (RWA) sign. Statistical analyses of vehicle speed data reveal that mean speed decreased at the treatment location with the treatments present, and mean speed differential was greater with the treatments present. It is recommended that state DOTs and roadway contractors incorporate placement of the treatments upstream of the RWA sign for traffic control to enhance safety during traffic control set-up and removal on multi-lane, high-speed roadways.

17. Key Words: Work zone set-up, Traffic control removal, Temporary traffic control installation, Temporary traffic control		18. Distribution Statement Copies available from NTIS, and online at www.oregon.gov/ODOT/TD/TP_RES/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 153	22. Price

Technical Report Form DOT F 1700.7 (8-72) Reproduction of completed page authorized Printed on recycled paper.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
M	meters	3.28	feet	ft
M	meters	1.09	yards	yd
Km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
Ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
Ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
G	grams	0.035	ounces	oz
Kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

This research study was funded by the Oregon Department of Transportation (ODOT). The authors thank ODOT for its support and input provided to conduct the research. The Technical Advisory Committee members are:

Jon Lazarus, Oregon Department of Transportation (ODOT)

Justin King, Oregon Department of Transportation (ODOT)

Nick Fortey, Federal Highway Administration (FHWA)

William Warner, Oregon Department of Transportation (ODOT)

Cory Hamilton, Oregon Department of Transportation (ODOT)

Casey Evans, Oregon Department of Transportation (ODOT)

Darrin Neavoll, Oregon Department of Transportation (ODOT)

The authors would also like to thank all of the participants in the focus group interviews, and the ODOT and construction personnel who assisted the researchers during the field site observations and case study data collection. Your assistance made it possible to complete the study successfully.

DEDICATION AND RECOGNITION

The research efforts and outcomes of this study are dedicated to those workers and motorists who have been injured or lost their lives in highway maintenance and construction work zones. Our work is dedicated to their lives and to preventing additional worker and motorist injuries and fatalities in the future.

The authors would also like to recognize former TAC member Dennis Barlow who sadly passed away during the course of this study. Dennis's dedication to improving worker safety through his long career in roadway construction and at the Associated General Contractors Oregon-Columbia Chapter provides inspirational guidance to all involved in roadway construction.

DISCLAIMER

This document is disseminated under the sponsorship of the Oregon Department of Transportation and the United States Department of Transportation in the interest of information exchange. The State of Oregon and the United States Government assume no liability of its contents or use thereof. The contents of this report reflect the view of the authors who are solely responsible for the facts and accuracy of the material presented. The contents do not necessarily reflect the official views of the Oregon Department of Transportation or the United States Department of Transportation. The State of Oregon and the United States Government do not endorse products of manufacturers. Trademarks or manufacturers' names appear herein only because they are considered essential to the object of this document. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

Construction and maintenance work zones on active roadways require implementing temporary traffic control to safely modify the travel path, warn drivers of the work taking place, and protect both the workers and drivers during the work operations. Traffic control personnel work diligently to place the required traffic control devices on the roadway and remove it after the work is complete. The temporary traffic control may also need to be modified during construction. During these work operations, the workers installing, removing, and modifying the traffic control devices are often exposed to additional risk and/or different hazards than during the course of the work after the traffic control is set up. In addition, during the set-up and removal periods, passing motorists are transitioning from the normal traffic flow and patterns to the temporary traffic flow and patterns, or vice versa. These transition periods can expose workers to hazardous conditions, create confusion about the driving path, distract drivers, and alter the driving path such that a queue temporarily develops and presents both safety and mobility impacts.

Phase I of the research study reported on present knowledge and practices related to temporary traffic control set-up and removal. The Phase I report (Gambatese & Moeung, 2022) described the temporary work zone traffic control devices commonly used, govering traffic control regulations and standards, recommended procedures for setting up and removing traffic control, variables to consider when designing set-up and removal operations, and a comparison of nighttime and daytime risks when setting up and removing traffic control. The literature review conducted as part of Phase I and presented in the interim report also explored safety risk before and during work zone construction, and the time required for traffic control set-up and removal. Based on all of the archival information reviewed, there still remains a lack of information about consensus best practices for traffic control set-up and removal.

Following the literature review, the researchers conducted industry survey to identify current practices and worker perspectives of the risk exposures during work zone set-up and removal. The survey results are presented in the Phase I report (Gambatese & Moeung, 2022). According to the perspectives of the survey respondents, safety risk for both motorists and workers is particularly high when there is difficulty access a lane or blocking traffic, when there is a lack of space available for workers or equipment, when the speed of passing vehicles is high, and when drivers exhibit aggressive driving behavior. Treatments (i.e., traffic control measures) suggested to mitigate the risk, shown in the Phase I report, both pre-condition the drivers before they enter the work zone and maintain safe and consistent driving behavior while they are in the work zone. Some treatments are designed to improve efficiency and safety controls used during the traffic control operation. Most of the suggested treatments are implemented on the roadway, equipment, or worker, and represent engineering controls. The researchers then matched the treatments to the high- and moderate-risk conditions during traffic control set-up and removal based on the ability of the treatment to migate the impacting condition. For example, flashing blue lights located on equipment help to mitigate the risk associated with the high speed of passing vehicles, aggressive drivers, and lack of light during nighttime work. The results, shown in the Phase I report, reveal that most of the recommended treatments positively influence high vehicle speed and aggressive drivers.

The goal of the overall research study is to develop additional knowledge and guidance for state transportation agencies and contractors that can be used to improve driver and worker safety on roadways, specifically during the set-up, removal, and modification of temporary work zones on high-speed roadways. The initial research activities reported in the Phase I report provided a base level of knowledge regarding the traffic control practices used, high-risk conditions, and potential mitigating treatments. To augment the literature review and survey results with more detailed and quantitative data, the research study included multiple additional research tasks using other complementary research methods. This Phase II report supplements the Phase I report. It presents the results of the additional research activities, along with conclusions from the overall study and recommendations for application in practice. Specifically, Phase II utilized the results of Phase I to conduct in-depth investigation of risk exposures and potential interventions. The case study investigations in Phase II included experiments in which three highly promising treatments were examined closely to evaluate their applicability and potential benefit. Lastly, Phase II included the development of conclusions and recommendations from the overall study. The specific content included in the Phase I and Phase II reports is as follows:

- Phase I report:
  - Problem Statement, Research Objectives, Benefits, Implementation
  - Literature Review
  - Survey of Current Practice
  - Updated Methodology
- Phase II report:
  - Observations of Construction and Maintenance Operations
  - Focus Group Interviews
  - Case Study Investigations
  - Overall Conclusions and Recommendations

2.0 RESEARCH METHODS

Following completion of the industry survey, the additional research activities included observations of ongoing construction and maintenance operations, focus group interviews of ODOT and industry personnel, and field evaluations of selected treatments on case study projects.

2.1 OBERSERVATIONS OF CONSTRUCTION AND MAINTENANCE OPERATIONS

The purpose of the field observations was to capture the actual worksite setting during traffic control placement and removal as well as to record hazardous situations that pose safety concerns for workers and motorists. In accordance with the ODOT work plan, three projects based in Oregon were to be selected for the field observations. First, the researchers reviewed the ODOT website to identify on-going roadway construction and maintenance projects that required a short-term traffic control operation and were possibly available for the observation. The review of the ODOT website revealed a list of 20 projects located in Oregon that were potential candidates for field observations. Among those 20 projects, only three projects were chosen for the observation:

- Project 1: I-5 paving between I-205 and Boone Bridge
- Project 2: I-5 road surfacing, Milepost 216-235
- Project 3: I-405 fence repair on Marquam Bridge

The selection of the projects was made based on input from the TAC members and were selected according to the following criteria: project involvement with a work zone traffic control set-up and removal operation, proximity of project work location, type of roadway (e.g., freeway or highway), and whether the project schedule was within the research study's timeline. For the three selected projects, the researchers collaborated with the ODOT project representative and contacted the roadway contractor who was primarily responsible for the project tasks to discuss current work progress on the project, possible dates and times for a field visit, safety precautions needed for the visit, and expectations of the field observations (e.g., purpose of the observation for the research study and how the observation process will be executed).

The observation process was identical for all the three observed projects. On the day of each field observation, the roadway construction field staff were asked to conduct their work operation according to their plan without any changes made or treatments applied. To retain the information from the observation, the researchers used several data collection methods such as in-person interviews, note-taking, photographing, and videotaping of the traffic control work activities from inside a work vehicle, inside a personal vehicle, and/or a safe location in the right of way.

2.2 FOCUS GROUP INTERVIEWS

The purpose of conducting the focus group interviews was to gain additional knowledge from ODOT and industry personnel of hazards related to traffic control operations, explore remedies to reduce risks in the traffic control operation, and identify focus areas of the study that the researchers should put more attention on to improve safety during traffic control set-up, removal, and modification. The targeted audiences of the focus group interviews were Oregon Department of Transportation personnel and Oregon roadway construction and roadway maintenance contractors.

First, invitational emails which included Doodle poll links were created and sent to both groups along with a sample of the focus group interview questions that was prepared in advance. The purpose of sending the interview questions to the participants in advance was to provide sufficient time for the participants to think about and prepare their answers. The Doodle poll link included in the invitational emails allowed the participants to indicate their availability for the interview. Then, to increase participation, follow-up emails were distributed to potential participants to remind them to indicate their availability on the poll.

To conduct the focus group interviews, the researchers split up the focus group interviews into two sessions, one for ODOT personnel and the other for roadway contractors that are based in Oregon. The chosen date of the interview for each group was made based on the results received from the majority of participants who indicated their availability for an interview in the Doodle poll. Each group was interviewed separately on different dates via an online Zoom meeting. Due to time constraints, both groups were asked similar questions, approximately seven to nine questions including follow-up questions. The questions guided the discussion towards the following content:

- For those traffic control activities/tasks identified in the previous tasks, the safety issues associated with each activity/task
- The perceived relative risk associated with each traffic control activity/task
- Ideas for how to change the traffic control operation in a way to mitigate the perceived risks associated with traffic control placement and removal.
- Traffic control set-up and removal safety improvements that the researchers should focus on for the research study.
- Traffic control quality control (Contractor focus group only)
- Traffic control quality assurance (ODOT focus group only)

The researchers recorded the discussions for subsequent analysis. The analysis targeted common trends and themes that were exposed during the focus group discussions. Where possible, quantitative and qualitative measures from the literature and ODOT sources were also used to quantify risks. For example, near misses and crashes that are reported by ODOT Maintenance personnel could be reviewed to identify the traffic control conditions and actions in which safety issues commonly occur. This information, along with the extent to which the traffic control operations take place, can be used to assess the risk associated with specific parts of the operation.

During the course of the research, the researchers also received commentary from an FHWA roundtable discussion on traffic control operations. The commentary provided additional insights into practices implemented in other states. A summary of the commentary is provided for additional context as well.

2.3 CASE STUDY INVESTIGATIONS

The results of the literature review and survey reported in the Phase I report highlight points in the traffic control set-up and removal process in which further risk mitigation measures are needed or warranted, along with promising means to mitigate the risk. The last step of the research study was to conduct detailed investigations of promising traffic control measures on actual roadway projects. The research method chosen for this task was an experimental process in which selected traffic control measures (treatments) are implemented during traffic control set-up and removal operations to assess their impacts on vehicle speeds and their feasibility of implementation.

2.3.1 Selection of Traffic Control Measures to Evaluate

To begin the experimental process, the researchers identified an initial list of potential traffic control measures based on results and feedback from the ODOT and contractor survey, site observations, and focus group interviews. The identified traffic control measures are listed below, and comprised the potential options for consideration to study further as part of the case study investigations:

- Place multiple portable radar speed signs in the following areas: upstream of the initial warning sign placement, prior to the taper, within the work zone, and at on-ramps.
- Mount flashing blue lights on barrels/drums in the merging taper area.
- Attach a warning device, such as sensor device or proximity alert system, to alert nearby workers of a backing-up truck.
- Deploy law enforcement at the initial sign set-up area in the work zone.
- Utilize an automatic cone retrieval truck.
- Implement a railway crossing gate control at on-ramp entrances or use red traffic lights at on-ramps to stop traffic entering the on-ramps when workers are setting-up traffic control devices near the on-ramps.
- Use a mobile barrier when operating work zone closures near curved road structures.

- Provide public service announcements of work zones in advance of the work (e.g., provide a message of the upcoming roadwork activity on a PCMS one month before the road construction or maintenance starts).

- Use a rolling slow down for setting up the first sign in a work zone.

- Extend the merging taper length to allow more time for drivers to react to or merge into the through lane.

- Provide a magnetic base for cones to prevent the cones from being knocked over.

- Utilize a truck equipped with a barrel mover to move barrels from the roadside to the lane in a work zone, or vice versa, instead of moving the barrels using workers on foot.

- Install additional advance warning signs when the road is curvy or in hazardous weather conditions such as snow or heavy rain.

- Use highly visible or reflective material for cones and barrels in a work zone, especially for the taper.

- Place flashing yellow lights on cones that are located close to on-ramps to attract the attention of road users entering/exiting the roadway.

As described in the Phase I report, to assist in making decisions about the identified traffic control measures, the researchers developed a table (presented herein as Table 2.1 for convenience) which organizes potential control measures according to objective, type, and placement location. The table shows each control measure with its purpose, which can be used to pre-condition driving behavior before drivers enter the work zone and maintain safe driving behavior while they travel within the work zone. Of those traffic control measures suggested, some are designed to enhance efficiency and safety during the traffic control operation. Most of the control measures suggested are identified as engineering controls and are mainly implemented on the workers or the equipment.

Furthermore, the Phase I report provided a table (presented herein as Table 2.2 for convenience) to address the moderate and high risk conditions identified. The correlation shows the ability of the traffic control measures to mitigate the impacting condition. For instance, utilizing a PCMS with radar speed board and placing them before the "Road Work Ahead" sign can mitigate risk related to the high speed of passing vehicles, and aggressive driver behavior. As can be seen from the table, the majority of suggested control measures positively address the conditions that are impacted by an issue related to aggressive drivers and high vehicle speeds. As a guide for selecting control measures to implement in field operations, contractors should prioritize those that target high risk activities and consider wisely control measures based on the following criteria: availabitity, cost of implementation, duration of the actual workzone operation versus the traffic control operation, objective of the control measure, feasibility of implementation, long term and short-term effectivness, hierarchy level of control (e,g, higher level of control would be better), and ability to serve multi-purposes in risk reduction.

Table 2.1: Characterization of Recommended Traffic Control Measures (Gambatese & Moeung, 2022)

	Objective			Location				Type		Type of Control				
Traffic Control Measure	Pre-condition driving behavior before work zone	Maintenance of driving behavior in work zone	Efficient or reduced effort and improved safety controls for traffic control crew	Prior to work zone	On roadway in work zone	On equipment or worker in work zone	Other	Change in roadway, worker, or equipment feature	Change in work process or procedure	Elimination	Substitution	Engineering	Adminstation	PPE
PCMS with radar speed board located before Road Work Ahead signs	X			X				X				X		
Flashing lights on work equipment (e.g., blue lights)		X				X		X				X		
Flashing lights on roadway (e.g., electronic orange flares)	X			X								X		
Balloon lights or light towers		X			X			X				X		

Traffic Control Measure	Objective			Location				Type		Type of Control				
	Pre-condition driving behavior before work zone	Maintenance of driving behavior in work zone	Efficient or reduced effort and improved safety controls for traffic control crew	Prior to work zone	On roadway in work zone	On equipment or worker in work zone	Other	Change in roadway, worker, or equipment feature	Change in work process or procedure	Elimination	Substitution	Engineering	Adminstation	PPE
located at regular spacing in work zone														
Attach sensors to workers and equipment to give an alert when in close proximity			X			X		X				X		X
Police enforcement	X	X		X	X			X				X	X	
360° camera on every truck to view surrounding area			X			X		X				X		

Traffic Control Measure	Objective			Location				Type		Type of Control				
	Pre-condition driving behavior before work zone	Maintenance of driving behavior in work zone	Efficient or reduced effort and improved safety controls for traffic control crew	Prior to work zone	On roadway in work zone	On equipment or worker in work zone	Other	Change in roadway, worker, or equipment feature	Change in work process or procedure	Elimination	Substitution	Engineering	Adminstation	PPE
Railway crossing gate control at on-ramps			X				X	X				X		
Automatic cone retrieval truck			X			X		X	X		X	X		
Magnetic base for cones			X			X		X			X			
Mobile barrier		X	X			X		X	X			X		
Barrel mover truck			X			X		X	X		X			
Rolling slow down during traffic control operations	X			X					X	X				
Public service announcement	X	X					X		X				X	

Traffic Control Measure	Objective			Location				Type		Type of Control				
	Pre-condition driving behavior before work zone	Maintenance of driving behavior in work zone	Efficient or reduced effort and improved safety controls for traffic control crew	Prior to work zone	On roadway in work zone	On equipment or worker in work zone	Other	Change in roadway, worker, or equipment feature	Change in work process or procedure	Elimination	Substitution	Engineering	Adminstation	PPE
of work zone operations														
Highly reflective material on cones and barrels		X				X		X			X			
Extend taper length		X			X			X				X		
Provide additional advance warning signs	X			X				X				X		
Provide flashing yellow lights on cones		X				X		X				X		

Table 2.2: Relationship Between Recommended Traffic Control Measures and High And Moderate Risk Conditions (Gambatese & Moeung, 2022)

Traffic Control Measure	High Risk Conditions			Moderate Risk Conditions		
	Difficult accessing lane or blocking traffic	Lack of space available for workers or equipment	High speed of passing vehicles	Aggressive drivers	Lack of light (e.g., nighttime work)	Workers not following planned process
PCMS with radar speed board located before Road Work Ahead signs			X	X		
Flashing lights on work equipment (e.g., blue lights)			X	X	X	
Flashing lights on roadway (e.g., electronic orange flares)			X	X	X	
Balloon lights or light towers located at regular spacing in work zone					X	
Attach sensors to workers and equipment to give an alert when in close proximity		X			X	
Police enforcement	X		X	X	X	
360° camera on every truck to view surrounding area		X			X	X
Railway crossing gate control at on-ramps	X	X	X	X		
Automatic cone retrieval truck		X		X		X
Magnetic base for cones				X		

Traffic Control Measure	High Risk Conditions			Moderate Risk Conditions		
	Difficult accessing lane or blocking traffic	Lack of space available for workers or equipment	High speed of passing vehicles	Aggressive drivers	Lack of light (e.g., nighttime work)	Workers not following planned process
Mobile barrier	X		X	X		
Barrel mover truck		X				X
Rolling slow down during traffic control operations	X	X	X	X		
Public service announcement of work zone operations			X	X		
Highly reflective material on cones and barrels				X	X	
Extend taper length				X		
Provide additional advance warning signs			X	X		
Provide flashing yellow light on cones			X	X	X	

Based on multiple discussions with TAC members about the potential traffic control measures along with information about the cost, availability, and feasibility of implementing the control measures both in practice and as part of the research study, the researchers selected three traffic control measures to evaluate further as treatments in the case study evaluations. The selection targeted those potential traffic control measures that could be easily implemented, were relatively low cost, did not depart significantly from current practice, were familiar to and could be clearly interpreted by motorists, and were deemed to likely have a positive impact on reducing speed and risk during traffic control set-up and removal. Given these criteria, the following potential traffic control measures were selected:

- Electronic roadway flares,
- A portable changeable message sign (PCMS), and
- A portable radar speed sign.

All three traffic control measures help to address the high-risk condition of high-speed passing vehicles and the moderate risk condition of aggressive drivers. In addition, all three control measures could be positioned on the roadway prior to (upstream of) the location where the traffic control set-up and removal take place, and be the first traffic control measure placed on the roadway in the sequence of work operations. Their potential positive impact on safety risk, placement location, and placement timing, plus their ease of use, familiarity, accessibility, and cost, make the traffic control measures attractive for ODOT and construction contractors. Each of the three control measures is described in more detail below.

2.3.1.1 Electronic Roadway Flares

A temporary electronic roadway flare is a flashing light that is placed on a roadway to call attention to a specific hazard or help guide the motorist's path. Electronic flares typically emit orange colored light, and flash in a pre-set or programmed pattern and at a specified rate. The flares are placed directly on the roadway surface or on temporary or permanent equipment or roadway infrastructure.

A variety of different types of electronic roadway flares are publicly available. For the present study, the researchers elected to use pi-lit® Smart Sequential Road Flares (pi-lit©, 2023) as representative of flares that could be used. These flares can be programmed to automatically sequence the flash within a radio-linked network of flares. Figure 2.1 shows the set of 10 pi-lit® flares purchased for use in the study.

Figure 2.1: Electronic roadway flares used in case study investigations (pi-lit®, 2023)

Based on conversations with ODOT personnel knowledgeable about traffic control measures and designs, the plan was to place a series of five flares in a diagonal line on each roadway shoulder. The flares were to flash in a sequence from the first to the last flare in the line. Figure 2.2 shows a typical roadway work zone with A-lane closure and the recommended locations of the electronic flares and other treatments (PCMS and radar speed sign).

While the plan was to place the flares on both sides of the roadway (left and right shoulders), conversations with the site safety representative on the initial case study projects led to placing the flares on only one side of the roadway to prevent driver confusion. For example, if the A-lane (left lane) was to be closed, the flares were only placed in the left shoulder to suggest to the drivers to move to the lane to the right (B-lane), away from the closed lane. In this example, flares located on the right shoulder may be confusing to drivers and suggest that they move in the direction towards the closed lane ahead.

The actual locations of the treatments were selected by the traffic control personnel and took into consideration the roadway geometry, work operations, and other critical factors. In most cases, the electronic roadway flares were placed at the recommended locations. However, the locations of the PCMS and radar speed sign were often located where the site personnel had originally planned. In some cases, an additional PCMS or radar speed sign was added by the site personnel and located as shown in the figure.

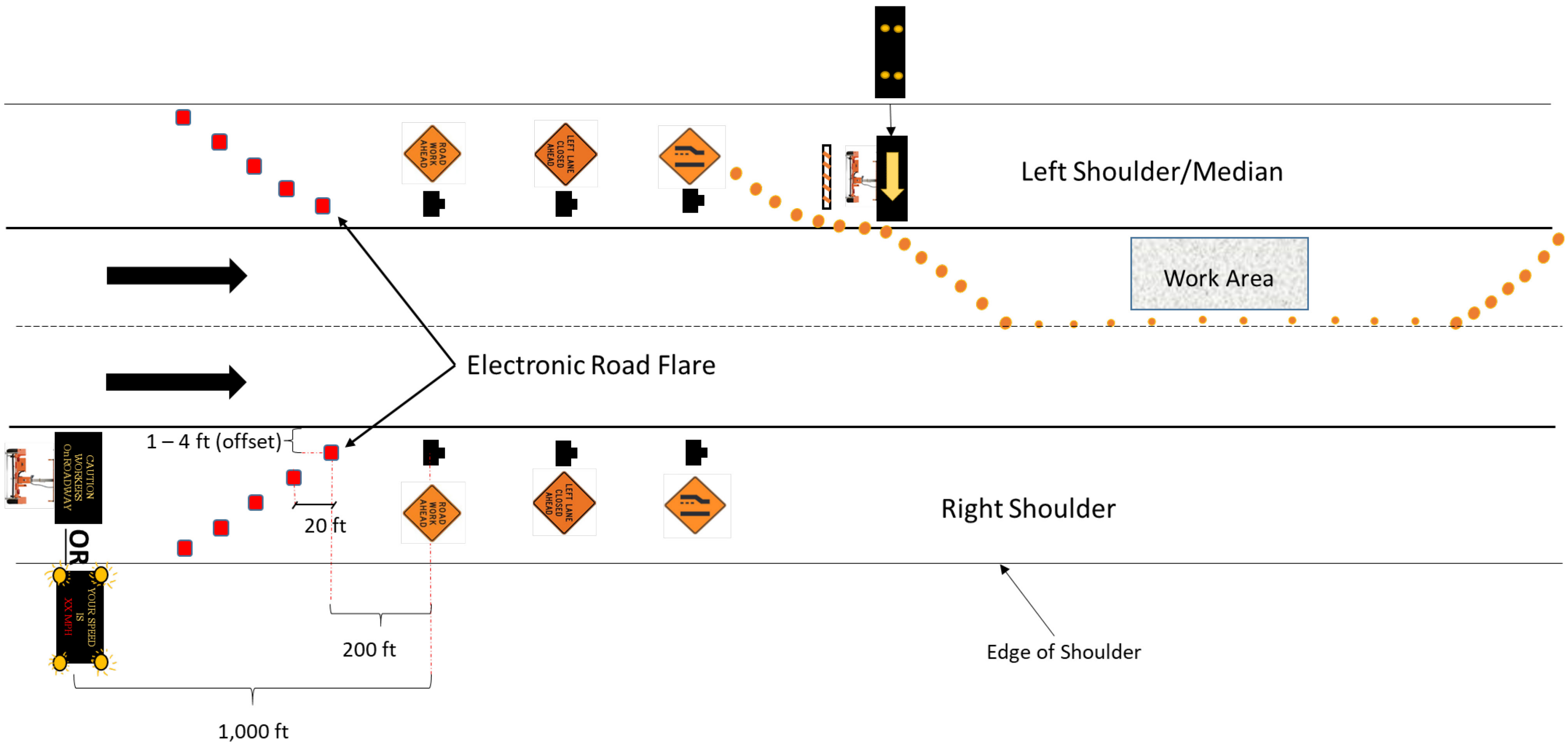


Figure 2.2: Planned locations of treatments in case study investigations

2.3.1.2 Portable Changeable Message Sign (PCMS)

A PCMS, also referred to as a portable variable message sign (PVMS), is a large electronic sign used to display programmable, dynamic messages to provide traffic with timely warnings, guidance, or notification of approaching roadway conditions (ODOT, 2018). This device can be mounted on either a trailer or work vehicle. Figure 2.3 shows examples of a PCMS. The ODOT *Portable Changeable Message Sign Handbook* (ODOT, 2018) provides guidance for the safe and effective use of PCMSs and illustrates proper set-up and delineation for a PCMS as well as provide a variety of example messages for a broad range of roadway activities.

Figure 2.3: Examples of portable changeable message signs: trailer-mounted (left) and truck-mounted (right) (ODOT, 2018)

The PCMS signs used in the study were those present on the case study projects for the work operation. The researchers did not provide additional PCMS signs for use and evaluation as part of the research study.

During the course of the case studies, the researchers asked the site personnel to place the PCMS either as typically planned (control) or upstream of the RWA signs (treatment). For the treatment, the PCMS was to be placed at least 1,000 ft upstream of the RWA signs as shown in Figure 2.2. It was also the first traffic control measure placed during the operation (i.e., before the RWA signs were placed). The PCMS could be placed on either roadway shoulder (right or left). The location of the PCMS could be modified, if needed, to account for roadway geometry, lanes to be closed, or other limiting conditions. The site personnel were asked to program the PCMS to present the following alternating messages:

- Panel 1: “Caution / Workers / on Roadway”
- Panel 2: “Slow for / Workers / in Road”

In some cases, the site personnel elected to use other pre-programmed messages typically used for the work operation rather than those suggested above.

2.3.1.3 Radar Speed Sign

A radar speed sign (also referred to as radar speed display), is a digital speed panel that shows feedback to road users of their vehicle speed along with the posted speed limit, and usually presents a message such as: “Your speed is XX mph” (Gambatese & Zhang, 2014). Portable radar speed signs may either be trailer-mounted or truck-mounted. Figure 2.4 shows an example of a trailer-mounted radar speed sign.

Figure 2.4: Example of trailer-mounted radar speed sign (Veneziano et al. 2012)

Similar to the PCMS signs, the radar speed signs used in the study were those present on the case study projects for the work operation. The researchers did not provide additional radar speed signs for use and evaluation as part of the research study.

During the course of the case studies, the researchers asked the site personnel to place the radar speed sign either as typically planned (control) or upstream of the RWA signs (treatment). For the treatment, the radar speed sign was to be placed at least 1,000 ft upstream of the RWA signs as shown in Figure 2.2. It was also the first traffic control measure placed during the operation (i.e., before the RWA signs were placed). The radar speed sign could be placed on either roadway shoulder (right or left). The location of the radar speed sign could be modified, if needed, to account for roadway geometry, lanes to be closed, or other limiting conditions. The site personnel were asked to program the speed display as they would typically do for the work operation.

2.3.2 Case Study Project Selection and Data Collection

After idenfying the three promising traffic control measures to study further, the researchers, with ODOT's assistance, identified multiple potential projects on which to implement and assess the traffic control measures (treatments). The case study projects were to be located on high-speed roadways (e.g., Interstate 5) in Oregon, and involve temporary closure of one or more lanes of traffic to allow the work to proceed. It is was expected that the traffic control design for the projects would be similar to that typically designed for construction and/or maintenance work in Oregon. The actual case study projects selected are described in Section 3.0. The three selected traffic control measures would then be implemented by the construction contractors and/or ODOT staff on each case study project. Due to the lack of control that the researchers and ODOT Research have over the contractors and ODOT staff, the schedule for implementation of the treatments was governed by the case study projects selected. The researchers aimed to select opportunities for implementation that allowed for maintaining the planned study schedule.

The researchers prepared an example testing matrix to help guide the application of the treatments on the case study projects and communicate to the site personnel the desired applications of the three treatments. The example testing matrix is provided in Table 2.3. The example shows testing over a total of 12 days on three case study projects (4 days per project). The actual number of projects and number of days per project would depend on the availability of projects and the duration of each selected project. As can be seen in the matrix, the plan was to test treatments both individually and in combination, as well as for different lane closures and on different days of the week.

Table 2.3: Example Case Study Testing Matrix

Case Study	Day	Closed Lane	Open Lane(s)	Date	Day of Week	Treatments A: TCP as planned (control)	B: Electronic roadway flares	C: PCMS	D: Radar speed display
1	Day 1	A (fast)	B (slow)		Monday	●			
	Day 2	A (fast)	B (slow)		Tuesday	●	●		
	Day 3	A (fast)	B (slow)		Wednesday	●		●	
	Day 4	A (fast)	B (slow)		Thursday	●			●
2	Day 1	B (slow)	A (fast)		Monday	●			
	Day 2	B (slow)	A (fast)		Tuesday	●	●		
	Day 3	B (slow)	A (fast)		Wednesday	●		●	
	Day 4	B (slow)	A (fast)		Thursday	●			●
3	Day 1	A (fast)	B (slow)		Monday	●			
	Day 2	A (fast)	B (slow)		Tuesday	●	●	●	
	Day 3	A (fast)	B (slow)		Wednesday	●	●		●
	Day 4	A (fast)	B (slow)		Thursday	●		●	●

Treatments:

A. TCP as planned (control): No added treatments. Typical work zone set-up and removal plan and process only.
B. Electronic road flares: Place five (5) electronic road flares on the shoulder on each side of the roadway, starting 200 feet upstream of the first advance warning sign.
C. Portable changeable message sign (PCMS): Place PCMS on the right shoulder approximately 1,000 feet upstream of the first advance warning sign. Alternating sign messages: "Caution / Workers / on Roadway" and "Slow for / Workers / in Road."
D. Radar speed display: Place radar speed display on the right shoulder approximately 1,000 feet upstream of the first advance warning sign.

On each case study project, the field staff was asked to conduct the operations according to two procedures: as originally planned and designed without the new, promising practice (control), and as revised with the promising practice (treatment). Unless fewer days of data collection were available or needed, data was collected for two days of control and two days of treatment on each case study project. The data collected on the control days was to be used as the baseline for comparison. For both the treatment and control cases, the researchers documented the operations (e.g., video record, photograph, and record pesonal observations) and recorded any observed benefits, limitations, and safety concerns. The observations and video recordings were performed from inside the work vehicles, inside the researchers' personal vehicles, and/or at a safe location in the right-of-way (e.g., on the shoulder or median) depending on the nature of the operation and the traffic and site conditions. Vehicle speeds adjacent the traffic control operations were collected through the Regional Integrated Transportation Information System (RITIS). RITIS is an automated data sharing, dissemination, and archiving system that includes many performance measures, include vehicle speeds and volumes (ODOT, n.d.). Finally, while onsite, the researchers interviewed the workers to gain their perspectives on the feasibility of the promising practices and their impact on safety.

While the intent of the research study was to include the examination of work zone safety during modification of traffic control in addition to the set-up and removal of traffic control, the researchers chose not to include an examination of traffic control modifications in the case study protocol. Traffic control modifications can be categorized into *planned* and *unplanned* modifications. *Planned* modifications constitute intentional and scheduled changes to the traffic control in place to accommodate known changes in the traffic patterns, work operations, and site conditions during the course of the work. An example of a planned modification is when an entry/exit ramp is opened up after the work during a mobile operation has moved downstream and it is safe for motorists to use the ramp to enter/exit the roadway. The researchers felt that the traffic control operations during planned modifications would be performed using processes similar to the current written protocols and guidance. In fact, when modifications occurred during the site investigations, the work operations to make the modifications proceeded generally according to the guidance described in literature. Therefore, since similar traffic control operations were being examined during set-up and removal for the case studies, no additional testing was needed during modifications in the case studies. *Unplanned* modifications are unanticipated and unforeseen changes needed to reconstruct the work zone. An example of an unplanned modification is when a traffic cone or barrel struck by a passing vehicle has to be retrieved and put back in the correct location. No unplanned modifications were observed during the case studies. Additionally, the researchers chose not to "stage" an unplanned modification specifically for the research study in order to not place motorists and workers at additional risk of injury during the test, and to not interrupt their work operations. Examination of unplanned modifications, along with potential treatments and operational protocols, could be conducted as part of a future study using a driving simulator or other research protocol.

3.0 RESULTS

This section of the report presents the results of the field observations of construction and maintenance operations, focus group interviews of ODOT and industry personnel, and field evaluations of the three selected traffic control measures on case study projects.

3.1 OBSERVATIONS OF CONSTRUCTION AND MAINTENANCE OPERATIONS

The field observations of construction and maintenance work operations were conducted to confirm and further understand the temporary traffic control set-up and removal processes, and the hazardous elements of the work process that present safety concerns to workers and motorists. The researchers additionally aimed to determine whether actual practice in the field differed from written protocols and procedures and, if so, in what circumstances did practice differ from the written guidance. As described above, three projects located in Oregon were selected for the field observations. The observation results from each of the projects is described in detail below.

3.1.1 Project 1: I-5 paving between I-205 and Boone Bridge

The project site was located on I-5 southbound between I-205 and Boone Bridge in Wilsonville, Oregon. The goal of the project was to repave the highway as well as rehabilitate the bridge structure to increase its life expectancy. The estimated total cost of the project was $9,976,289. The project construction schedule began in spring 2021 and the project was completed in late 2021. The on-going scope of work during the site observation were restriping, concrete repair, and some repaving work.

The observation took place on June 7, 2021, on a section of I-5 that contains four lanes in each direction. Three lanes were closed on southbound I-5 with each lane closed at different designated times. The researchers and contractor personnel first met at the project yard prior to departing to the work zone site, and discussed the best techniques for the observation, safety precautions that needed to be implemented, and the traffic control plan for where to begin the lane closure. How to coordinate between the work crew while performing the lane closure operation was then discussed at the field office. As stated above, the researchers documented the traffic control operation information by taking personal notes, videotaping and photographing the operation, and interviewing the traffic control crew members.

3.1.1.1 Traffic control set-up procedure

Three lanes of a section of I-5 southbound were terminated via three closure stages. The first stage was the A-lane closure, followed by the second stage to close the B-lane, and lastly the C-lane closure. The work zone traffic control set-up time varied from one stage to another due to concerns about the impacts of the closure on public vehicles. The A-lane closure started at 7:42pm, then the B-lane closure started at 9:45pm, and lastly the C-lane was closed after the B-lane was fully closed to traffic. During the observation, the researchers only observed the full process of the traffic control set-up for the A-lane and the B-lane. The lane closure processes for the A- and B-lanes were as follows:

Procedure for A-lane closure set-up:

1 Set up the advance warning signs on both sides of the roadway. The process of setting up the advance warning signs was performed by setting up the signs on the edge of the right shoulder first, then setting up the signs on the edge of the left shoulder. Then, the advance warning signs were installed in the following order starting from the right side to the left side of roadway: "Road Work Ahead," "Left Lane Closed in ½ mile," and "Left Lane Closed" sign. Two vehicles were used to set up the signs on both shoulders. One of the vehicles was a truck mounted with an attenuator (TMA) and used for installing signs on the left shoulder, and the other vehicle was a pick-up truck with a TMA used for installing signs on the right shoulder.

2 Once installation of the "Left Lane Closed" sign on the left shoulder was complete, the traffic control crews working on the right shoulder began installing barricade on the left shoulder. Meanwhile, the installation of the "Left Lane Closed" sign on the left shoulder was taking place, the traffic control crew working on the right shoulder simultaneously began installing barricade on the left shoulder.

3 Then, the crew installed an arrow board downstream of the barricade on the left shoulder and set it to "Caution mode" with four dots flashing on the panel.

4 Once the "Left Lane Closed" sign on the left shoulder was installed, the crew turned on the arrow board to "Merge right" mode.

5 The crew lined up the exiting barrels located on the side of the left shoulder to prepare to form a left shoulder taper.

6 Installed a merging taper on the A-lane. Three work crew members were used: one member pulling barrels from the side of the left shoulder and passing it to another work crew member to install the taper, and two work crew members aligning the barrels to create a merging taper for the A-lane. During the first taper installation, a cone truck mounted with a TMA was used as a protection vehicle by slightly encroaching on the traffic lane (A-lane) as the taper was extended into the lane.

7 Installed cones along the skip line between the A-lane and B-lane from the cone truck. Two workers were located on the back of the truck for placing cones. One worker was the cone installer, and the other worker was the cone passer. As the installation process of the cones along the skip line occurred, another work crew member worked on installing the following signs on the edge of the right shoulder and at on-ramps as follows:

    a Installed "Left 2 lanes closed ½ miles" on the on-ramps.

    b Installed the "Left Lane Closed" sign on the edge of the right shoulder c Installed the second “Left Lane Closed” sign on the edge of the right shoulder

<u>Procedure for B-lane closure set-up:</u>

1. Installed the second merging taper on the B-lane. The processes for installing the merging taper for the B-lane was similar to installing the merging taper for the A-lane. While installing the second (B-lane) merging taper, the barrels were already laid out on the skip line between the A- and B-lanes. The work crew just simply shifted the barrels from the skip line between the A- and B-lanes to form a second merging taper. One worker pulled barrels and passed them to the other two workers for aligning the barrels to form a merging taper on the B-lane. While installing the merging taper, the work vehicle (cone truck) mounted with a TMA slowly encroached into the B-lane to protect the workers as they installed the merging taper.

2. After the merging taper on the B-lane was installed, the cones along the skip line between the B- and C-lanes were installed from the work vehicle. The cones were already laid out on the skip line between the A-lane and the B-lane. Therefore, one worker standing on the work vehicle simply picked up the cones while the vehicle travelled on the B-lane and passed the cones to another worker on the vehicle to place on the skip line between the B-lane and C-lane.

3. Continued installing cones on the skip line between the B-lane and C-lane by repeating step 2 until the start of the third merging taper.

<u>Procedure for C-lane closure set-up:</u>

Due to the timing of the C-lane closure, the researchers did not have an opportunity to observe the operation for the C-lane closure. However, it can be assumed that the process followed for the C-lane closure was similar to the process used for the B-lane closure described above. In addition, at the end of the C-lane closure, the work crew installed the termination area.

3.1.1.2 Traffic control removal procedure

For nighttime work, the traffic control removal operation usually takes place in the early morning after the roadwork maintenance is completed. Unfortunately, researchers were not able to observe the full process of the entire work zone removal, but the contractors were able to briefly demonstrate how they remove cones from a skip line between A- and B-lanes. The process of cone removal started by backing up the work vehicle mounted with a TMA with two workers located on the back of the work vehicle. One crew member was the cone remover, and the other crew member was the cone keeper. While the work vehicle backed up at a slow speed, the cone remover picked up the cones from the skip line and passed them to the cone keeper for stockpiling on the truck.

3.1.2 Project 2: I-5 road surfacing, Milepost 216-235

For the second project, traffic control operations for a concrete section in the southbound direction of I-5 between mileposts 216 and 235 were observed. The roadway has two lanes in each direction at this section of the roadway. At this location, the road was aging and starting to deteriorate and rut due to studded tire and chain use. The road required resurfacing to repair the deteriorated sections. The maintenance cost of the project was estimated to be approximately $15,300,000. The ongoing operation tasks during the observation included grinding the concrete to reduce rutting and repairing the concrete where rebar was exposed on the roadway surface.

The observation began on Wednesday, June 9, 2021, at 6:00pm at the project laydown yard on Highway 34 east of Corvallis, OR. To begin, the researchers first met with the ODOT inspector and contractor personnel to discuss the traffic control set-up and removal operation plan and process. The observation methods and safety guidelines were also discussed during the brief meeting. After the meeting, the researchers then departed the project yard to go to the work zone site, which was about a 15-minute drive from the yard. The B-lane next to the right shoulder was to be closed for road maintenance. To ensure all important notes were captured, a similar observation process as that used for Project 1 was used that included notetaking, worker interviews, photographing, and videotaping.

3.1.2.1 Traffic control set-up procedure

The work zone closure operation of two lanes in each direction of I-5 southbound between mileposts 216 and 235 began at 7:52pm and lasted for approximately 40 minutes to complete the entire closure for the B-lane. The A-lane remained open to traffic. The equipment and traffic control devices used to perform the lane closure operation were a truck mounted with a TMA, a cone truck, arrow boards, cones, temporary signs, barrels, and a barricade. The process followed to create the lane closure for the B-lane is described below:

Procedure for B-lane closure set-up:

1. Set up the advance warning signs on both sides of the roadway. The process for installing the advance warning signs involved two work vehicles mounted with TMAs. First, the work crew installed the “Road Work Ahead” sign on the left shoulder, then installed another “Road Work ahead” sign on the right shoulder. Then, the work vehicles one on both sides of the roadway installed the following signs in order starting from the left side to the right side of the roadway: “50mph Speed ahead”, “Speed Limit 50mph”, “Right Lane Closed ½ mile”, and lastly, “Right Lane Closed.”

2. Once the advance warning signs were installed, the work crew installed the arrow board on the right shoulder.

3. Placed the barricade in front of the arrow board simultaneously as the shoulder taper was installed.

4. Installed the merging taper on the B-lane using barrels to form a taper. During the installation process, work crews pulled the barrels from the right shoulder and placed them on the B-lane to create a taper. As the workers installed the taper, the work vehicle mounted with a TMA and a changeable message sign showing the message

"SLOW FOR WORKERS" slowly encroached into the traffic lane to protect the workers.

5. Lastly, using the cone truck with a TMA, the workers installed cones along the skip line between the A- and B-lanes until the end of the work zone to form the full lane closure. During this operation, two work crew members, excluding the truck driver, were used, one was the cone installer, and the other was the cone passer.

3.1.2.2 Traffic control removal procedure

The traffic control removal operation on the B-lane began early the next morning at 4:26am and was fully completed by 5:25am. The B-lane traffic control removal procedure consisted of the following steps:

Procedure for B-lane closure removal:

1. Removed cones along the skip line between the A- and B-lanes. The removal operation started from the downstream end of the work zone and progressed back upstream until the end of the merging taper by backing up the cone truck. A protection vehicle with a TMA was situated upstream of the cone truck to protect the cone truck. Two workers worked from the back of the cone truck during the removal process. One crew member was the cone remover, and the other crew member was the cone keeper.

2. Close to the very end of the merging taper, there were two cones left on the skip line. One worker suddenly left the cone truck to pick up the other remaining cones on foot and put them back on the cone truck.

3. Removed the merging taper starting from the downstream end to the upstream end of the taper by placing the barrels on the side of shoulder. During this process, the work crew members were protected by the work vehicle mounted with a TMA. As the workers proceeded to remove the barrels, the work vehicle moved slightly back towards the shoulder.

4. Once the merging taper was removed from the lane, the workers removed the barricade and placed it back on the pick-up truck.

5. The workers then removed the shoulder taper starting from the downstream end of the taper to the upstream end of the taper.

6. Lowered the trailer-mounted arrow board at the start of the merging taper and attached it to the pickup truck for removal from the site.

7. Removed advance warning signs on the left shoulder.

8. Circled back to the start of the work zone and removed the advance warning signs on the right shoulder starting from the first warning, "Road Work Ahead" sign, approached by the traffic users.

9. Removed the following signs in sequence in the same direction as the traffic:

    a. “50 mph Speed Ahead” sign.

    b. “Speed Limit 50 MPH” sign.

    c. “Right lane closed ½ mile” sign.

    d. “Right lane closed” sign.

3.1.3 Project 3: I-405 fence repair on Marquam Bridge

The location of the third project was on the top deck of the Marquam Bridge that spans across the Willamette River in the Portland metropolitan area. The work operation occupied from the I-405 southbound lanes to the top deck of the Marquam Bridge. Inspection of the bridge revealed that a section of a fence on the bridge was structurally damaged due to an accident caused by a truck. The damaged public property included bridge rail and posts. Potential hazards associated with the damaged property, such as falling of damaged rails and fence onto motorists travelling below the bridge, could occur at any moment. To avoid the life-threating hazard to the public, the ODOT maintenance team was assigned to fix the issues.

On July 15, 2021, the researchers went to the ODOT Maintenance shop in Clackamas, OR to meet with the ODOT bridge maintenance crew. The intent of the meetings was to fully understand the planned traffic control set-up and removal process, what to expected during the operation, strategies for observing the traffic control operation, and safety practices before proceeding to and while at the work zone site. After the meeting finished, all work crew members along with the researchers proceeded to the work zone site and performed their duty as assigned. During the observation, the researchers asked work crew members questions related to hazardous processes. In the meantime, note-taking, photographing, and videotaping of the traffic control operation were also conducted to capture the work practices.

3.1.3.1 Traffic control set-up procedure

The work zone closure operation began at 10:00pm and finished at 10:47pm. Due to the bridge maintenance work, the B-lane was terminated for the operation. The length of the work zone was approximately 1.3 miles, measured from the first advance warning sign to the termination area of the work zone. The equipment and traffic control devices used in the work zone operation included: cones, trucks with a TMA, cone truck, arrow boards, warning signs, radio devices, flashing lights, and PPE equipment for the traffic control crew. The work zone closure set-up process was as follows:

<u>Procedure for B-lane closure set-up:</u>

1. The work crew set up the attenuator on the first work vehicle while on the left shoulder of I-405 northbound prior to the vehicle arriving at the site. In the meantime, the second work vehicle protected the first work vehicle by encroaching into the adjacent traffic lane. While setting up the attenuator, the other two work vehicles were stationary in a blocking mode behind the second work vehicle to protect the first

and second work vehicles in front of them. All vehicles were equipped with a message/arrow board containing a message to merge to the open lane, and with a flashing light turned on when setting up the attenuator.

2. Set up the “Right Lane Closed” sign in the median from I-405 northbound (i.e., from the opposite side of the roadway). Two work vehicles were placed behind the work crew working on sign installation. All vehicles displayed “Merge to the right” messages on the arrow board with their flashing yellow lights on while the operation took place.

3. Installed “Right Lane Closed ahead” sign in the median from I-405 northbound. Two work vehicles were used to protect workers while setting up the sign. All work vehicles encroached into the traffic lane with an arrow board showing “Merge to the right” and flashing yellow light indicated.

4. Installed the “Bridge Work Ahead” sign in the median from I-405 northbound. While a worker placed the sign, two work vehicles were lined up upstream of the worker with the front of the vehicle pointed toward the traffic lane to protect the worker. The “Merge to the right” message and flashing yellow lights were present on all vehicles during the operation.

5. The work crew performing the work from the northbound lanes circled back to I-405 southbound and proceeded toward the advance warning area.

6. Installed “Bridge work ahead” sign on the right shoulder of I-405 southbound. While a worker was working on sign installation, the same two work vehicles protected the worker from the back by pointing into the traffic lane with a message board displaying “Merge to the left lane.” All vehicles were equipped with a flashing yellowing light while installing the sign.

7. Installed “Right Lane Closed ahead” sign on the right shoulder of I-405 southbound. Due to insufficient space for work vehicles to park to provide protection for the operation, the first work protection vehicle parked at a neutral area, the paved triangular space between the on-ramp and the highway lane, and the second work protection vehicle parked at a convenient location behind the first protection vehicle where it was safe to park.

8. Installed “Right Lane Closed” sign on the right shoulder of I-405 southbound. The same practices described in Step 6 were applied when protecting the work crews setting up the sign.

9. Once the advance warning area was established, the workers placed the third work protection vehicle at the top of the Broadway Street on-ramp to block traffic from entering the on-ramp prior to installing the first merging taper near the Broadway Street on-ramp.

10. Installed the first merging taper and arrow board near the on-ramp once the on-ramp traffic terminated. The same practices described in Step 6 were applied when

stationing the protection vehicles. While workers were installing the taper and arrow board, the first work protection vehicle was positioned at a neutral area, whereas the second work protection vehicle was parked at a convenient location behind the first work protection vehicle.

11. The work crew continued to install the first merging taper from the cone truck, starting from the first arrow board until progressing downstream of the first merging taper. The same practices as described in Step 6 were applied when protecting the work crews operating the traffic control set-up.

12. Installed the second merging taper near the 5th Avenue off-ramp. The taper was installed by workers on foot until the two farthest right lanes were closed. In the meantime, all of the work protection vehicles, including the work vehicle parked on the right shoulder of I-405 southbound close to the 5th avenue on-ramp, were stationed upstream of the work.

13. The work crew continued installing cones on the skip line between A- and B-lanes from the second merging taper until downstream of the work zone. The process for installing cones was operated from the work vehicle and was protected by the two work protection vehicles that followed the work vehicles. All vehicles indicated a "Merge to the left lane" message on the arrow board with a flashing yellow light turned on.

3.1.3.2 Traffic control removal procedure

Removal of the work zone traffic control began early in the morning the next day (July 16, 2021) at 4:36am. The researchers were not able to observe the process of removing the advance warning signs. However, the researchers had an opportunity to observe the process to remove the traffic control from the termination area to the first merging taper, which took less than 20 minutes to complete. A detailed description of the removal process is provided below:

<u>Procedure for B-lane closure removal:</u>

1. First, the work crew removed the cones from the skip line between the A-lane and B-lane starting from the downstream end of the work zone until the second merging taper. The removal process was performed using a work vehicle backing up toward the upstream end of the work zone with one work vehicle used to protect the work vehicle from the back. A caution mode was displayed on the arrow board on the protection vehicle while backing up the vehicle.

2. As the work vehicles proceeded with the traffic removal operation close to the downstream end of the second merging taper, the third work protection vehicle that was initially placed at the downstream end of the second merging taper was removed for the first two work vehicles to continuously operate the removal operation.

3. Continued to remove the second merging taper starting from downstream to upstream in the work zone. The work protection vehicle backed up slowly behind the work vehicle as the removal operation was on-going.

4. Prior to removing the first merging taper, the third work protection vehicle was placed on the top of the on-ramp to block on-ramp traffic and ensure a safe removal operation for the first merging taper.

5. Once on-ramp traffic was blocked, removed the first merging taper starting from the downstream end of the taper until the start of the first taper. The removal was performed by continually backing up the work vehicle slowly with assistance from the protection vehicle behind it.

6. Removed the arrow board at the first merging taper. The protection vehicle was placed behind the work vehicle while a worker removed the arrow board.

7. After the arrow board was removed, the third protection vehicle that blocked the on-ramp traffic released the on-ramp traffic.

The site observations reveal that traffic control crews generally follow the operational plans and written protocols established for traffic control set-up and removal. Deviations from the recommended practices occur in some circumstances based on real-time traffic and roadway conditions. Workers may intentionally deviate from the plan when they feel that the traffic and roadway conditions do not support safe work and modified procedures would lead to a safer operation for motorists and workers. For example, workers may operate or park their vehicles in different locations than planned when there is insufficient space available to protect themselves and the vehicles. Workers may place or remove signs in a slightly different order to allow for safer operations and efficiency in the work. Greater efficiency is desired to reduce the amount of exposure to traffic. The findings suggest a need for targeted training and oversight, and supporting protocols and procedures, for situations when the conditions vary from that planned and improvisation is needed.

3.2 FOCUS GROUP INTERVIEWS

As stated above, the interviews targeted Oregon Department of Transportation personnel and Oregon roadway construction and maintenance contractors. The interviews of both groups were held online via Zoom on different dates, and each lasted for approximately 1 hour and 30 minutes. The contractor focus group interview took place on August 24, 2021, and the ODOT focus group interview was held on August 26, 2021. The total number of participants joining the interviews was 5 participants for the contractor group and 4 participants for the ODOT group.

During both focus group sessions, the researchers asked the participants each of the interview questions and then facilitated responses from the participants to each question. Table 3.1 provides a summary of the input received from both focus groups in terms of similar perspectives and dissimilar perspectives that they had related to the main interview questions about traffic control set-up and removal.

Table 3.1: Comments from Focus Group Interviews

Similar Perspectives, both ODOT and Contractor Personnel	Dissimilar Perspectives	
	ODOT Personnel	**Contractor Personnel**
1. What safety issues are associated with temporary traffic control set-up and removal?		
• Driver behavior influenced by alcoholic substances and pressure from work causes safety concerns to work crews while setting up and removing the traffic control from work zone. • Lack of protective devices/equipment and pre-warning message devices to protect work crews and inform drivers of road work condition ahead while operating the traffic control. • Lack of skills and knowledge of traffic control crew in setting up and removing the traffic control devices. Due to this reason, work crews sometime were reported using their own judgement to set-up and remove traffic control devices without following standard procedures for the traffic control operation. Deviating from planned or standard procedures primarily occurs when real-time traffic or roadway conditions are not as expected.	• Working too close to high-speed passing vehicles, especially when working on traffic control installation and removal close to on-ramp. • Drivers videotape work zone traffic control operation while driving through the work zone. • Insufficient space available for the sign set-up, especially when installing signs on the bridge structure. As a result, workers consumed considerable time finding a set-up spot. Hence, exposing workers to passing traffic for a longer period of time. • Installing traffic control devices on a complex configuration of a highway work zone. One ODOT personnel witnessed this issue on I-84 along the Columbia River near Multnomah Falls where drivers were typically confused about the direction to go in a work zone as a result of an exit located on the left side of the roadway. • Drivers swerve their vehicle to avoid rumble strips placed in a work zone.	• Picking up knocked over cones or barrels on a live traffic lane. • Poor lighting and glare in a work zone. • Lack of help from police enforcement to slow and maintain the speed of vehicles travelling in a work zone.

<table>
<tr><th rowspan="2">Similar Perspectives, both ODOT and Contractor Personnel</th><th colspan="2">Dissimilar Perspectives</th></tr>
<tr><th>ODOT Personnel</th><th>Contractor Personnel</th></tr>
<tr><td colspan="3">2. What are the three riskiest processes of temporary traffic control set-up and removal?</td></tr>
<tr><td>Initial setup of the first advance warning signs and merging taper were deemed as the riskiest processes during traffic control set-up and removal.
Operating traffic control installation/removal close to an on-ramp was described as the second-most hazardous process.</td><td>The third riskiest process was high speed of passing vehicles during all activities of the set-up and removal operation.</td><td>The third riskiest process was retrieving a knocked over cone/barrel from the live traffic lane.</td></tr>
<tr><td colspan="3">3. What are the challenges associated with traffic control set-up and removal?</td></tr>
<tr><td>Lack of labor force resulting in increasing workload pressure on traffic control crews to get the task done.</td><td>Complexity of the road configuration such as a curvy road, and limited sight distance of drivers driving in work zone. As a result, increasing the drivers’ reaction time to an obstacle in a worker zone.
Light and glare in a work zone impair drivers’ visibility while driving through the work zone.
Complexity of road structures also causes difficulty for workers to find the best spot to set up signs, especially when working on bridge structures. They often struggle to find a spot to install the signs.
Due to budget constraints, interviewees reported a lack of providing protective equipment for</td><td>Having tight schedules for the traffic control set-up and removal operation.
Difficulty in creating the public’s understanding of the safety risks associated with the traffic control set-up and removal in a work zone.</td></tr>
</table>

Similar Perspectives, both ODOT and Contractor Personnel	Dissimilar Perspectives	
	ODOT Personnel	**Contractor Personnel**
	traffic control crews to operate the lane closure. • Over speed vehicles driving through the work zone during the traffic control set-up and removal operation. • Drivers disobeying the work zone traffic signs while maneuvering through the work zone.	
4. What are the challenges associated with traffic control setup and removal during daytime compared to nighttime?		
• At night, the traffic volume is lower than daytime. Hence, vehicles drive faster than in the daytime, which poses a safety concern to workers during the set-up and removal operation at night. • Nighttime often results in poorer visibility than daytime. Due to this reason, there is an increase in the reaction time of drivers driving at night which results in a higher probability of accidents occurring within a work zone than in the daytime. • The darker it gets, the greater the number of intoxicated drivers and aggressive drivers. As a result, it does not feel safe for workers to operate the traffic control set-up and removal at night.	•	• More resources are required for a nighttime traffic control operation to enhance visibility of the work zone than in a daytime operation.

Similar Perspectives, both ODOT and Contractor Personnel	Dissimilar Perspectives	
	ODOT Personnel	**Contractor Personnel**
5. What suggestions do you have for the research study for improving the safety of workers and motorist during traffic control installation and removal operation?		
• Provide workers on-site safety training on work zone traffic control operations related to set-up and removal. • Deploy highway patrol vehicles during the set-up and removal operation. • Implement the use of radar speed board in work zones to keep the speed in the work zone constant.	• Enhance visibility in the work zone by using additional lighting, reflective materials, equipment, and PPE. • Install extra signs for "Lane closed ahead" sign to remind road users of upcoming closed lane.	• Provide more public service announcements prior to the start of the project. • Provide more public service announcements before road construction or maintenance projects start. • Work zone traffic control designers should actively collaborate and listen to the feedback from contractors regarding their experiences with the use of traffic control devices (e.g., safety of implementing devices in work zone and their impact on the public). • Integrate into a guideline the use of a headlamp on workers and reflective materials for tapers. • Increase the timeframe of the traffic control set-up and removal operation to ensure safe practices and high quality of the operation. • Increase public incident response vehicles in a work zone while setting up and removing a work zone.

<table>
<tr><th rowspan="2">Similar Perspectives, both ODOT and Contractor Personnel</th><th colspan="2">Dissimilar Perspectives</th></tr>
<tr><th>ODOT Personnel</th><th>Contractor Personnel</th></tr>
<tr><td></td><td></td><td>Use radar speed board either upstream of the transition area or within the work zone.</td></tr>
<tr><td colspan="3">6. Which parts of the set-up/removal process should the study focus on to significantly improve safety of workers and motorists?</td></tr>
<tr><td>Investigate the best practices to improve the safety of the initial set-up of signs or taper.
Examine the most effective pre-warning devices or reflective materials to be used during the traffic control set-up and removal.
Increase the use of pre-warning signs in work zones.</td><td>Explore a method for safely deploying and removing temporary rumble strips in the work zone.
Conduct a study of the most effective sequential arrow that should be used in a work zone during the traffic control operation.</td><td>Investigate traffic control indicators such as variable message boards showing “SLOW DOWN” messages to drivers in the work zone.</td></tr>
<tr><td colspan="3">7. ODOT expectations from contractors to ensure safe operation of traffic control set-up and removal (applies to ODOT interviewees only)</td></tr>
<tr><td colspan="3">Have sufficient protective devices or equipment before performing traffic control set-up and removal.
Follow work zone traffic control installation and removal standards and guidelines.
Develop a contingency plan for the traffic control set-up and removal operation.
Inspect traffic control device quality and condition before use.
Actively collaborate with traffic control inspector on safety plan and procedure for traffic control set-up and removal operation
Maintain safe practices of the work zone closure installation and removal throughout the whole operation and entire work zone.</td></tr>
</table>

3.3 CASE STUDY INVESTIGATIONS

3.3.1 Case Study Projects

The original work plan for the study prescribed application of the promising traffic control measures on at least three construction or maintenance projects. The case study projects were to be located on high speed roadways in Oregon and involve temporary closure of one or more lanes of traffic to allow the work to proceed. It was also expected that the traffic control design on the projects would be similar to that typically designed for construction and/or maintenance work in Oregon. To facilitate safe and efficient speed data collection, the researchers also targeted projects at locations where speed data is available through the RITIS system. This criterion allowed for collecting speed data anytime before and after the traffic control operation as well as during the traffic control operation. Using RITIS speed data also enabled collecting speed data without placing sensors on the roadway, a process that potentially exposes the work crews and researchers to hazardous conditions and interrupts the work operation. Lastly, the number of projects needed to provide sufficient data collection days for statistical analyses.

Based on the established selection criteria, the researchers identified six case studies projects for data collection. The roadway location of the case study projects is shown in Table 3.2 along with the travel direction, lane(s) closed, and type of work conducted during data collection. All of the projects were located in the Portland or Salem, OR areas.

Table 3.2: Case Study Projects and Traffic Control Operation Assessed

Project	Roadway	Travel Direction	Lane(s) Closed	Type of Work	
				Construction	Maintenance
1	OR-217	Northbound	C-lane (auxiliary)	X	
	OR-217 – US-26 ramp	Northbound to Westbound	B-lane	X	
2	OR-217	Northbound	A-lane		X
3	US-26	Eastbound	C-lane	X	
		Westbound	C-lane	X	
		Eastbound	A-lane and B-lane	X	
		Westbound	A-lane and B-lane	X	
4	I-5	Southbound	B-lane and C-lane		X
5	I-5	Northbound	B-lane and C-lane	X	
		Northbound	A-lane	X	
6	I-205	Southbound	A-lane and B-lane		X
		Northbound	C-lane		X

For each case study project, the researchers contacted the ODOT and/or contractor personnel to schedule days for observation and data collection. To provide sufficient data for statistical analyses, the researchers aimed to collect data during at least 30 observations of traffic control set-up and removal operations. Additionally, multiple applications of the treatments individually, and in combination, were desired. Table 3.3 shows the 30 observations on the six case study projects. The observations are shown chronologically.

As indicated in the table notes, the electronic flares were placed on the right shoulder for all flare treatments except for Observation #3. Based on a recommendation from the traffic control supervisor (TCS) on the Case Study Project #1 job site, the electronic flares were placed on one side of the roadway only (the side that contained the lane closure) in order to suggest that the drivers move over to the open lane. The TCS indicated that flares located on the shoulder opposite the lane closure, as shown in the research plan in Figure 2.2, would likely confuse the drivers and may suggest that they move towards the closed lane. This recommendation was reported to, and confirmed by the TAC, and then applied on the other case study projects as well.

Table 3.3: Case Study Observation Details

No.	Project	Date	Road	Direction	Lane(s) closed	Type of Work		Operation observed		Treatment			
						Construction	Maintenance	Set-up	Removal	Control	Flares[1]	PCMS	Radar speed sign
1	1	7/11/2022	OR-217	Northbound	C-lane (auxiliary)	X		X		X			
2	1	7/12/2022	OR-217	Northbound	C-lane (auxiliary)	X		X			X		
3	2	7/15/2022	OR-217	Northbound	A-lane		X	X			X		
4	3	7/16/2022	US-26	Eastbound	C-lane	X		X			X		
5	3	7/16/2022	US-26	Westbound	A-lane and B-lane	X		X			X	--[3]	
6	1	7/17/2022	OR-217 – US-26 ramp	Northbound to Westbound	B-lane	X		X		X			
7	1	7/17/2022	OR-217 – US-26 ramp	Northbound to Westbound	B-lane	X			X	X			
8	3	7/18/2022	US-26	Eastbound	A-lane and B-lane	X		X			X		
9	3	7/18/2022	US-26	Eastbound	A-lane and B-lane	X			X		X		

No.	Project	Date	Road	Direction	Lane(s) closed	Type of Work		Operation observed		Treatment			
						Construction	Maintenance	Set-up	Removal	Control	Flares[1]	PCMS	Radar speed sign
10	3	7/18/2022	US-26	Westbound	C-lane	X		X		X			
11	4	9/9/2022	I-5	Southbound	B-lane and C-lane		X	X		X			
12	4	9/9/2022	I-5	Southbound	B-lane and C-lane		X		X	X			
13	4	9/11/2022	I-5	Southbound	B-lane and C-lane		X	X			X		
14	4	9/11/2022	I-5	Southbound	B-lane and C-lane		X		X		X		
15	5	9/19/2022	I-5	Northbound	B-lane and C-lane	X		X		X		--[3]	
16	5	9/20/2022	I-5	Northbound	B-lane and C-lane	X			X	X		--[3]	
17	5	10/25/2022	I-5	Northbound	A-lane	X		X				X[2, 3]	--[4]
18	5	10/26/2022	I-5	Northbound	A-lane	X			X			X[2, 3]	--[4]
19	5	10/26/2022	I-5	Northbound	A-lane	X		X				X[2, 3]	--[4]
20	5	10/27/2022	I-5	Northbound	A-lane	X			X			X[2, 3]	--[4]
21	5	10/27/2022	I-5	Northbound	A-lane	X		X			X	X[2, 3]	--[4]
22	5	10/28/2022	I-5	Northbound	A-lane	X			X		X	X[2, 3]	--[4]
23	5	11/3/2022	I-5	Northbound	A-lane	X		X			X	X[2, 3]	--[4]
24	5	11/4/2022	I-5	Northbound	A-lane	X			X		X	X[2, 3]	--[4]

No.	Project	Date	Road	Direction	Lane(s) closed	Type of Work		Operation observed		Treatment			
						Construction	Maintenance	Set-up	Removal	Control	Flares[1]	PCMS	Radar speed sign
25	5	11/4/2022	I-5	Northbound	A-lane	X		X			X	X[2, 3]	--[4]
26	5	11/4/2022	I-5	Northbound	A-lane	X			X		X	X[2, 3]	--[4]
27	6	3/26/23	I-205	Southbound	A-lane and B-lane		X	X			X	--[3]	
28	6	3/26/23	I-205	Southbound	A-lane and B-lane		X		X		X	--[3]	
29	6	3/26/23	I-205	Northbound	C-lane		X	X		X			--[4]
30	6	3/26/23	I-205	Northbound	C-lane		X		X	X			--[4]
Total number of observations						21	9	18	12	10	16	10	0
Percent of observations						70%	30%	60%	40%	33%	53%	33%	0%

Table 3.3 notes:

1. Based on the recommendation from the traffic control supervisor (TCS) on the Case Study Project #1 job site, the electronic flares were placed on one side of the roadway only (the side that contained the lane closure) for all flare treatments.

2. A PCMS was placed at the designed treatment location for the research study.

3. At least one or more PCMS signs included as part of the planned traffic control (not added as a treatment for the research study) were located downstream of the RWA signs.

4. A radar speed sign included as part of the planned traffic control (not added as a treatment for the research study) was located downstream of the RWA signs. For Observations #29 and #30, the radar speed sign was located on a truck.

As shown in Table 3.3, twenty-one of the observations (70%) took place on construction projects, and 9 (30%) were on ODOT maintenance projects. The researchers observed 18 instances of traffic control set-up (60% of observations) and 12 removal operations (40% of observations).

Data was collected with each additional research treatment applied individually or with multiple treatments applied simultaneously. Electronic flares were added on 16 (53%) of the observations, and an additional PCMS located prior to the RWA sign was included on 10 (33%) of the observations. No observations included an additional radar speed sign located upstream of the RWA sign due to the lack of availability of an extra radar speed sign during the case study projects that could be dedicated for research purposes only. The impact of radar speed signs on vehicle speeds in work zones has been previously studied and quantified by ODOT, as discussed in Section 4.0 of the report.

In some cases, as noted in the table, a PCMS and/or a radar speed sign was part of the planned work operation and located downstream of the RWA signs, i.e., they were part of the traffic control planned by the work crews and not additional treatments implemented for the research study. The downstream PCMS and/or radar speed sign was left in place to maintain the traffic control plan rather than have the work crew relocate them upstream for the research study.

During Observation #15, the researchers saw a law enforcement vehicle present in the work zone during the operation at 20:49. While law enforcement vehicles were not seen by the researchers on other observation days, they may have been present during the traffic control operations.

The start and end times for the traffic control operations and the observations are shown in Table 3.4. The set-up times typically took place in the evening and the removals typically took place in the early morning. For treatment days, the reported observation time represents the time when the treatment was placed on the roadway (start) and the time when the treatment was removed from the roadway (end). For control days, the reported observation times are the start and end times between which the traffic control team was working on either the set-up or the removal of the roadway. For those days in which two lanes were closed, start and end times are shown for both lane closures. The start and end times for the traffic control set-up and removal were recorded to know the periods of time in which to download vehicle speed data from RITIS for analysis.

Observations involving the electronic flares (#2-#5, #8-#9, #13-#14, and #21-#28) primarily took place during the evening and early morning hours, except for the removal during Observation #28 which ended at approximately 09:00. Therefore, motorists primarily observed the flares during twilight and nighttime hours. Given the timing of the observations, the amount of light emitted by the flares, and the flashing light pattern, the impact of natural light on the visibility of the flares was not perceived to be a confounding factor in the present study.

Table 3.4: Case Study Traffic Control Set-Up/Removal and Observation Start and End Times

No.	Project	Date	Roadway	Traffic Control Set-up or Removal time		Observation Time[1]	
				Start	End	Start	End
1	1	7/11/2022	OR-217	06:45	07:10	06:45	07:10
2	1	7/12/2022	OR-217	06:47	07:27	06:47	07:47
3	2	7/15/2022	OR-217	21:36	22:18	21:36	23:13
4	3	7/16/2022	US-26	00:56	01:07	00:56	01:48
5	3	7/16/2022	US-26	00:13	01:07	00:13	01:36
6	1	7/17/2022	OR-217 – US-26 ramp	20:00	20:35	20:00	
7	1	7/17/2022	OR-217 – US-26 ramp	21:19	21:47		21:47
8	3	7/18/2022	US-26	19:50 21:50	21:08 21:57	19:50	
9	3	7/18/2022	US-26	23:45	00:22		00:22
10	3	7/18/2022	US-26	21:19 22:22	21:22 23:03	21:19	23:03
11	4	9/9/2022	I-5	20:17	21:48	20:17	21:48
12	4	9/9/2022	I-5	22:28	00:14	22:28	00:14
13	4	9/11/2022	I-5	00:22	01:13	00:20	
14	4	9/11/2022	I-5	01:48	02:26		02:26
15	5	9/19/2022	I-5	19:00	20:48	19:00	
16	5	9/20/2022	I-5	04:04	05:06		05:06
17	5	10/25/2022	I-5	19:31	21:15	19:31	21:15
18	5	10/26/2022	I-5	03:26	04:17	03:26	04:17
19	5	10/26/2022	I-5	19:05	20:50	19:05	20:50
20	5	10/27/2022	I-5	02:40	03:38	02:40	03:38
21	5	10/27/2022	I-5	19:05	20:50	19:16	
22	5	10/28/2022	I-5	03:50	04:46		04:31
23	5	11/3/2022	I-5	19:07	20:58	19:21	
24	5	11/4/2022	I-5	01:30	03:07		02:57
25	5	11/4/2022	I-5	19:04	20:55	19:15	
26	5	11/4/2022	I-5	22:52	23:48		23:40
27	6	3/26/2023	I-205	03:30	04:09	03:50	
28	6	3/26/2023	I-205	07:20	09:16		09:07
29	6	3/26/2023	I-205	07:39	08:40	07:39	08:40
30	6	3/26/2023	I-205	11:38	12:06	11:38	12:06

Table 3.4 notes:

1. For treatment days, the reported observation times are the time when the treatment was placed on the roadway (start) and the time when the treatment was removed from the roadway (end). For control days, the reported observation times are the start and end times between which the traffic control team was working on either the set-up or the removal on the roadway.

3.3.2 Vehicle Speed Data Collection

The information recorded and data collected for each of the observations was quite extensive. Detailed information and data for all of the observations is too much to realistically describe in full in the report. For efficiency in presenting the results, only the results for Observations #8 (set-up) and #9 (removal) with A- and B-lane closures and electronic flares are described in the remaining part of this section of the report. Similar tables and figures showing the results for all 30 of the observations are provided in the Appendix.

In order to download vehicle speeds from RITIS, the researchers began by first identifying the RITIS segment codes representing the sections of roadway in which the traffic control was placed. RITIS reports vehicle speeds within specified sections of roadway. Each section is given a segment code by RITIS. The sections begin and end at different, easily identified points along the roadway, such as at an on-ramp, off-ramp, or overpass. The roadway sections represented by the segment codes also have different lengths. Observations #8 and #9 took place on Case Study Project #3 on US-26 eastbound. The segment codes for the roadway sections before, after, and through the length of, Case Study Project #3 are shown in Table 3.5. Similar segment code information for all of the case study project is provided in the Appendix.

Table 3.5: RITIS Segment Codes for Observations #8 and #9 on Case Study Project #3

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114-04377	Cornell Rd./Exit 65	0.23	45.53224	-122.84244	45.53065	-122.83820
114N04377	Cornell Rd./Exit 65	0.27	45.53065	-122.83820	45.52880	-122.83332
114-04376	Murray Blvd./Exit 67	0.73	45.5288	-122.83332	45.52381	-122.82013
114N04376	Murray Blvd./Exit 67	0.55	45.52381	-122.82013	45.51998	-122.81015
114-04375	Cedar Hills Blvd./Exit 68	0.65	45.51998	-122.81015	45.51557	-122.79831
114N04375	Cedar Hills Blvd./Exit 68	0.62	45.51557	-122.79831	45.51137	-122.78693
114-04374	OR-217/Exit 69	0.28	45.51137	-122.78693	45.50948	-122.78174
114N04374	OR-217/Exit 69	0.54	45.50948	-122.78174	45.50660	-122.77143
114-04373	Camelot Ct.	0.84	45.50660	-122.77143	45.50586	-122.75427
114N04373	Camelot Ct.	0.28	45.50586	-122.75427	45.50666	-122.74860
114-04372	OR-8	0.14	45.50666	-122.74860	45.50724	-122.74586
114N04372	OR-8	0.34	45.50724	-122.74586	45.50870	-122.73919
114-04371	Skyline Blvd./Exit 71	0.154992	45.5087	-122.73919	45.50866	-122.73599
114N04371	Skyline Blvd./Exit 71	0.192922	45.50866	-122.73599	45.50869	-122.73201

Given the lengths of the work zones and the lengths of the roadway sections, the work zones covered multiple segment codes. Therefore, a segment code was identified for the location of each of the temporary traffic control measures placed in the work zone, from the start to the end of the work zone. Downloading the vehicle speed data also requires knowing the day and timeframe of interest. For the present study, speeds of interest were those recorded before, during, and after the traffic control was placed and removed. Therefore, the researchers recorded the times when each temporary traffic control element was placed on the roadway and when it was removed from the roadway. Table 3.6 presents the associated segment codes, placement times, and removal times for each of the traffic control elements placed in the work zone for Observations #8 and #9. Similar tables for all of the data collection observations are provided in the Appendix.

Table 3.6: Temporary Traffic Control Measures and Placement/Removal Times During Observations #8 And #9 On Case Study Project #3

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114N04376	19:50	00:15
Road Work Ahead signs	114N04376	R: 19:50 L: 20:05	00:15
Left Lane Closed Ahead signs	114-04375	R: 19:53 L: 20:07	00:18
Merge signs (A-lane closure)	114-04375	R: 19:54 L: 20:08	00:20
Merge signs (B-lane closure)	114N04375	R: 19:55 L: 20:08	23:46
Arrow board	114N04375	20:10	23:55
Start of taper (A-lane)	114N04375	20:10	23:45
End of taper (A-lane)	114N04375	20:35	23:45
Arrow board	114-04374	21:50	23:45
Start of taper (B-lane)	114-04374	21:50	23:45
End of taper (B-lane)	114-04374	21:57	23:45
Work zone ends sign	114N04374	NA	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Figure 3.1 shows a graphical view of the work zone location, locations of the traffic control measure, RITIS segments, and RITIS segment codes for Observations #8 and #9 on Case Study Project #3. Similar figures for all of the data collection observations are provided in the Appendix. The figures were developed to assist with identifying the segment codes and visualizing how the work zone and traffic control measures overlay the RITIS segments.

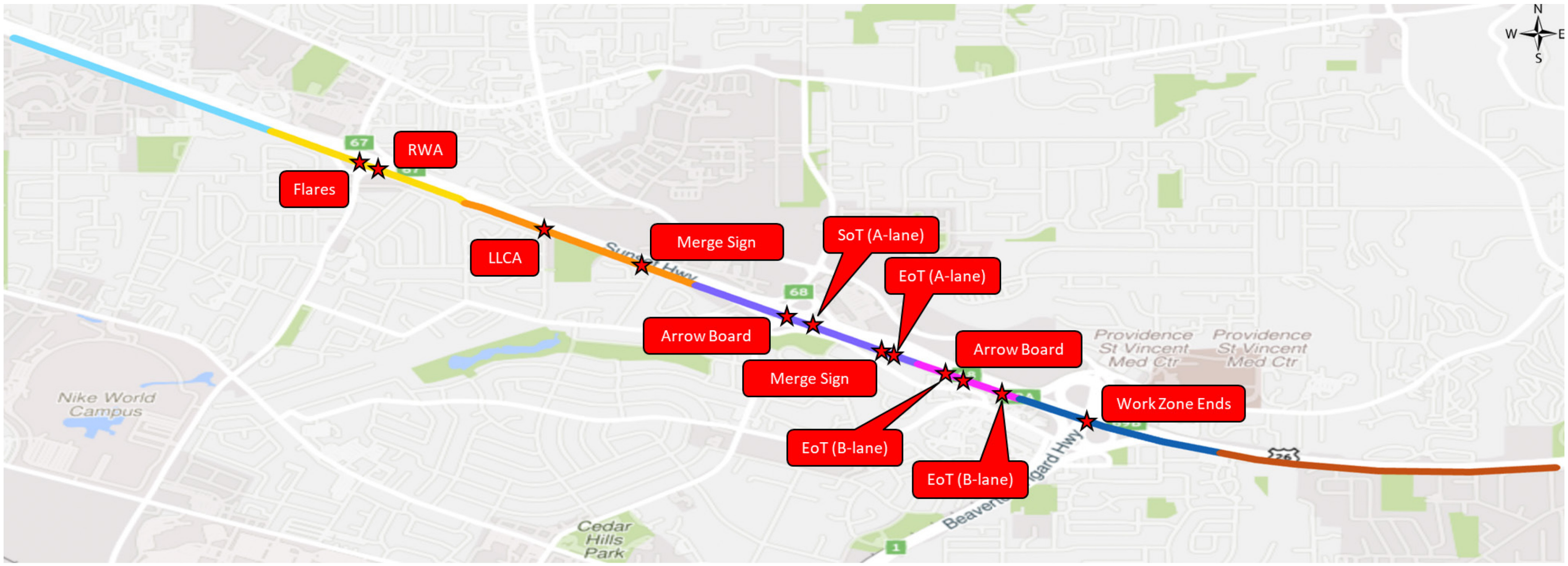


Figure 3.1: Traffic control measures, RITIS segments, and RITIS segment codes for Observations #8 and #9 on Case Study Project #3

Figure 3.1 notes:

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

Segment codes:

114-04376 | 114N04376 | 114-04375 | 114N04375 | 114-04374 | 114N04374 | 114-04373

For the next step, the researchers downloaded vehicle speeds from RITIS. For the speeds at a specific roadway location, the researchers downloaded speeds in each of the segments located within the work zone limits (from RWA sign to Work Zone End sign) for each of the observations. In addition, the researchers downloaded speeds in the segments located immediately upstream of the beginning work zone segment, and immediately downstream of the ending work zone segment. Speeds within these additional segments were used for comparison of work zone speeds with work zone entry speeds and work zone exit speeds based on location.

In terms of time, the researchers downloaded vehicle speeds during the period of time when the traffic control operations took place. The researchers additionally downloaded speeds during a 15-minute period immediately prior to the start of the traffic control operation, and a 15-minute period immediately following the end of the traffic control operation. Speeds within these additional time periods were used for comparison of speeds during the active traffic control operation with speeds both before and after the traffic control operation in terms of time. Fifteen minutes was assumed to allow sufficient time to capture free-flow speeds without any impacts from the presence of the traffic control operation, while also not being overly long to eliminate the impacts of potential changes in the traffic and driving conditions (traffic volume, vehicle mix, weather, etc.).

Table 3.7 presents an excerpt of RITIS speed data for Observations #8 and #9 on Case Study Project #3. The values reported by RITIS are as follows (ODOT, n.d.):

- *Tmc code*: RITIS segment code associated with the speed data.
- *Measurement tstamp*: Date and time of the recorded data, in 1-minute increments
- *Speed* (mph): The current estimated harmonic mean speed for the roadway segment during the 1-minute time interval
- *Average speed* (mph): Average historical speed recorded for the segment.
- *Reference speed* (mph): Calculated "free flow" speed for the segment, based on the 66^{th} percentile point of the observed speeds on the segment for all time periods.
- *Travel time* (minutes): Travel time required to drive through the segment based on the average real-time speed and segment length.
- *Confidence score*: An indicator of the quality of the reported speed based on the type of speed data used. Possible values are 10, 20, or 30, where: 10 = reference speed data, 20 = historical speed data, and 30 = real-time speed data.
- *C-value*: The probability that the current probe reading represents the actual roadway conditions based on recent and historical trends (0 = low probability; 100 = high probability). This value is only used when the confidence score is 30.

The number of vehicle speed records included in each 1-minute time interval for calculating the mean speed varies depending on the traffic volume during the time interval.

Table 3.7: Excerpt Of RITIS Speed Data For Observations #8 And #9 On Case Study Project #3

Tmc code	Measurement tstamp (date and time)	Speed (mph)	Average speed (mph)	Reference speed (mph)	Travel time (minutes)	Confidence score	C-value
114-04376	7/18/2022 19:30	65	59	58	0.67	30	100
114-04376	7/18/2022 19:31	65	59	58	0.67	30	100
114-04376	7/18/2022 19:32	66	59	58	0.66	30	100
114-04376	7/18/2022 19:33	68	59	58	0.64	30	100
114-04376	7/18/2022 19:34	66	59	58	0.66	30	100
114-04376	7/18/2022 19:35	65	59	58	0.67	30	100
114-04376	7/18/2022 19:36	65	59	58	0.67	30	100
114-04376	7/18/2022 19:37	63	59	58	0.69	30	100
114-04376	7/18/2022 19:38	65	59	58	0.67	30	100
114-04376	7/18/2022 19:39	67	59	58	0.65	30	100

3.3.3 Vehicle Speed Results

The researchers downloaded the RITIS vehicle speed data described above to an Excel spreadsheet for each of the 30 observations. The researchers then reviewed the data and removed from the data set those data entries that received low *C-values* and low *Confidence scores*. Data entries with *C-value* = 100 and *Confidence score* = 30 were retained for analysis.

Descriptive statistics of the vehicle speeds (mean, median, and standard deviation) were then calculated for each observation. The speed data used in the calculations were the 1- minute average real-time speed values recorded in the segment during the time period.

The descriptive statistics were calculated at three locations and for three time periods at each location. The three locations were as follows:

- One segment upstream of the treatment on treatment days, or one segment upstream of the RWA sign on control days.
- At the treatment location on treatment days, or at the RWA sign on control days.
- One segment downstream of the treatment on treatment days, or one segment downstream of the RWA sign on control days.

The three time periods at each of the above locations were as follows:

- Up to 15 minutes before the start of the traffic control operation (set-up or removal)
- During the traffic control placement (set-up or removal)
- Up to 15 minutes after the end of the traffic control operation (set-up or removal)

The descriptive speed statistics for Observations #8 and #9 are shown in Tables 3.8 and 3.9, respectively. Recall that Observations #8 (set-up) and #9 (removal) took place during work on US-26 eastbound when there was both an A-lane and B-lane closure. Flares were added as the treatment during these observations.

Table 3.8: Summary of Vehicle Speeds During Observation #8 (Set-Up) On Case Study Project #3 (Treatment = Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 128)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	64.7	65.0	1.9	64.4	65.0	1.9	61.3	62.0	1.0
At treatment	65.1	65.0	2.0	63.8	64.0	2.2	58.9	59.0	1.3
Downstream of treatment	64.7	65.0	1.9	62.1	62.0	2.4	56.8	57.0	1.5

n = number of 1-minute intervals of RITIS speed data

Table 3.9: Summary of Vehicle Speeds During Observation #9 (Removal) On Case Study Project #3 (Treatment = Flares)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 38)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	64.4	65.0	1.5	60.4	60.0	2.6	62.0	62.0	0.0
At treatment	63.1	64.0	1.4	61.0	61.0	2.5	60.0	60.0	0.0
Downstream of treatment	62.2	62.0	0.4	59.9	60.5	2.5	57.0	57.0	0.0

n = number of 1-minute intervals of RITIS speed data

The treatments are the first traffic control measure placed during set-up, and the last traffic control measure removed during removal. As shown in Tables 3.8 and 3.9, while electronic flares were the added treatment on the observation day, no flares were present when some of the vehicle speed data was recorded because of the timing when the treatment was placed. Specifically, no treatment was present for speed data recorded during the 15-minute time period before the set-up operation started, and during the 15-minute time period after the removal operation ended.

Similar tables showing the recorded vehicle speeds for all observations are provided in the Appendix. The speed values contained with the tables were used to assess the impacts of the treatments. Statistical analyses of the speed values are presented and discussed in Section 4.0 of the report.

4.0 ANALYSIS AND DISCUSSION

This section provides analyses and discussion of the results gained from the observations of ongoing construction and maintenance operations, focus group interviews of ODOT and industry personnel, and field evaluations of the three selected treatments on case study projects.

4.1 OBSERVATIONS OF CONSTRUCTION AND MAINTENANCE OPERATIONS

During the work operation observations, the researchers recorded periods of time and specific work tasks when workers and motorists were exposed to dangerous situations that could create safety concerns. The identified dangerous situations associated with the traffic control set-up and removal included:

- Setting up the initial signs and taper in work zone
- Operating the temporary traffic control set-up and removal close to an open on-ramp
- Insufficient personal fall restraint system on the work vehicle to secure workers while placing and removing channelizing devices such as cones and barrels.
- Not following the planned sequence for the traffic control set up and removal process.
- Missing physical components on the truck to provide for safety of the workers, such as a step or ladder on the passenger side of the work vehicle for passengers to use to climb up on the vehicle.
- Setting up the TMA close to a live traffic lane
- The driver of the work vehicle reading the traffic control plan while driving to the work zone
- Lack of space available for protection vehicle to protect the cone truck near the on-ramp.
- Driver confusion caused by backing up the truck during the removal operation.
- Wrong arrow direction on the arrow sign mounted on a truck.
- Setting up (lowering) the TMA on the back of the truck without a sufficient protection device present
- Loud truck engine created a high noise level for the workers and made it harder for the workers to communicate with each other during the traffic control operation.

- Blind spot present for the truck driver while backing up the truck during closure removal.

- A worker climbing up the roadway divider to give a hand signal to the driver of the work vehicle after merging from the fast lane into the work zone.

- Retrieving knocked over cones in a live traffic lane.

4.2 FOCUS GROUP INTERVIEWS

Based on the focus group interviews, it can be concluded that the safety issues generally linked with traffic control set-up and removal operations are driver behavior, lack of equipment and materials during the operation, insufficient space available for workers and equipment, high speed of passing vehicles, unpredictable events occurring such as a knocked over cone rolling on a live traffic lane, and lack of light. These findings were clearly confirmed by the results from the survey, where a majority of these issues were also identified as the primary issues that the survey respondents encountered while implementing traffic control operations. Among those issues identified, the results from survey Question #3.4 show "Aggressive drivers" associated with driver behavior was considered as the major critical issue among the other traffic and motorist issues that pose the highest safety impact to workers and motorists. In addition, the responses to Question #3.3 in the survey indicate "Lack of space available for workers/equipment" was identified as the issue that presents the highest safety impacts in terms of roadway and jobsite issues.

Further findings on the three riskiest processes during the traffic control set-up and removal operation reveal that both groups of interviewees have a similar perspective regarding the hierarchy of the processes for the top and second-most risky traffic control activities. Both groups viewed the part of the traffic control installation involving set-up of the first sign was the most dangerous process during set-up, whereas deploying traffic control devices close to an open on-ramp was perceived as the second-most risky process in the operation. Interestingly, the results from Questions #4.1 and #4.2 in the survey also show a very similar result, especially when asked to rank the safety risk level associated with the traffic control operation based on work zone area in which the "transition area" was identified as the highest risk area in work zones. Regarding the third-most risky activity, but not necessarily related to the process, the perspective from the ODOT group was different from the contractor group. On one hand, the ODOT group mentioned that a large speed variation in the work zone occurs while setting up and removing traffic control. This condition is not necessarily specific to one set-up/removal activity, but to the whole operation, and poses a significant safety impact to workers and motorists. The statement was also supported by evidence from a recent ODOT study on speed variation in work zones (Gambatese & Jin, 2021), which found that the difference between vehicle speed and average vehicle speed in a work zone was one of the factors that influences work zone crashes. On the other hand, the contractor group viewed picking up a knocked over cone on a live traffic lane as an unpredictable and potentially disastrous event that can adversely affect the safety of workers and motorists during the operation.

The traffic control step-up and removal challenges should be considered when planning and designing the traffic control operation. The identified challenges stated by ODOT and contractor personnel are complexity of road structure, lack of public understanding on risks associated with the traffic control set-up and removal operation, lack of labor force, limited budget, poor lighting, excessive glare, and a tight schedule for setting up and removing the traffic control. Those challenges are perceived as a “domino effect” where the one challenge is the root cause and ultimately effects the other tasks or activities. For instance, due to a limited budget, the contractor reduces the amount of protective equipment purchased and provides less training for their workers than the standard requirement for the lane closure operation. As a result, the combined conditions increase the probability of risk exposure to workers. This phenomenon may be an indication of the reasons why the finding from Question #3.2 in the survey indicated a lack of available equipment was ranked as the second highest impact to worker and motorist safety.

The safety and quality of the traffic control set-up and removal can be impacted differently depending on whether the work is performed in the daytime or nighttime. When asked which time of the day is preferable to perform the traffic control set-up and removal, both groups provided the same answer that daytime is preferable to nighttime operation. The groups indicated that it is generally safer in the daytime due to several reasons, such as better visibility in the daytime, daytime vehicle speed is lower as a result of high traffic volume, less probability of odd events such intimidating drivers (e.g., drunk drivers and intoxicated drivers), and less cost for the traffic control demand. This result is consistent with the results found from survey Questions #4.3 and #4.4, in which the majority of respondents typically ranked daytime operations as safer than nighttime traffic control operations. A previous study by Mostafavi et al. (2012) also reveals that nighttime traffic control operations are likely associated with more cost than daytime operations since nighttime operations require more traffic control devices to enhance the quality and brightness of a work zone, and require other costs associated with enhanced traffic control, and overtime payment. These impacts could potentially pose challenges for work crews to perform traffic control operations safely at night.

4.3 CASE STUDY INVESTIGATIONS

Analysis of the speed data began with compiling the mean vehicle speeds for the case study observations. Table 4.1 provides a compilation of the mean speed data for all 30 observations that were used in the analyses. The data is taken from the speed tables provided in the Appendix. Mean speed is the mean vehicle speed (mph) for the 1-minute intervals in the RITIS segment that contains the location of the treatment. For control observations where no treatment is present, the mean speed is the mean vehicle speed in the RITIS segment that contains the location of the RWA sign.

Table 4.1 organizes the mean speeds based on time and location. Mean speeds are grouped according to when they were recorded: 15 minutes before the operation started, during the traffic control operation, and 15 minutes after the operation ended. For each time period, mean speeds are shown upstream of the treatment or RWA signs, at the treatment or RWA signs location, and downstream of the treatment or RWA signs. Free-flow speeds (no impact of traffic volume on speed) were present for all observations except those instances in the shaded cells in the table. The non-free-flow speed data is omitted in analyses.

Table 4.1: Mean Vehicle Speeds Recorded for All Case Study Observations

No.	Treatment				Mean Speed (mph)								
	Control	Flares	PCMS	RSS	15 minutes before operation starts			During traffic control operation			15 minutes after operation ends		
					Upstream	At	Downstream	Upstream	At	Downstream	Upstream	At	Downstream
1	X				60.5	61.7	57.5	62.7	63.3	58.7	58.9	59.5	55.1
2		X			60.5	62.7	60.7	60.0	61.1	57.7	59.0	59.5	55.3
3		X			57.5	55.9	57.8	45.3	44.5	44.3	55.6	47.9	33.9
4		X			57.5	55.9	56.5	59.9	56.8	56.2	60.7	58.1	57.8
5		X			62.8	65.1	64.5	63.3	64.9	64.3	64.1	66.0	66.9
6	X				61.3	62.1	60.4	61.3	61.5	60.6	63.9	64.1	60.5
7	X				63.1	63.0	60.9	60.4	60.8	58.0	59.4	58.7	56.5
8		X			64.7	65.1	64.7	64.4	63.8	62.1	61.3	58.9	56.8
9		X			64.4	63.1	62.2	60.4	61.0	59.9	62.0	60.0	57.0
10	X				64.8	63.7	64.8	62.0	62.4	62.7	66.3	65.7	66.0
11	X				70.1	71.7	70.7	69.2	69.3	53.1	68.7	60.7	6.3
12	X				70.9	65.1	7.3	69.7	69.2	29.1	70.1	70.2	67.9
13		X			66.4	66.2	66.0	69.4	67.7	68.1	68.8	64.8	61.1
14		X			69.0	63.6	54.7	66.6	62.8	60.0	67.6	66.5	64.9
15	X				64.7	66.8	61.5	62.4	63.6	60.1	62.1	62.5	60.5
16	X				63.7	55.1	49.5	65.7	64.1	60.4	65.9	64.1	61.4
17			X		60.0	60.3	59.3	61.2	60.9	57.8	59.9	60.4	58.3
18			X		62.3	61.8	59.3	65.1	62.5	60.2	67.9	66.6	63.3
19			X		63.3	66.7	60.5	62.7	65.0	60.7	62.7	64.7	60.5
20			X		61.5	53.3	51.1	63.3	60.9	58.5	65.4	62.3	60.1
21		X	X		65.1	63.7	59.4	63.0	64.0	61.5	59.8	65.2	62.8
22		X	X		69.3	65.5	63.3	66.3	64.8	62.3	63.9	63.4	63.3
23		X	X		63.2	60.9	55.8	63.3	64.9	61.6	64.7	64.6	60.4
24		X	X		61.3	61.6	59.5	60.3	58.6	58.7	60.3	56.7	56.2
25		X	X		57.5	60.7	55.1	58.4	58.3	56.2	63.1	62.7	60.2
26		X	X		65.1	62.9	62.3	61.9	62.1	59.0	60.9	65.5	61.7

No.	Treatment				Mean Speed (mph)								
	Control	Flares	PCMS	RSS	15 minutes before operation starts			During traffic control operation			15 minutes after operation ends		
					Upstream	At	Downstream	Upstream	At	Downstream	Upstream	At	Downstream
27		X			60.5	59.0	59.1	61.2	58.7	57.7	63.1	62.3	57.9
28		X			65.4	65.5	63.8	62.4	63.3	62.5	66.9	66.5	64.1
29	X				63.6	64.3	64.3	65.1	65.4	65.2	64.3	65.3	67.0
30	X				61.1	63.1	64.7	62.8	63.5	64.8	61.4	63.2	64.7
Mean					63.37	62.54	58.57	62.66	62.32	58.73	63.29	62.55	58.28
Median					63.25	63.05	60.45	62.70	63.05	60.05	63.10	63.30	60.50
Minimum					57.50	53.30	7.30	45.30	44.50	29.10	55.60	47.90	6.30
Maximum					70.90	71.70	70.70	69.70	69.30	68.10	70.10	70.20	67.90
Standard Deviation					3.49	3.86	10.66	4.35	4.46	7.00	3.48	4.16	11.56
Variance					12.18	14.92	113.69	18.94	19.86	48.93	12.12	17.28	133.62
Chi-Square Statistic					9.840	14.257	9.974	6.504	3.567	8.174	3.945	10.548	10.209
Degrees of Freedom					11	11	11	11	11	11	11	11	11
p-Value					0.545	0.219	0.533	0.838	0.981	0.698	0.971	0.482	0.512

Table 4.1 notes:

Upstream = mean speed of the 1-minute intervals in the RITIS segment immediately upstream of the treatment or RWA signs (i.e., mean work zone entry speed)

At = mean speed of the 1-minute intervals in the RITIS segment that contained the treatment or RWA signs (i.e., mean speed at the treatment)

Downstream = mean speed of the 1-minute intervals in the RITIS segment immediately downstream of the treatment or RWA signs

Shaded cells: Traffic volume impeded free-flow speed. These data are omitted from the dataset in analyses.

Statistical analyses of the case study speed data were conducted with the goal of determining whether the applied treatments affect vehicle speed. The statistical analyses compared the speed data of two groups: control and treatment. Welch's t-test was used for the analysis for various reasons. The test is used for comparing the mean between two groups, whereas ANOVA is used to compare means between three or more groups. Welch's t-test assumes that both groups of data are sampled from populations that follow a normal distribution, but the test does not assume that the groups have the same variance and sample size. Therefore, Welch's t-test, rather than the traditional student t-test, was used because the present analyses compare two groups of data that have different sample sizes and unequal variances.

As indicated above, Welch's t-test also assumes that the population follows a normal distribution. The researchers used the Chi-Square Goodness-of-Fit test to assess the normality of the mean speed data for each location and time. The null hypothesis (H_0) for each Chi-Square Goodness-of-Fit test was that the data is normal. The alternative hypothesis (H_1) for each Chi-Square Goodness-of-Fit test was that the data is not normal. A p-value of 0.05 was used to assess statistical significance. P-values greater than 0.05 indicate that the data is normally distributed, and the null hypothesis should be accepted. The results of the Chi-Square Goodness-of-Fit tests are shown in Table 4.1. The p-values for all sets of data are greater than 0.05, indicating that all data sets are normally distributed. As an example, Figure 4.1 shows a histogram of the mean speeds recorded at the treatment/RWA sign location during the traffic control operations for all 30 case study observations. Therefore, the data meets the normality assumption of Welch's t-test.

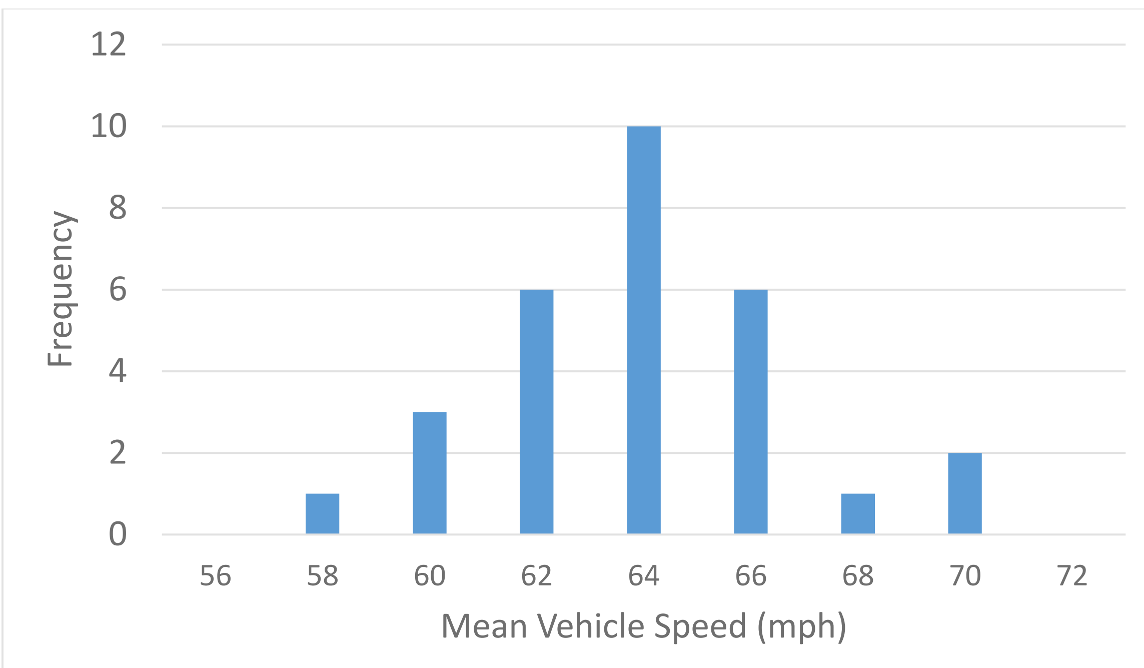


Figure 4.1: Histogram of recorded mean speeds at treatment/RWA sign location during traffic control operations for all case study observations (n = 30 observations)

Furthermore, to confirm that the data of the present study does not violate the t-test assumption of independence, visual examination of the data was performed. The data may suggest two types of dependence based on the data collection technique utilized: serial (time) dependence and spatial (location) dependence. With respect to serial dependence, a vehicle might drive through more than one RITIS segment in the work zone within the same 1-minute interval, so that the recorded speed taken in the same 1-minute interval at multiple locations might be from the same vehicle. For spatial dependence, the RITIS segments are located in a sequential order based on the direction of traffic in the work zones. As an example of the visual assessment performed, Figure 4.2 shows a plot of the 1-minute mean speeds with connecting lines between successive locations (upstream location, at the treatment location, and the downstream location) for the 15-minute time period before the traffic control operation started on Observation #8. Upon visual examination of the plot, there is no obvious trend across the RITIS segments, which suggests a strong argument for independence. Examination of similar plots of the data for the other case study observations leads to similar conclusions of independence.

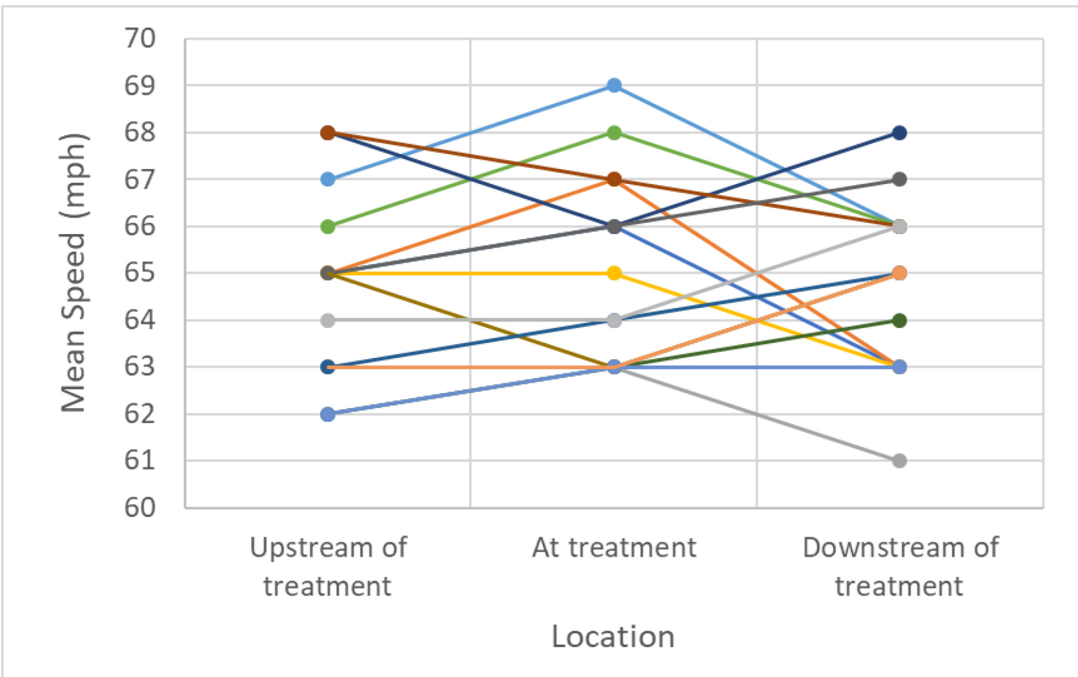


Figure 4.2: Example plot for visual assessment of independence: 15-minute period before traffic control operation started on Observation #8 (n = 15 time periods)

Following confirmation of normality and independence, Welch's t-test was then applied to examine the impacts of the treatments on mean vehicle speed. The analyses focused on two speed values: vehicle speed and vehicle speed differential.

4.3.1 Impact of Treatments on Vehicle Speed

As described above, mean speed is the mean vehicle speed for the 1-minute intervals in the RITIS segment that contains the location of the treatment. For control observations where no treatment is present, the mean vehicle speed in the RITIS segment that contains the location of the RWA sign is used. The hypotheses related to the mean vehicle speed analyses were as follows:

- H_0: There is no difference in mean vehicle speed between the control condition and treatment condition.

- H_1: There is a difference in mean vehicle speed between the control condition and treatment condition.

A 95% confidence interval (p-value = 0.05) was selected to assess statistical significance. If the computed p-value is more than 0.05, then the result suggests that the speeds recorded for the two groups are the same. In other words, the result does not support the hypothesis that the speed with the treatment is statistically different than the speed without the treatment, and the alternative hypothesis (H_1) should be rejected. However, if the computed p-value is less than 0.05, then statistical evidence was found to claim that there is a difference in the speed measurements, and the alternative hypothesis (H_1) should be accepted.

Figure 4.3 shows box plot distributions of the mean speed for each treatment at the treatment/RWA sign location during the traffic control operation. For all treatments, the mean speed recorded for all observations with the treatment added is lower than the mean speed of the control observations. Statistical analyses comparing each treatment to the control are provided below.

Figure 4.3: Box plots of recorded mean speeds at treatment/RWA sign location during traffic control operations for all case study observations.

4.3.1.1 Electronic Flares

Table 4.2 presents the analysis results related to the electronic flares. The analysis was conducted using the vehicle speeds recorded at the location of the flares for the treatment group, and at the RWA sign location for the control group, during the traffic control operation. The analysis shows a decrease in mean speed by an average of 3.9 mph (from 64.3 mph to 60.4 mph) when the electronic flares were added. The difference was not found to be statistically significant (one-tail p-value = 0.053, two-tail p-value = 0.107), but the p-value indicates suggestive evidence that the lower mean speeds were caused by the electronic flares.

Table 4.2: Analysis of Vehicle Speeds at Treatment Location During Traffic Control Operation – Treatment: Electronic Flares

Statistical Measurement	Control	Treatment: Electronic Flares
Mean speed (mph)	64.3	60.5
Variance	8.45	40.97
Number of observations	10	10
Hypothesized mean difference	0	
Degrees of freedom	13	
t-statistic	1.732	
p-value (one-tail)	0.053	
t-critical value (one-tail)	1.771	
p-value (two-tail)	0.107	
t-critical value (two-tail)	2.160	

4.3.1.2 PCMS

The analysis results related to the PCMS are shown in Table 4.3. The analysis was conducted using the vehicle speeds recorded at the PCMS location for the treatment group, and at the RWA sign location for the control group, during the traffic control operation. The analysis shows a decrease in mean speed by an average of 2.0 mph (from 64.3 mph to 62.3 mph) when the PCMS is added. The difference was not found to be statistically significant (one-tail p-value = 0.086, two-tail p-value = 0.171).

Table 4.3: Analysis of Vehicle Speeds at Treatment Location During Traffic Control Operation – Treatment: PCMS

Statistical Measurement	Control	Treatment: PCMS
Mean speed (mph)	64.3	62.3
Variance	8.45	3.75
Number of observations	10	4
Hypothesized mean difference	0	
Degrees of freedom	9	
t-statistic	1.487	
p-value (one-tail)	0.086	
t-critical value (one-tail)	1.833	
p-value (two-tail)	0.171	
t-critical value (two-tail)	2.262	

4.3.1.3 Electronic Flares and PCMS

Table 4.4 presents the analysis results for the combined treatment of the electronic flares and PCMS. The analysis was conducted using the vehicle speeds recorded at the flare/PCMS location for the treatment group, and at the RWA sign location for the control group, during the traffic control operation. The mean vehicle speed was less with the flares and PCMS present, decreasing by 2.2 mph on average from 64.3 mph to 62.1 mph. However, the difference was not found to be statistically significant (one-tail p-value = 0.092, two-tail p-value = 0.184).

Table 4.4: Analysis of Vehicle Speeds at Treatment Location During Traffic Control Operation – Treatments: Electronic Flares And PCMS

Statistical Measurement	Control	Treatments: Electronic Flares and PCMS
Mean speed (mph)	64.3	62.1
Variance	8.45	9.09
Number of observations	10	6
Hypothesized mean difference	0	
Degrees of freedom	10	
t-statistic	1.428	
p-value (one-tail)	0.092	
t-critical value (one-tail)	1.813	
p-value (two-tail)	0.184	
t-critical value (two-tail)	2.228	

4.3.2 Impact of Treatments on Vehicle Speed Differential

For the purposes of the present study, the mean speed differential is the calculated difference between the mean speed for the 1-minute intervals in the RITIS segment immediately upstream of the treatment (i.e., the mean work zone entry speed) and the mean speed for the 1-minute intervals in the RITIS segment that contained the treatment (i.e., the mean speed at the treatment). Speed differential indicates the extent to which vehicle speed changes when the drivers observe the treatments in place. Mean speed differential is calculated as the mean speed at the treatment minus the mean work zone entry speed. A positive mean speed differential value indicates that the mean speed increased as the vehicles travelled between the two locations, and a negative value indicates that the mean speed decreased between the two locations. For control observations (no treatment present), mean speed in the segment that contained the RWA signs was used in the calculation.

The hypotheses related to the mean speed differential analyses were as follows:

- H_0: There is no difference in mean speed differential between the control condition and treatment condition.
- H_1: There is a difference in mean speed differential between the control condition and treatment condition.

A 95% confidence interval (p-value = 0.05) was again selected to assess statistical significance. If the computed p-value is more than 0.05, then the result suggests that the speed differentials recorded for the two groups are the same and the alternative hypothesis (H_1) should be rejected. However, if the computed p-value is less than 0.05, then statistical evidence was found to claim that there is a difference in the speed differential, and the alternative hypothesis (H_1) should be accepted.

Figure 4.4 shows box plot distributions of the mean speed differential for each treatment during the traffic control operation. For all treatments, the mean speed differential recorded for all observations with the treatment added is negative (decrease in mean speed), while the mean speed differential of the control observations was positive (increase in mean speed). Statistical analyses comparing each treatment to the control are provided below.

Figure 4.4: Box plots of recorded mean speed differentials during traffic control operations for all case study observations.

4.3.2.1 Electronic Flares

The results of the speed differential analysis for the electronic flares are shown in Table 4.5. The analysis was conducted using speed differential for the vehicle speeds recorded at the location of the flares for the treatment group, and at the RWA sign location for the control group, during the traffic control operation. The analysis shows that, on average, vehicle speeds increased by 0.18 mph for the control observations and decreased by 0.83 mph for the treatment observations when the electronic flares were added. The difference was not found to be statistically significant (one-tail p-value = 0.072, two-tail p-value = 0.144), but the p-value indicates suggestive evidence that the decrease in vehicle speed differential was due to the application of the electronic flares.

Table 4.5: Analysis of Vehicle Speed Differential at Treatment Location During Traffic Control Operation – Treatment: Electronic Flares

Statistical Measurement	Control	Treatment: Electronic Flares
Mean speed differential (mph)	0.18	-0.83
Variance	0.582	3.58
Number of observations	10	10
Hypothesized mean difference	0	
Degrees of freedom	12	
t-statistic	1.565	
p-value (one-tail)	0.072	
t-critical value (one-tail)	1.782	
p-value (two-tail)	0.144	
t-critical value (two-tail)	2.179	

4.3.2.2 PCMS

Table 4.6 shows the results of the speed differential analysis for the PCMS treatment. The analysis was conducted using speed differential for the vehicle speeds recorded at the PCMS location for the treatment group, and at the RWA sign location for the control group, during the traffic control operation. With the PCMS present, vehicle speeds in the RITIS segment containing the PCMS were on average 0.75 mph lower than when the vehicles were upstream of the PCMS. However, the difference was not found to be statistically significant (one-tail p-value = 0.242, two-tail p-value = 0.484).

Table 4.6: Analysis of Vehicle Speed Differential at Treatment Location During Traffic Control Operation – Treatment: PCMS

Statistical Measurement	Control	Treatment: Electronic Flares
Mean speed differential (mph)	0.18	-0.75
Variance	0.582	5.22
Number of observations	10	4
Hypothesized mean difference	0	
Degrees of freedom	3	
t-statistic	0.797	
p-value (one-tail)	0.242	
t-critical value (one-tail)	2.353	
p-value (two-tail)	0.484	
t-critical value (two-tail)	3.182	

4.3.2.3 *Electronic Flares and PCMS*

Table 4.7 presents the results of the speed differential analysis for the combined treatment of the electronic flares and PCMS. The analysis was conducted using speed differential for the vehicle speeds recorded at the flare/PCMS location for the treatment group, and at the RWA sign location for the control group, during the traffic control operation. With the flares and PCMS present, vehicle speeds in the RITIS segment containing the flares and PCMS were on average 0.08 mph lower than when the vehicles were upstream of the PCMS. The differential is very small, and when compared to the differential for the control, it was not found to be statistically significant (one-tail p-value = 0.334, two-tail p-value = 0.669).

Table 4.7: Analysis of Vehicle Speed Differential at Treatment Location During Traffic Control Operation – Treatment: Electronic Flares And PCMS

Statistical Measurement	Control	Treatment: Electronic Flares
Mean speed differential (mph)	0.18	-0.083
Variance	0.582	1.74
Number of observations	10	6
Hypothesized mean difference	0	
Degrees of freedom	7	
t-statistic	0.446	
p-value (one-tail)	0.334	
t-critical value (one-tail)	1.895	
p-value (two-tail)	0.669	
t-critical value (two-tail)	2.364	

5.0 CONCLUSIONS AND RECOMMENDATIONS

This research study aimed to identify ways to improve work zone safety during the period when temporary traffic control is being set-up, removed, and modified. The study goal was achieved by investigating the risks and safety hazards associated with traffic control operations and developing and evaluating potential recommendations to improve motorist and worker safety during the operations. The study utilized multiple different research methods: a review of existing literature on work zone safety, industry and state DOT surveys, on-site observations of temporary traffic control operations, focus group interviews, and case study investigations of selected additional traffic control measures. This section of the report presents conclusions that can be drawn from the overall study and limitations in their application in practice. The findings from the literature review and industry survey were reported in the Phase I report and are summarized below to provide a comprehensive presentation of the study conclusions. Recommendations for implementation of the findings in practice, and for further research, are also provided.

5.1 CONCLUSIONS

As described in the Phase I report, multiple existing technologies are available to assist work crews in safely performing traffic control operations. An automated cone retrieval truck and a standing platform for placing and removing devices are two examples of beneficial technologies. The innovative technologies are effective in mitigating worker exposure to direct contact with and involvement in hazardous activities. State DOTs and roadway contractors should consider incorporating the existing and newly developed safety technologies into their traffic control operations as doing so is expected to enhance roadway safety while also improving worker productivity.

Guidance on work zone traffic control set-up and removal procedures is available from state DOTs for implementation in practice. The general process described for traffic control set-up on a high-speed roadway begins upstream of the work zone and proceeds toward the downstream end of the work zone, excluding detour installation. The process is reversed for removal operations, starting from the downstream end of the termination area and working back upstream to the advance warning area. However, existing guidance provides limited descriptions and detail on the specific set-up and removal steps within this process, and the guidance varies from state to state. State DOTs could benefit from the creation of detailed guidance that is consistent from one state to another. The most common guidance for work zone traffic control operations is for stationary lane closure installation and removal. Availability of guidance for other work operations and conditions (e.g., installing a work zone closure on a multi-lane freeway that requires lane closure of two or more lanes) is still insufficient for contractors and state DOTs. Further development of traffic control set-up and removal procedures for additional conditions is needed.

The study results confirm that traffic control crews are exposed to dangerous situations while performing work zone traffic control operations. The highest risk traffic control activities identified by those involved in the survey and focus group interviews were:

- placement of the initial signs and merging taper,
- retrieving knocked over cones and barrels in a live traffic lane, and
- working on device installation and removal close to an open on-ramp.

Furthermore, high-risk and moderate-risk situations are present in all of the traffic control activities. The participants felt that high-risk situations exist particularly when there is:

- difficulty in accessing lanes or blocking traffic,
- a lack of space available for workers and equipment, and
- vehicles passing by at high speeds.

Based on the participant responses, moderate-risk situations are present when:

- workers do not follow the planned process,
- there is a lack of light during the operation (e.g., during nighttime work), and
- aggressive drivers are present.

The findings show that both high- and moderate-risk situations are present in all locations of the work zone, starting from the advance warning area through to the termination area. Extra effort and attention should be invested to mitigate the risk associated with the hazardous conditions present during traffic control activities.

Furthermore, based on the perspectives of those who participated in the survey and focus group interviews, daytime traffic control operations (from 07:00 to 19:00) are generally safer than nighttime operations (from 19:00 to 07:00). The primary reasons given for such a claim were:

- daytime generally contains a higher volume of traffic which results in lower speeds of passing vehicles.
- better visibility in the daytime.
- lower costs for enhancing traffic control devices for daytime operation, and
- smaller probability of odd events, such as intoxicated drivers and stressed drivers on the roadway, occur during the daytime than in the nighttime.

The participants also believe that the most hazardous condition during nighttime traffic control operations occurs when there is high traffic volume, but no congestion.

The on-site observations revealed the elements of traffic control set-up and removal that are risky for motorists and workers, some of which are similar to those found from the survey and focus group interviews. Examples of elements that induce risks during the traffic control operation are, among others:

- workers reading the traffic control plans while driving to the work zone,
- insufficient space available for protection vehicles to cover the work vehicles,
- setting up signs in the wrong order,
- a misleading arrow sign on the arrow board mounted on a truck,
- setting up and removing traffic control close to an open on-ramp, and
- installing the initial signs and closure taper.

The results of the observations indicate that further risk mitigation measures are needed, including work planning, worker training, and oversight regarding worker behavior. Written guidance and training are needed that address worker actions and decisions in instances when real-time field conditions deviate from planned and expected conditions, i.e., when improvisation is needed, and when further information is needed.

To reduce the impacts and mitigate the risks identified in traffic control set-up and removal operations, the current study revealed suggested additional traffic control measures for use in practice and further research. The suggested treatments are reported in Tables 2.1 and 2.2 herein. Examples of the potential treatments include placing flashing blue lights on cone devices, placing a radar speed board with a PCMS in advance of the RWA sign, implementing a rolling slowdown during the initial sign set-up, and using an automated cone retrieval truck during set-up and removal, among others. The majority of the suggested treatments primarily target speed reduction in work zones, which aims to increase safety during both traffic control placement and removal.

Following a review of the suggested additional traffic control measures, the TAC felt that three of the suggested measures were promising: electronic flares, PCMS, and radar speed sign. Their opinion was based in part on the potential for the measures to mitigate the risk in high-risk situations, ease of implementation, ability to be located upstream of the traffic control operations, low cost, and availability. In addition, previous ODOT research has shown the beneficial effects of a PCMS and radar speed sign on speed reduction in work zones. Statistical analyses of implementations of the three treatments on the six case study projects revealed the following findings:

- Mean vehicle speed at treatment location:
  - Electronic flares placed on the shoulder upstream of the RWA sign led to lower mean speeds (3.9 mph less) at the flare location during the traffic control operation. The difference was not found to be statistically significant using a 95%

confidence interval, but the p-value indicates suggestive evidence that the lower mean speeds were due to the electronic flares.

    - Mean speed during the traffic control operation with the PCMS present upstream of the RWA sign was 2.0 mph less, on average, than without the PCMS present. However, the difference was not found to be statistically significant and therefore cannot be confidently attributed to the presence of the PCMS.

    - The combination of electronic flares and PCMS resulted in a reduction in mean speed at the treatment location of 2.2 mph during the traffic control operation. However, the difference in mean speed was not found to be statistically significant and therefore cannot be confidently attributed to the combined presence of the flare and PCMS.

- Mean vehicle speed differential between work zone entry speed and speed at treatment location:

    - The mean speed differential during the traffic control operation changed from +0.18 without the electronic flares present to -0.83 with the electronic flares present. The results reveal that drivers increased their speed slightly without the flares present and decreased their speed with the electronic flares present. The difference was not found to be statistically significant using a 95% confidence interval, but the p-value indicates suggestive evidence that the change in mean speed differential was related to the electronic flares.

    - Mean speed during the traffic control operation with the PCMS present upstream of the RWA sign was 0.75 mph less, on average, compared to 0.18 mph without the treatment present. However, the difference was not found to be statistically significant and therefore cannot be confidently attributed to the presence of the PCMS.

    - Similar to the treatment with just the PCMS, the magnitude of speed differential changed from +0.18 mph (slight increase in speed) to -0.083 mph (slight decrease in speed) for those case study observations with the combination of flares and PCMS. However, the difference was not found to be statistically significant and therefore cannot be confidently attributed to the presence of the flares and PCMS.

The speed reductions associated with the PCMS are consistent with those found in previous ODOT research (Gambatese and Zhang, 2014; Gambatese et al., 2013). As mentioned above, the lack of case study projects on which an additional radar speed sign was available prevented further evaluation of a radar speed sign as a treatment in the case studies. However, the speed impacts associated with the presence of a radar speed sign have been studied previously (Gambatese and Jafarnejad, 2015; Gambatese and Zhang, 2014; Gambatese et al., 2013) and can be considered applicable in the present study context as well. Previous research has shown that the presence of a radar speed sign leads to a reduction in vehicle speeds in work zones.

5.2 LIMITATIONS

The study contains limitations that can affect the ability to extend results to larger populations with confidence. For example, the focus group interviews solely targeted participants from ODOT and roadway construction and maintenance contractors in Oregon. Therefore, the results could be biased towards perceptions held in Oregon and not represent the perceptions of the population across the US as a whole regarding safety risks associated with work zone traffic control set-up and removal operations. The scope of inference is more reliable when making judgements about risk present in traffic control operations in the State of Oregon.

Furthermore, the small samples of participants from ODOT and contractor groups introduce additional impacts on data reliability into the study. Nevertheless, the industry and state surveys, along with the site observations, reveal some common findings with the focus group interview results when investigating subjects related to work zone traffic control set-up and removal. As a result, the use of multiple methods provides convincing evidence to confirm that the results from the focus group interviews are logical and accurate. Moreover, the results in the personal demographics section of the survey reveal the average experience of respondents working in the transportation and construction industry was 13 years, with the majority of respondents indicating that they are very familiar with traffic control planning, design, and execution. These results strongly help to further verify that the participants have sufficient experience with respect to work zone traffic control placement and removal, thereby supporting the accuracy of the study findings.

For the case study observations, generalization of the results to all projects with a high level of confidence is limited given the number of observations and case study projects. Potentially confounding variables, such as the specific conditions of the roadway, sequence of traffic control activities, amount and sizes of work equipment present, and dynamic nature of the work operation, may exist within the datasets and, as a result, affect the accuracy of the results. In addition, while differences in mean speeds and mean speed differential were confirmed, the small magnitude of the differences may not have any practical effect. A decrease in mean speed of 3 mph or less, for example, may not facilitate safer work operations nor result in any difference in frequency and/or severity of work zone crashes.

Lastly, consistent with prior work zone research studies involving other traffic control measures, the difference in mean speed resulting from the applied treatments is not constant throughout the entire length of the work zone. The difference in mean speed is typically greatest at or near the added traffic control measure and then diminishes downstream of the traffic control measure.

Overall, notwithstanding the limitations present, the level of impact of the limitations on the overall study is believed to be very low. The researchers believe the findings are valid for future use and reference and can be widely distributed both locally and nationally for practical application to enhance safety during the work zone traffic control set-up and removal process.

5.3 RECOMMENDATIONS

State guidelines and procedures for work zone traffic control set-up and removal are available to a limited extent and generally contain very broad guidance for their use. It is essential for state DOTs and future studies to develop a detailed temporary traffic control standard procedure for each specific type of work zone operation. The procedure should contain the number of resources to be used in the work zone traffic control operations such as the quantity of traffic control devices, the timing of each traffic control activity, and the location of workers and work vehicles to be positioned in the work zone while installing and removing the traffic control. This information helps ensure the proper standard of care in traffic control operations is followed and maintained throughout the whole operation. Providing this information is expected to increase efficiency in the traffic control operation and enhance the safety of both motorists and workers in work zones.

To ensure the highest level of safety performance during traffic control operations, roadway construction and maintenance contractors should only attempt to perform traffic control work activities when sufficient protective devices and equipment are available. Following the traffic control installation and removal plan and guidelines is a must. When field conditions change, a contingency plan should be in place to take alternative actions. A traffic control contingency plan should include at least the following elements: alternative methods of device placement and removal, and escape routes for an emergency event. In addition, the plan should be developed in advance of the start of the lane closure operation. Contractors should actively communicate with traffic control crews and work zone traffic control planners on safety plans and procedures that affect traffic control set-up and removal operation. Inspecting traffic control device quality and conditions should always be performed before the work takes place. It is necessary to maintain safe traffic control operation practices throughout the entire work zone placement and removal, even while the work operations are taking place.

The researchers recommend application of the three treatments – electronic flares, PCMS, and radar speed sign – in practice. The treatments should be placed upstream of the RWA signs and be the first traffic control measures placed on the roadway. Used in combination, these additional treatments will help get the attention of drivers and alert them of the traffic control operations downstream. The additional treatments should also be the last traffic control measures removed from the roadway during removal of the traffic control. It is recommended that ODOT traffic control guidelines be updated to include the use and location of these additional traffic control measures.

If future research is conducted, it is recommended that the research examines the risks in more detail and explore the three selected treatments further. Future research should aim to assess pre-defined risks associated with each traffic control activity, as well as identify how worker and driver behavior changes over periods of time based on given roadway factors such as weather, vehicle speed, traffic volume, lack of work crew members, level of visibility, road configuration, and so forth. As a result, the research will help road contractors to better visualize risks in reality in advance, prior to going out to the work zone site, and to be prepared to take additional measures against hazards. The research may be best accomplished using a driving simulator to simulate the risks rather than expose research participants to the actual risks.

The current study involved a limited number of participants and case study projects. Future studies should target more participants from both local and national locations, and additional case study projects, to ensure that the study results can be interpreted widely and are accurate for the current research topic.

Due to time and budget constraints, the present study only implemented and evaluated electronic flares and a PCMS in the case study projects. However, additional investigation of the recommended treatments should be carried out further to examine the level of effectiveness of each treatment in reducing work zone crashes, risk exposure, and vehicle travel speed in work zones. The additional research will benefit those who work in the transportation and construction industry and promote a high level of safety for motorists driving through roadway work zones. For the flares, in particular, further research is recommended to document their effectiveness in daylight and in adverse weather conditions (e.g., rainy weather).

In addition, as noted above, the study did not specifically examine traffic control operations during planned and unplanned modifications to the traffic control in-place. Hence, additional research is recommended that explores best practices for performing the modifications and recommended additional traffic control devices to implement while the modifications take place. The research should examine different types of planned and unplanned modifications and produce guidance for workers in each situation.

Lastly, further research is recommended to investigate ways to maintain slower driving speeds and safe driving behavior through the entire work zone, not just at and immediately downstream of a traffic control device. This recommendation relates the period of time during traffic control set-up and removal, and during the period of time when the traffic control is in place and work is being performed. As is observed in past work zone speed studies, drivers commonly slow down when they enter the work zone and/or see particular traffic control devices (e.g., a radar speed sign) and then speed up downstream. Increases in speed may occur for a variety of reasons including, for example, when drivers do not see any workers and equipment present. Research should be conducted to examine the correlations between the length of a work zone, vehicle speed at different locations in the work zone, and the distance between temporary traffic control devices. Decreasing the distance between traffic control devices and/or adding more devices may provide a more optimal result. A desired output from the research would be guidance on spacing of different types of traffic control devices and the use of multiple traffic control devices (e.g., radar speed signs spaced every half mile) for different work zone lengths to promote lower vehicle speeds and speed variation throughout the entire work zone.

6.0 REFERENCES

Gambatese, J. & Jafarnejad, A. (2015). *Evaluation Of Radar Speed Display for Mobile Maintenance Operations* (No. OR-RD-16-09; p. 180). Salem, OR: Oregon Department of Transportation, Research Section. Retrieved from: http://www.oregon.gov/ODOT/Programs/ResearchDocuments/RSS_Final_Report_OR_RD_16_09.pdf.

Gambatese, J. & Jin, Z. (2021). *Speed Variation and Safety In Work Zones* (No. FHWA-OR-RD-22-01). Salem, OR: Oregon Department of Transportation, Research Section. Retrieved from: https://www.oregon.gov/odot/Programs/ResearchDocuments/SPR822SpeedVariationinWorkZones.pdf.

Gambatese, J. & Moeung, S.R. (2022). *Best Practices For Work Zone Safety During Traffic Control Placement, Removal, And Modification – Phase I* (Report No. FHWA-OR-RD-23-06). Salem, OR: Oregon Department of Transportation, Research Section. Retrieved from https://www.oregon.gov/odot/Programs/ResearchDocuments/SPR839WZTrafficControl.pdf.

Gambatese, J.A. & Zhang, F. (2014). *Safe And Effective Speed Reductions for Freeway Work Zones Phase 2* (Report No. FHWA-OR-RD-15-04). Salem, OR: Oregon Department of Transportation, Research Section. Retrieved from https://www.oregon.gov/odot/Programs/ResearchDocuments/SPR769_HighSpeed_Final.pdf.

Gambatese, J.A., Zhang, F., & Vahed, A.M. (2013). *Implementing Speed Reductions at Specific Interstate Work Zones From 65 Mph To 35 Mph* (Report No. FHWA-OR-RD-13-11). Salem, OR: Oregon Department of Transportation, Research Section. Retrieved from http://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR751_SpeedReductions.pdf.

Mostafavi, A., Valentin, V., Abraham, D. M., & Louis, J. (2012). Assessment Of the Productivity of Nighttime Asphalt Paving Operations. *Journal Of Construction Engineering and Management*, *138*(12), 1421–1432. https://doi.org/10.1061/(asce)co.1943-7862.0000531.

Oregon Department of Transportation (ODOT) (2018). *Portable Changeable Message Sign Handbook*, 2nd Edition. Salem, OR: Oregon Department of Transportation. Retrieved from https://www.oregon.gov/ODOT/Engineering/Docs_TrafficEng/PCMS-Handbook.pdf.

Oregon Department of Transportation (ODOT) (n.d.). *Regional Integrated Transportation Information System*. Salem, OR: Oregon Department of Transportation. Retrieved from: https://www.oregon.gov/odot/Data/Pages/RITIS.aspx.

Smart Sequential Road Flares—Road Safety. (n.d.). Retrieved December 20, 2023, from Pi-Lit website: https://pi-lit.com/product/smart-sequential-road-flares/.

Veneziano, D., Ye, Z., Westoby, K., Turnbull, I., & Hayden, L. (2012). "Guidance for Radar Speed Sign Deployments." *91^{st} Annual Meeting of the Transportation Research Board (TRB)*, Washington, D.C., Jan. 2012.

APPENDIX A: CASE STUDY OBSERVATIONS – RITIS SEGMENT CODES

RITIS Segment Codes for Case Study Projects #1 And #2 (Observations #1, #2, #3, #6, And #7): OR-217 Northbound, Kruse Way to US-26

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114P05200	I-5/Kruse Way	0.11	45.4188	-122.74357	45.42035	-122.74391
114+04411	72^{ND} Ave./Exit 7	0.52	45.42035	-122.74391	45.42596	-122.75085
114P04411	72^{ND} Ave./Exit 7	0.23	45.42596	-122.75085	45.42804	-122.75442
114+04412	OR-99W/Pacific Hwy./Exit 6	0.32	45.42804	-122.75442	45.43174	-122.75832
114P04412	OR-99W/Pacific Hwy./Exit 6	0.54	45.43174	-122.75832	45.43775	-122.76539
114+04413	Greenburg Rd./Exit 5	0.54	45.43775	-122.76539	45.44233	-122.77434
114P04413	Greenburg Rd./Exit 5	0.37	45.44233	-122.77434	45.44526	-122.78062
114+04414	OR-210/Scholls Ferry Rd./Exit 4	0.31	45.44526	-122.78062	45.449	-122.7837
114P04414	OR-210/Scholls Ferry Rd./Exit 4	0.30	45.449	-122.7837	45.45332	-122.78448
114+04415	Hall Blvd./Exit 4A	0.31	45.45332	-122.78448	45.45783	-122.78458
114P04415	Hall Blvd./Exit 4A	0.28	45.45783	-122.78458	45.46177	-122.78569
114+04416	Denney Rd./Exit 3	0.32	45.46177	-122.78569	45.4664	-122.78608
114P04416	Denney Rd./Exit 3	0.38	45.4664	-122.78608	45.47195	-122.78607
114+04417	Allen Blvd./Exit 2B	0.22	45.47195	-122.78607	45.47476	-122.78797
114P04417	Allen Blvd./Exit 2B	0.34	45.47476	-122.78797	45.47912	-122.79141

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114+04418	OR-10/Beaverton Tigard Fwy.	0.28	45.47912	-122.79141	45.48302	-122.79282
114P04418	OR-10/Beaverton Tigard Fwy.	0.24	45.48302	-122.79282	45.48654	-122.79283
114+04419	OR-8/Canyon Rd./Exit 2	0.29	45.48654	-122.79283	45.49074	-122.7921
114P04419	OR-8/Canyon Rd./Exit 2	0.23	45.49074	-122.7921	45.49399	-122.79155
114+04420	Walker Rd./Exit 1	0.10	45.49399	-122.79155	45.49549	-122.79126
114P04420	Walker Rd./Exit 1	0.40	45.49549	-122.79126	45.5009	-122.78863
114+04421	US-26	0.38	45.5009	-122.78863	45.50426	-122.78241
114P04421	US-26	0.37	45.50426	-122.78241	45.50859	-122.77801
114P14124	Ramp OR-217 to US-26 West*	0.42	45.50859	-122.77801	45.51031	-122.78316
114P14126	Ramp OR-217 to US-26 West*	0.53	45.51031	-122.78316	45.51371	-122.79284

* Intersection name given by authors; not provided by RITIS

RITIS Segment Codes for Case Study Project #3 (Observations #4, #8, And #9): US-26 Eastbound, Exit 65 To Exit 71

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114-04377	Cornell Rd./Exit 65	0.23	45.53224	-122.84244	45.53065	-122.83820
114N04377	Cornell Rd./Exit 65	0.27	45.53065	-122.83820	45.52880	-122.83332
114-04376	Murray Blvd./Exit 67	0.73	45.5288	-122.83332	45.52381	-122.82013
114N04376	Murray Blvd./Exit 67	0.55	45.52381	-122.82013	45.51998	-122.81015
114-04375	Cedar Hills Blvd./Exit 68	0.65	45.51998	-122.81015	45.51557	-122.79831
114N04375	Cedar Hills Blvd./Exit 68	0.62	45.51557	-122.79831	45.51137	-122.78693
114-04374	OR-217/Exit 69	0.28	45.51137	-122.78693	45.50948	-122.78174
114N04374	OR-217/Exit 69	0.54	45.50948	-122.78174	45.50660	-122.77143
114-04373	Camelot Ct.	0.84	45.50660	-122.77143	45.50586	-122.75427
114N04373	Camelot Ct.	0.28	45.50586	-122.75427	45.50666	-122.74860
114-04372	OR-8	0.14	45.50666	-122.74860	45.50724	-122.74586
114N04372	OR-8	0.34	45.50724	-122.74586	45.50870	-122.73919
114-04371	Skyline Blvd./Exit 71	0.154992	45.5087	-122.73919	45.50866	-122.73599
114N04371	Skyline Blvd./Exit 71	0.192922	45.50866	-122.73599	45.50869	-122.73201

RITIS segment codes for Case Study Project #3 (Observations #5 and #10): US-26 Westbound, Exit 71 to Exit 65

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114+04371	Skyline Blvd./Exit 71	0.43	45.50844	-122.72291	45.50895	-122.73121
114P04371	Skyline Blvd./Exit 71	0.23	45.50895	-122.73121	45.50881	-122.73584
114+04372	OR-8	0.03	45.50881	-122.73584	45.50881	-122.73637
114P04372	OR-8	0.46	45.50881	-122.73637	45.50744	-122.74565
114+04373	Camelot Ct.	0.18	45.50744	-122.74565	45.50668	-122.74926
114P04373	Camelot Ct.	0.05	45.50668	-122.74926	45.50654	-122.75037
114+04374	OR-217/Exit 69	1.12	45.50654	-122.75037	45.50711	-122.77326
114P04374	OR-217/Exit 69	0.60	45.50711	-122.77326	45.51064	-122.78448
114+04375	Cedar Hills Blvd./Exit 68	0.28	45.51064	-122.78448	45.51253	-122.78968
114P04375	Cedar Hills Blvd./Exit 68	0.48	45.51253	-122.78968	45.51584	-122.7985
114+04376	Murray Blvd./Exit 67	0.69	45.51584	-122.7985	45.52067	-122.81087
114P04376	Murray Blvd./Exit 67	0.50	45.52067	-122.81087	45.52404	-122.82003
114+04377	Cornell Rd./Exit 65	0.72	45.52404	-122.82003	45.52908	-122.83308
114P04377	Cornell Rd./Exit 65	0.26	45.52908	-122.83308	45.53082	-122.83791

RITIS Segment Codes for Case Study Project #4 (Observations #11, #12, #13, And #14): I-5 Southbound, Exit 271 To Exit 258

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114N04429	OR-214/Exit 271	0.67	45.15429	-122.878	45.14639	-122.886
114-04428	Brooklake Rd./Exit 263	7.78	45.14659	-122.88547	45.05241	-122.97143
114N04428	Brooklake Rd./Exit 263	0.45	45.05241	-122.97143	45.04635	-122.9747
114-04427	OR-99E Bus./Salem Expy./Exit 260	2.65	45.04635	-122.9747	45.01044	-122.99405
114N04427	OR-99E Bus./Salem Expy./Exit 260	0.90	45.01044	-122.99405	44.99818	-123.00045
114-04426	OR-99E/Exit 258	0.84	44.99818	-123.00045	44.98691	-122.99567

RITIS Segment Codes for Case Study Project #5 (Observations #15 – #26): I-5 Northbound, Exit 292 To Exit 295

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114+04439	OR-217/Exit 292	0.36	45.41164	-122.744	45.41685	-122.744
114P04439	OR-217/Exit 292	0.60	45.41685	-122.744	45.42559	-122.744
114+04440	Haines St./Exit 293	0.40	45.42559	-122.744	45.43143	-122.744
114P04440	Haines St./Exit 293	0.22	45.43143	-122.744	45.43463	-122.744
114+04441	OR-99W/Barbur Blvd./Exit 294	0.23	45.43463	-122.744	45.43802	-122.744
114P04441	OR-99W/Barbur Blvd./Exit 294	0.66	45.43802	-122.744	45.44521	-122.736
114+04442	Capitol Hwy./Exit 295	0.82	45.44521	-122.736	45.45333	-122.725

RITIS Segment Codes for Case Study Project #6 (Observations #27 And #28): I-205 Southbound, Exit 12 To Exit 10

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114-04391	OR-212/OR-224/Exit 12	0.39	45.41587	-122.574	45.41037	-122.572
114N04391	OR-212/OR-224/Exit 12	0.58	45.41037	-122.572	45.4021	-122.572
114-04390	82ND Dr./Exit 11	1.04	45.4021	-122.572	45.38755	-122.578
114N04390	82ND Dr./Exit 11	0.48	45.38755	-122.578	45.3808	-122.581
114-04389	OR-213/Exit 10	0.49	45.3808	-122.581	45.37547	-122.586
114N04389	OR-213/Exit 10	0.30	45.37547	-122.586	45.37237	-122.591

RITIS Segment Codes for Case Study Project #6 (Observations #29 And #30): I-205 Northbound, Exit 9 To Exit 12

RITIS Segment Code	Intersections	Segment Length (miles)	Start Latitude	Start Longitude	End Latitude	End Longitude
114+04388	OR-99E/Exit 9	0.23	45.36388	-122.606	45.36509	-122.602
114P04388	OR-99E/Exit 9	0.27	45.36509	-122.602	45.36671	-122.597
114+04389	OR-213/Exit 10	0.48	45.36671	-122.597	45.37222	-122.591
114P04389	OR-213/Exit 10	0.47	45.37222	-122.591	45.37709	-122.584
114+04390	82ND Dr./Exit 11	0.31	45.37709	-122.584	45.38074	-122.58
114P04390	82ND Dr./Exit 11	0.35	45.38074	-122.58	45.38562	-122.579

APPENDIX B: CASE STUDY OBSERVATIONS – TRAFFIC CONTROL

Temporary Traffic Control Measures: Observation #1 (Set-Up) On Case Study Project #1

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
RWA	114P04411	NA	NA
RWA	114+04412	NA	NA
Right Lane Closed Ahead	114P04412	NA	NA
Merge Sign	114P04412	NA	NA
Start of Taper	114+04413	NA	NA
Arrow Board	114+04413	NA	NA
End of Taper	114+04413	NA	NA
Work Zone Ends	114P04413	NA	NA

NA = Not available or applicable

Temporary Traffic Control Measures: Observation #2 (Set-Up) On Case Study Project #1

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
RWA	114P04411	NA	NA
Flares	114+04412	06:47	07:47
RWA	114+04412	NA	NA
Right Lane Closed Ahead	114P04412	07:11	NA
Merge Sign	114P04412	07:12	NA
Arrow Board	114+04413	07:13	NA
Start of Taper	114+04413	07:18	NA
End of Taper	114+04413	07:27	NA
Work Zone Ends	114+04413	NA	NA

NA = Not available or applicable

Temporary Traffic Control Measures: Observation #3 (Set-Up) On Case Study Project #2

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114+04415	21:36	23:13
RWA	114+04415	R: 21:56 L: 21:36	NA
Left Lane Closed Ahead	114+04416	R: 22:00 L: 21:43	NA
Merge Sign	114P04416	R: 22:02 L: 21:44	NA
Start of Taper	114P04416	22:06	NA
Arrow Board	114P04416	22:06	NA
End of Taper	114P04416	22:18	NA
Work Zone Ends	114+04417	NA	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observation #4 (Set-Up) On Case Study Project #3

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114-04375	00:56	01:36
RWA	114N04375	00:56	NA
Right Lane Closed Ahead	114N04375	01:03	NA
Merge Sign	114-04374	01:05	NA
Start of Taper	114N04374	01:06	NA
Arrow Board	114N04374	NA	NA
Arrow Board	114N04374	NA	NA
End of Taper	114N04374	01:07	NA
Work Zone Ends	114N04374	NA	NA

NA = Not available or applicable

Temporary Traffic Control Measures: Observation #5 (Set-Up) On Case Study Project #3

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114P04372	00:13	01:36
RWA	114P04372	00:13	NA
Left Lane Closed Ahead	114+04374	00:19	NA
PCMS	114+04374	00:21	NA
Merge Sign	114+04374	00:23	NA
Start of Taper (A-lane)	114+04374	00:26	NA
Arrow Board	114+04374	00:26	NA
End of Taper (A-lane)	114+04374	00:28	NA
Arrow Board	114+04374	00:30	NA
Start of Taper (B-lane)	114P04374	01:06	NA
End of Taper (B-lane)	114P04374	01:07	NA
Work Zone Ends	114P04374	NA	NA

NA = Not available or applicable

Temporary Traffic Control Measures: Observations #6 (Set-Up) And #7 (Removal) On Case Study Project #1

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
RWA	114P04420	R: 20:16 L: 20:01	R: 21:44 L: 21:35
PCMS	114+04421	NA	NA
Right Lane Closed Ahead	114+04421	R: 20:18 L: 20:03	R: 21:46 L: 21:36
Merge Sign	114P04421	R: 20:20 L: 20:04	R: 21:47 L: 21:38
Start of Tapers	114P14124	20:28	21:30
Arrow Board	114P14124	20:28	21:30
End of Taper	114P14124	20:35	21:19
Work Zone Ends	114P14124	NA	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #8 (Set-Up) And #9 (Removal) On Case Study Project #3

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114N04376	19:50	00:15
RWA	114N04376	R: 19:50 L: 20:05	00:15
Left Lane Closed Ahead	114-04375	R: 19:53 L: 20:07	00:18
Merge Sign	114-04375	R: 19:54 L: 20:08	00:20
Merge Sign (second)	114N04375	R: 19:55 L: 20:08	23:46
Arrow Board	114N04375	20:10	23:55
Start of Taper (A-lane)	114N04375	20:10	23:45
End of Taper (A-lane)	114N04375	20:35	23:45
Arrow Board	114-04374	21:50	23:45
Start of Taper (B-lane)	114-04374	21:50	23:45
End of Taper (B-lane)	114-04374	21:57	23:45
Work Zone Ends	114N04374	NA	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observation #10 (Set-Up) On Case Study Project #3

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
RWA	114+04374	R: 22:22 L: 21:19	NA
Right Lane Closed Ahead	114P04372	R: 22:23 L: 21:21	NA
PCMS	114P04372	22:23	NA
Merge Sign	114P04372	R: 22:25 L: 21:22	NA
Arrow Board	114P04372	22:27	NA
Start of Taper (C-lane)	114P04372	22:27	NA
End of Taper (C-lane)	114P04372	NA	NA
Arrow Board	114+04372	NA	NA
Start of Taper (B-lane)	114+04372	NA	NA
End of Taper (B-lane)	114+04372	NA	NA
Arrow Board	114+04372	NA	NA
Work Zone Ends	114+04372	23:03	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #11 (Set-Up) And #12 (Removal) On Case Study Project #4

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
PCMS	114-04428	NA	NA
RWA	114-04428	R: 20:17 L: NA	R: 23:55 L: NA
Right Lane Closed Ahead	114N04428	R: 20:25 L: NA	R: 00:01 L: NA
RWA	114N04428	R: 20:23 L: NA	R: 00:03 L: NA
Merge Sign	114N04428	R: 20:29 L: 20:42	R: 00:09 L: 00:14
Start of Taper (C-lane)	114-04427	20:38	00:14
Arrow Board	114-04427	20:38	00:14
End of Taper (C-lane)	114-04427	21:09	23:57
Merge Sign (second)	114-04427	R: NA L: 21:21	R: NA L: 00:05
Start of Taper (B-lane)	114-04427	21:18	22:38
Arrow Board	114-04427	21:18	22:38
End of Taper (B-lane)	114-04427	21:24	22:28
Work Zone Ends	114N04427	21:48	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #13 (Set-Up) And #14 (Removal) On Case Study Project #4

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114-04427	00:22	02:26
RWA	114-04427	R: 00:20 L: 00:42	R: 02:21 L: 02:21
Right Lane Closed Ahead	114-04427	R: 00:35 L: 00:47	R: 02:25 L: 02:25
Merge Sign	114-04427	R: 00:40 L: 00:52	R: 02:26 L: 02:14
Start of Taper (C-lane)	114-04427	00:53	02:12
Arrow Board	114-04427	00:53	02:12
End of Taper (C-lane)	114-04427	00:55	01:57
Merge Sign (second)	114-04427	R: NA L: 00:58	R: NA L: 02:09
Start of Taper (B-lane)	114-04427	01:00	01:50
Arrow Board	114-04427	01:00	01:50
End of Taper (B-lane)	114-04427	01:03	01:48
Work Zone Ends	114N04427	01:13	NA

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #15 (Set-Up) And #16 (Removal) On Case Study Project #5

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
RWA	114P04439	R: NA L: 19:05	R: 05:01 L: 04:52
Right Two Lane Closed Ahead	114P04439	R: 19:20 L: 19:10	R: 05:00 L: 04:50
PCMS	114+04440	NA	NA
Merge Sign	114+04440	R: 20:03 L: NA	R: 04:48 L: NA
Start of Taper (C-lane)	114P04440	19:30	04:16
Arrow Board	114P04440	19:30	04:26
End of Taper (C-lane)	114P04440	19:40	04:15
Merge Sign (second)	114P+4441	R: 20:06 L: NA	R: 04:20 L: NA
Start of Taper (B-lane)	114P04441	21:30	04:09
Arrow Board	114P04441	21:30	04:09
End of Taper (B-lane)	114P04441	21:36	04:06
Work Zone Ends	114P04441	01:13	04:04

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Observation #15: A law enforcement officer was present on site at 20:49 and located at segment 114P04441.

Temporary Traffic Control Measures: Observations #17 (Set-Up) And #18 (Removal) On Case Study Project #5

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
PCMS	114P04439	R: 19:36 L: 00:42	R: 03:26 L: 02:21
Flares	114P04439	NA	NA
RWA	114P04439	NA	NA
Left Lane Closed Ahead	114P04439	R: 19:41 L: 19:31	R: 04:11 L: 04:05
PCMS	114+04440	19:42	04:12
Merge Sign	114+04440	R: 19:44 L: 19:29	R: 04:15 L: 04:02
Radar Speed Sign	114P04440	21:15	03:30
Merge Sign (second)	114P+4441	R: 19:46 L: 19:27	R: 04:17 L: 04:00
Start of Taper	114P+4441	19:58	03:50
Arrow Board	114P04441	19:57	03:40
End of Taper	114P04441	20:08	03:46
Work Zone Ends	114P04441	20:16	03:40

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #19 (Set-Up) And #20 (Removal) On Case Study Project #5

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
PCMS	114P04439	R: 19:14 L: NA	R: 02:40 L: NA
Flares	114P04439	NA	NA
RWA	114P04439	NA	NA
Left Lane Closed Ahead	114P04439	R: 19:19 L: 19:09	R: 03:31 L: 03:25
PCMS	114+04440	R: 19:20 L: NA	R: 03:32 L: NA
Merge Sign	114+04440	R: 19:44 L: 19:07	R: 04:15 L: 03:23
Radar Speed Sign	114P04440	20:50	02:44
Merge Sign (second)	114P+4441	R: 19:46 L: 19:05	R: 04:17 L: 03:20
Start of Taper	114P+4441	19:37	03:12
Arrow Board	114P04441	19:36	03:00
End of Taper	114P04441	19:48	03:07
Work Zone Ends	114P04441	19:55	03:01

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #21 (Set-Up) And #22 (Removal) On Case Study Project #5

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
PCMS	114P04439	R: 19:14 L: NA	R: 02:40 L: NA
Flares	114P04439	19:16	04:31
RWA	114P04439	NA	NA
Left Lane Closed Ahead	114P04439	R: 19:21 L: 19:11	R: 04:35 L: 04:24
PCMS	114+04440	R: 19:23 L: NA	R: 04:39 L: NA
Merge Sign	114+04440	R: 19:26 L: 19:09	R: 04:42 L: 04:21
Radar Speed Sign	114P04440	20:50	03:45
Merge Sign (second)	114P+4441	R: 19:29 L: 19:06	R: 04:46 L: 04:18
Start of Taper	114P+4441	19:40	04:08
Arrow Board	114P04441	19:42	03:58
End of Taper	114P04441	19:48	04:03
Work Zone Ends	114P04441	19:53	03:59

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #23 (Set-Up) And #24 (Removal) On Case Study Project #5

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
PCMS	114P04439	R: 19:28 L: NA	R: 03:01 L: NA
Flares	114P04439	19:21	02:57
RWA	114P04439	NA	NA
Left Lane Closed Ahead	114P04439	R: 19:26 L: 19:14	R: 03:00 L: 02:51
PCMS	114+04440	R: 19:21 L: NA	R: 01:30 L: NA
Merge Sign	114+04440	R: 19:30 L: 19:12	R: 03:05 L: 02:48
Radar Speed Sign	114P04440	20:58	01:40
Merge Sign (second)	114P+4441	R: 19:33 L: 19:07	R: 03:07 L: 02:45
Start of Taper	114P+4441	19:46	02:35
Arrow Board	114P04441	19:46	02:25
End of Taper	114P04441	19:54	02:29
Work Zone Ends	114P04441	20:00	02:26

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary traffic control measures: Observations #25 (set-up) and #26 (removal) on Case Study Project #5

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
PCMS	114P04439	R: 19:15 L: NA	R: 22:54 L: NA
Flares	114P04439	19:15	23:40
RWA	114P04439	NA	NA
Left Lane Closed Ahead	114P04439	R: 19:21 L: 19:09	R: 23:42 L: 23:34
PCMS	114+04440	R: 19:22 L: NA	R: 23:44 L: NA
Merge Sign	114+04440	R: 19:25 L: 19:07	R: 23:46 L: 23:32
Radar Speed Sign	114P04440	20:55	22:52
Merge Sign (second)	114P+4441	R: 19:27 L: 19:04	R: 23:48 L: 23:29
Start of Taper	114P+4441	19:39	23:19
Arrow Board	114P04441	19:39	23:09
End of Taper	114P04441	19:48	23:13
Work Zone Ends	114P04441	19:55	23:10

NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #27 (Set-Up) And #28 (Removal) On Case Study Project #6

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
Flares	114N04391	03:50	09:07
RWA	114N04391	R: 03:31 L: 03:47	R: 09:13 L: 09:07
Left Lane Closed Ahead	114-04390	R: 03:34 L: 03:51	R: 09:14 L: 09:05
Merge Sign	114-04390	R: 03:37 L: 03:53	R: 09:16 L: 09:03
PCMS	114-04390	NA	NA
Start of Taper (A-lane)	114-04390	03:55	08:51
Arrow Board	114-04390	03:55	08:50
End of Taper (A-lane)	114N04390	04:00	08:57
Merge Sign (second)	114N04390	R: 03:39 L: 04:00	R: NA L: 08:52
RWA (Stationary)	114N04390	NA	NA
Start of Taper (B-lane)	114N04390	04:03	07:22
Arrow Board	114N04390	04:02	07:25
End of Taper (B-lane)	114N04390	04:08	07:20
Work Zone Ends	114-04389	04:09	08:50

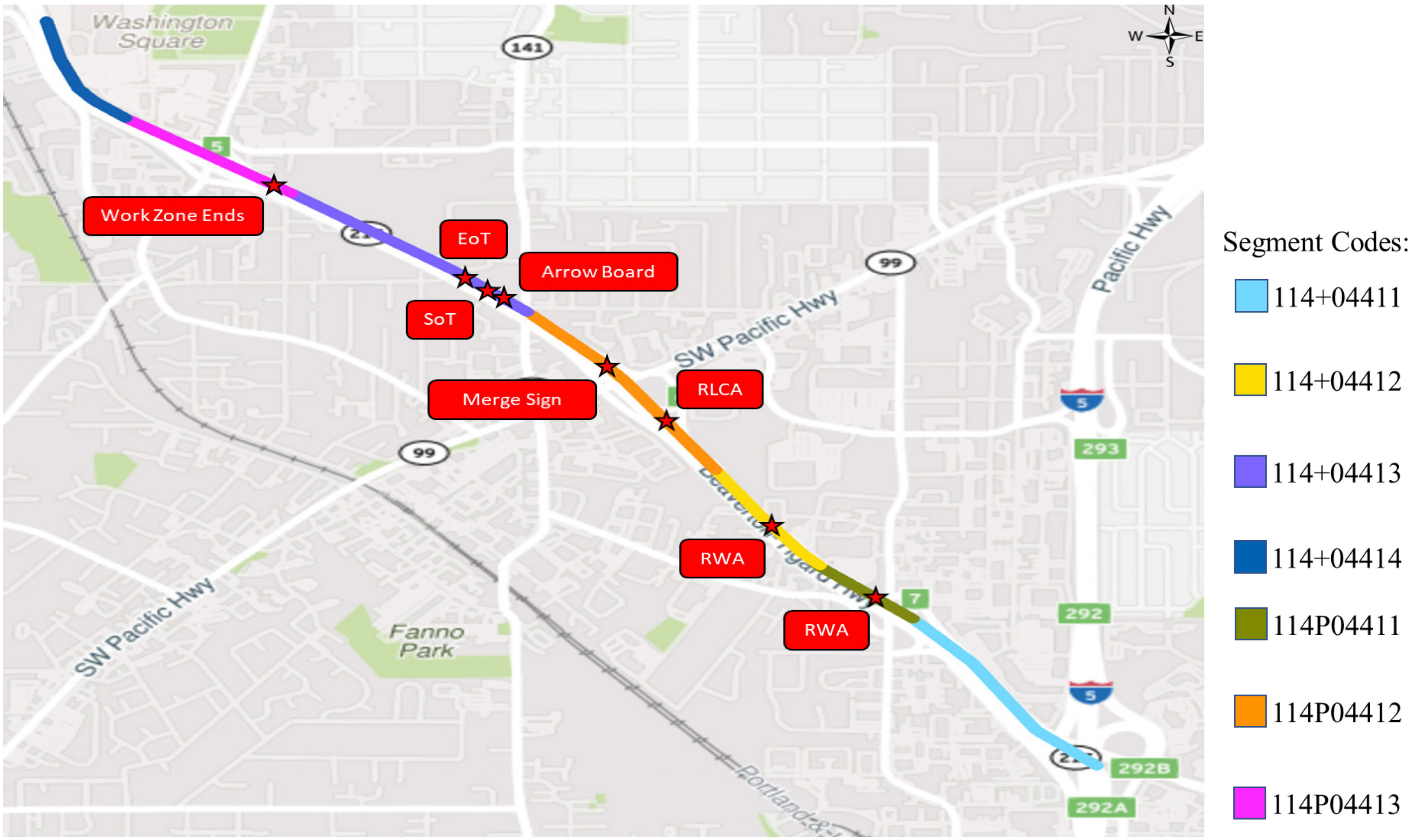
NA = Not available or applicable; R = right side of roadway; L = left side of roadway

Temporary Traffic Control Measures: Observations #29 (Set-Up) And #30 (Removal) On Case Study Project #6

Traffic Control Measures	RITIS Segment Code	Placement Time	Removal Time
RWA	114P04388	R: 07:40 L: 7:57	R: 12:03 L: 11:58
Right Lane Closed Ahead	114P04389	R: 07:41 L: 07:59	R: 12:05 L: 11:57
Merge Sign	114P04389	R: 07:43 L: 08:01	R: 12:06 L: 11:55
Start of T1aper	114P04389	08:37	11:43
Arrow Board	114+04390	08:37	11:45
End of Taper	114+04390	08:40	11:38
Radar Speed Sign on Truck	114+04390	NA	NA
Work Zone Ends	114+04390	08:42	NA

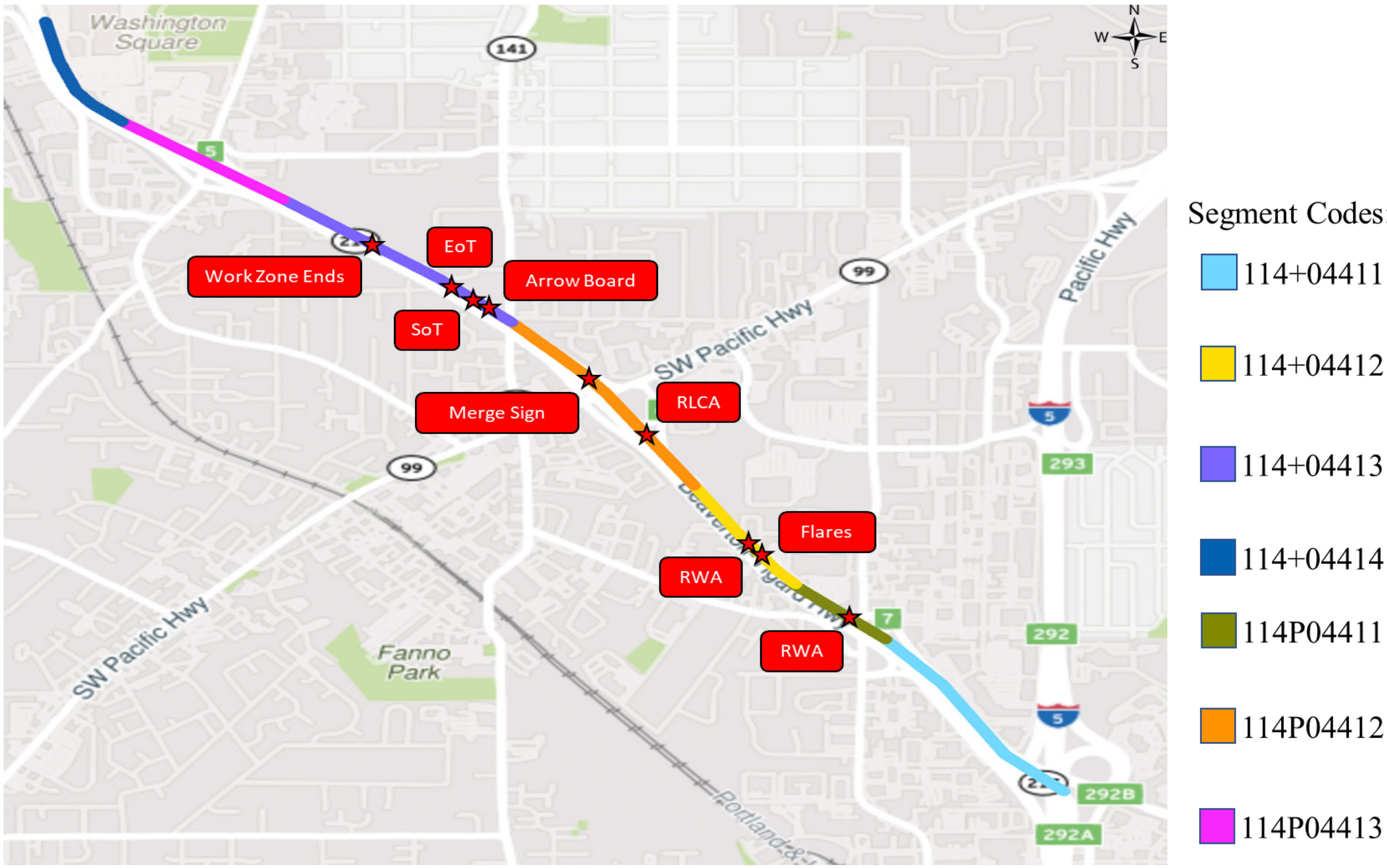
NA = Not available or applicable; R = right side of roadway; L = left side of roadway

APPENDIX C: CASE STUDY OBSERVATIONS – TRAFFIC CONTROL LAYOUTS



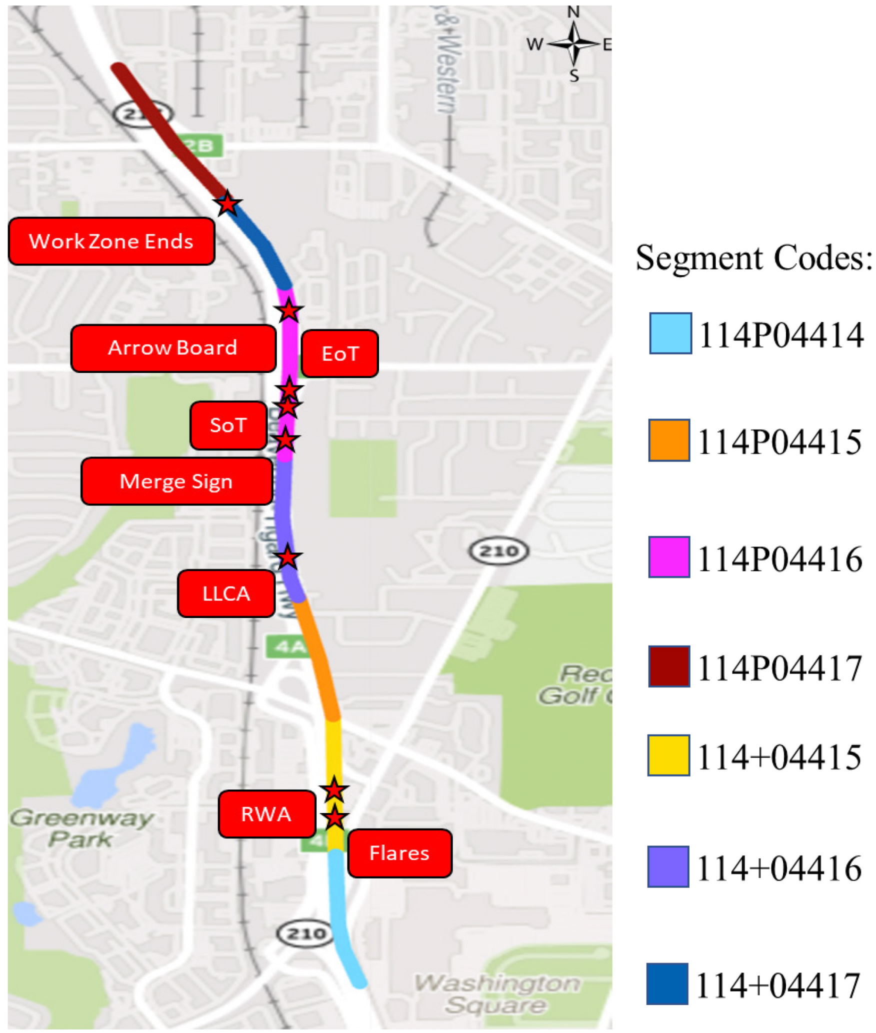
Traffic control measures, RITIS segments, and RITIS segment codes for Observation #1 on Case Study Project #1

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



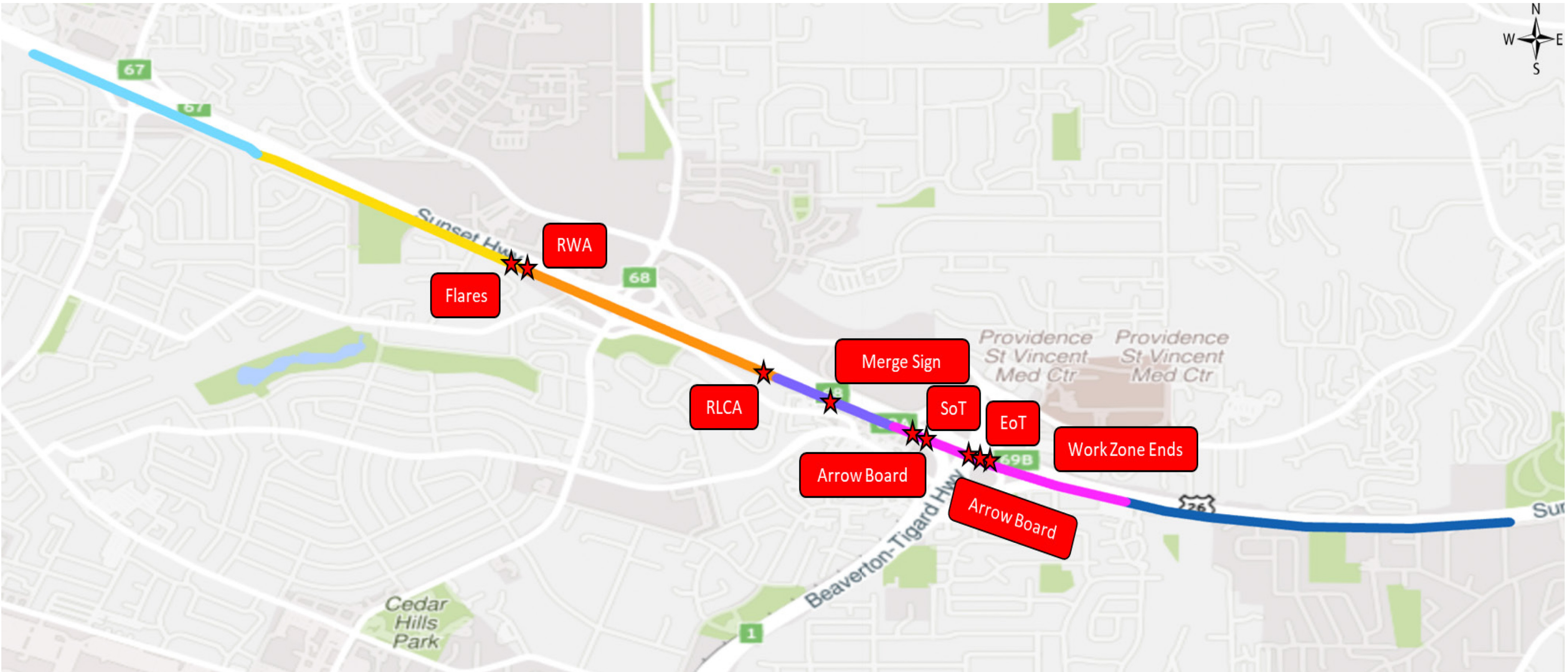
Traffic control measures, RITIS segments, and RITIS segment codes for Observation #2 on Case Study Project #1

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



Traffic control measures, RITIS segments, and RITIS segment codes for Observation #3 on Case Study Project #2

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

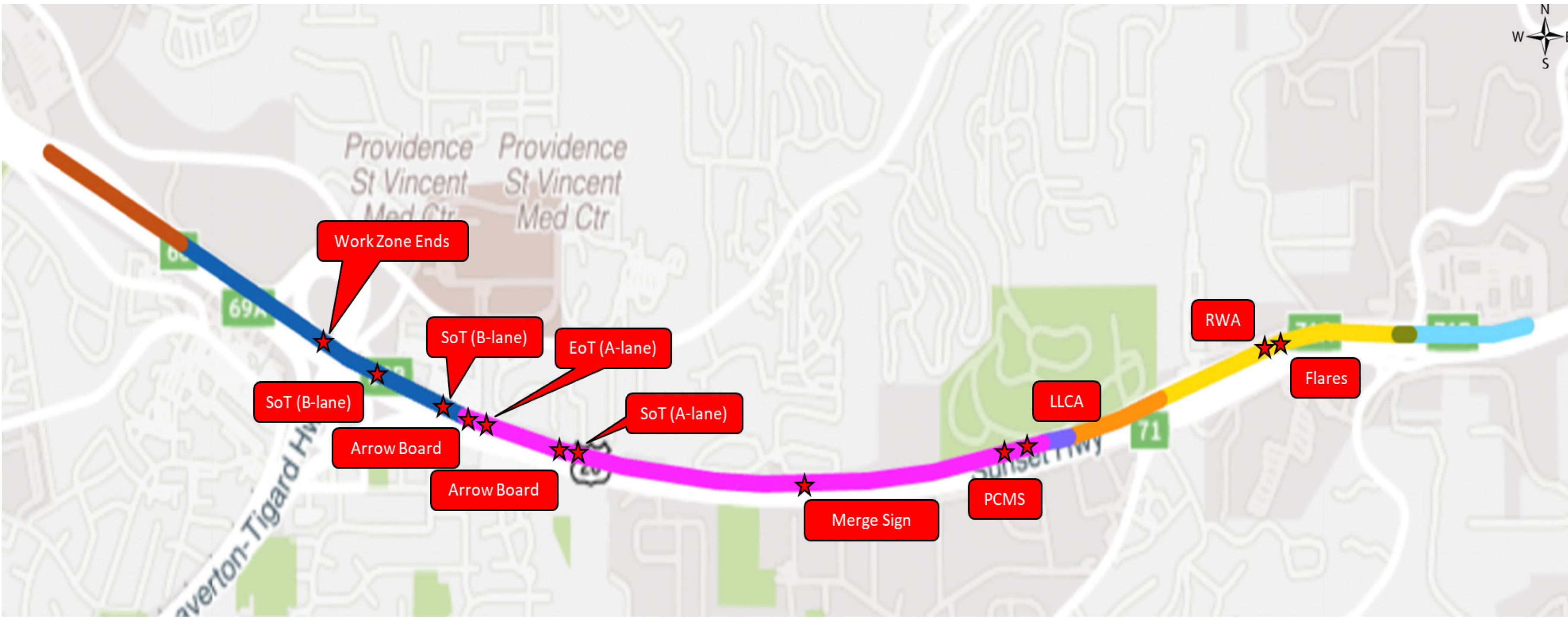


Traffic control measures, RITIS segments, and RITIS segment codes for Observation #4 on Case Study Project #3

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

Segment codes:

114N04376 114-04375 114N04375 114-04374 114N04374 114-04373

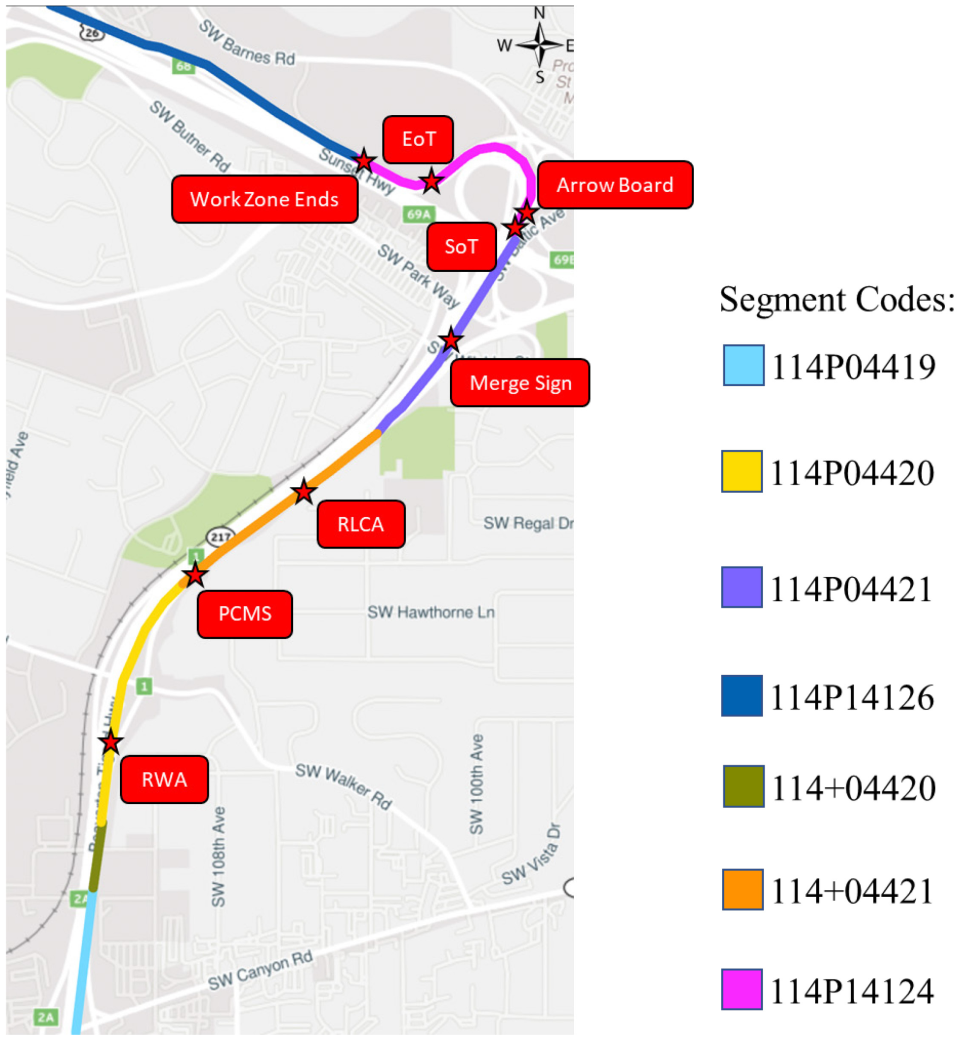


Traffic control measures, RITIS segments, and RITIS segment codes for Observation #5 on Case Study Project #3

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

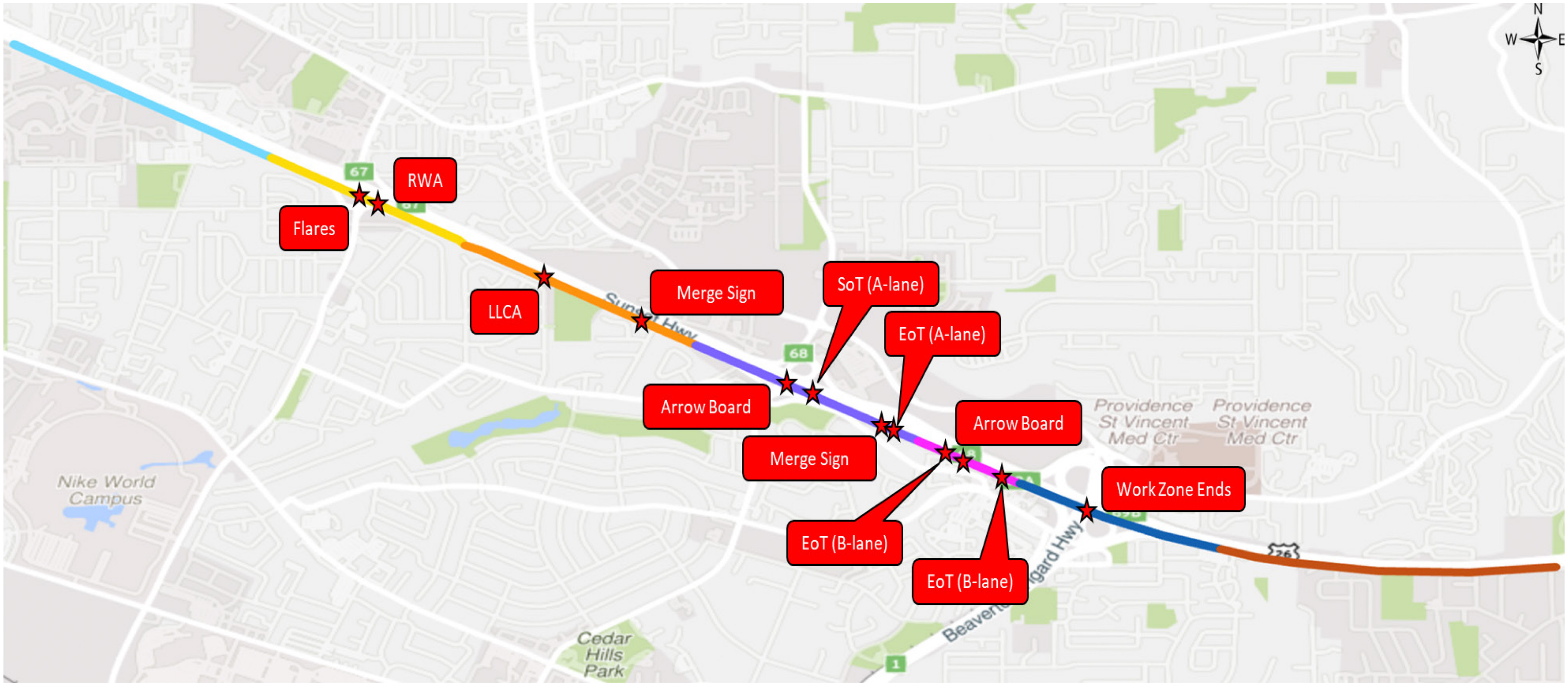
Segment codes:

114P04371	114+04372	114P04372	114+04373
114P04373	114+04374	114P04374	114+04375



Traffic control measures, RITIS segments, and RITIS segment codes for Observations #6 and #7 on Case Study Project #1

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

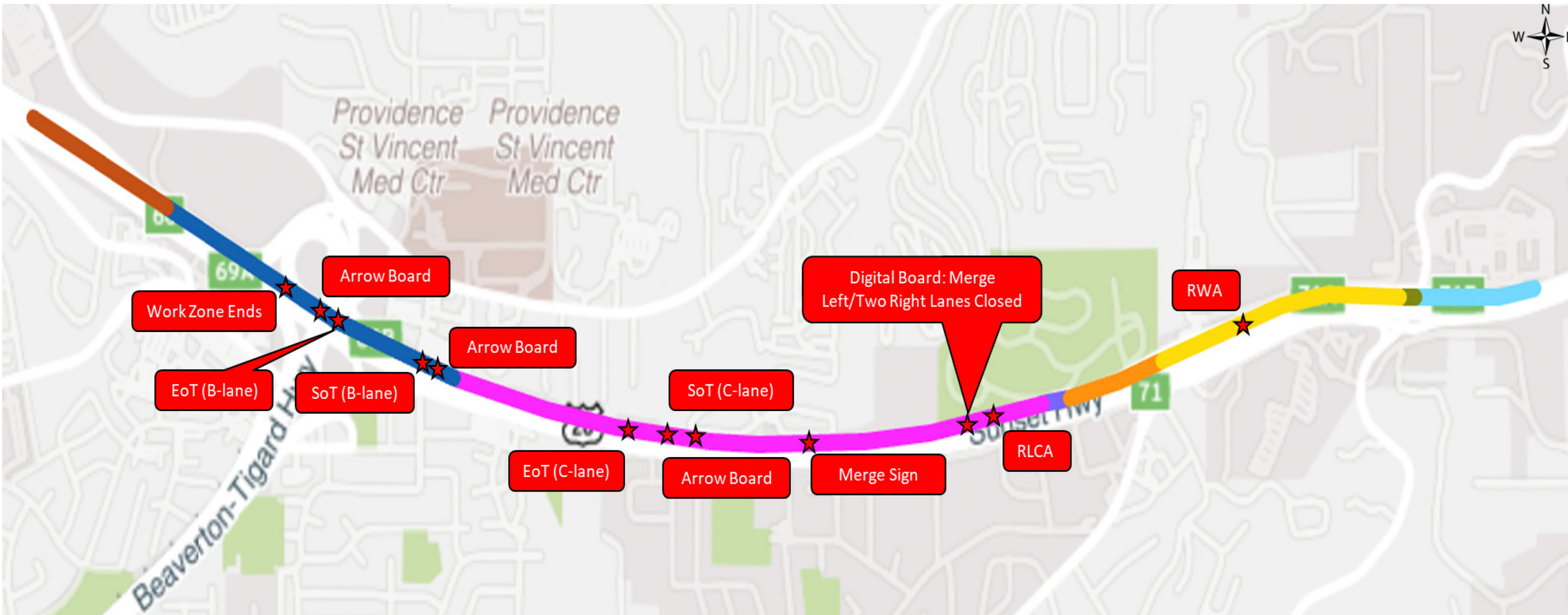


Traffic control measures, RITIS segments, and RITIS segment codes for Observations #8 and #9 on Case Study Project #3

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

Segment codes:

114-04376 114N04376 114-04375 114N04375 114-04374 114N04374 114-04373



Traffic control measures, RITIS segments, and RITIS segment codes for Observation #10 on Case Study Project #3

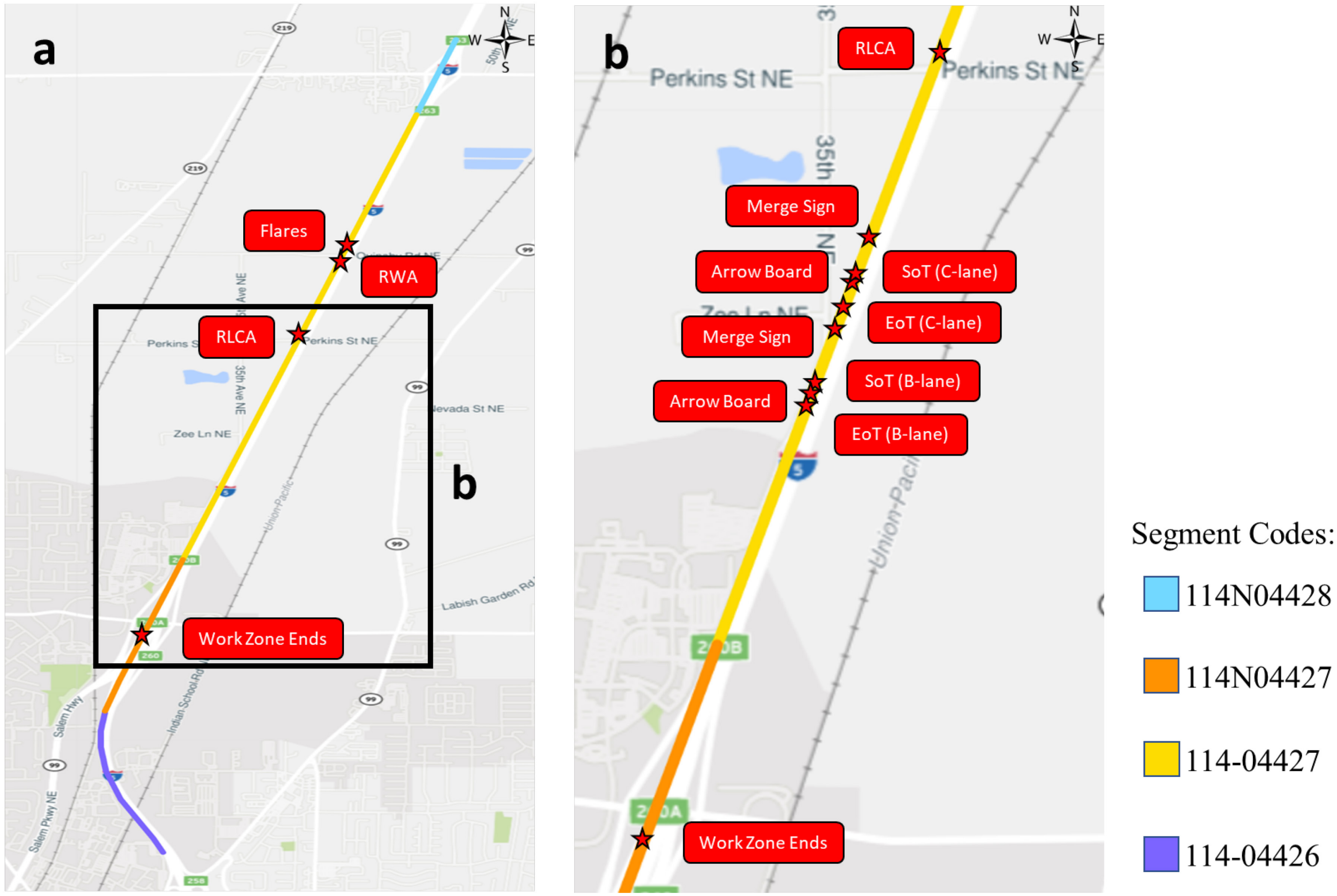
Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

Segment codes:

114+04375	114P04374	114+04374	114P04373
114+04373	114P04372	114+04372	114P04371

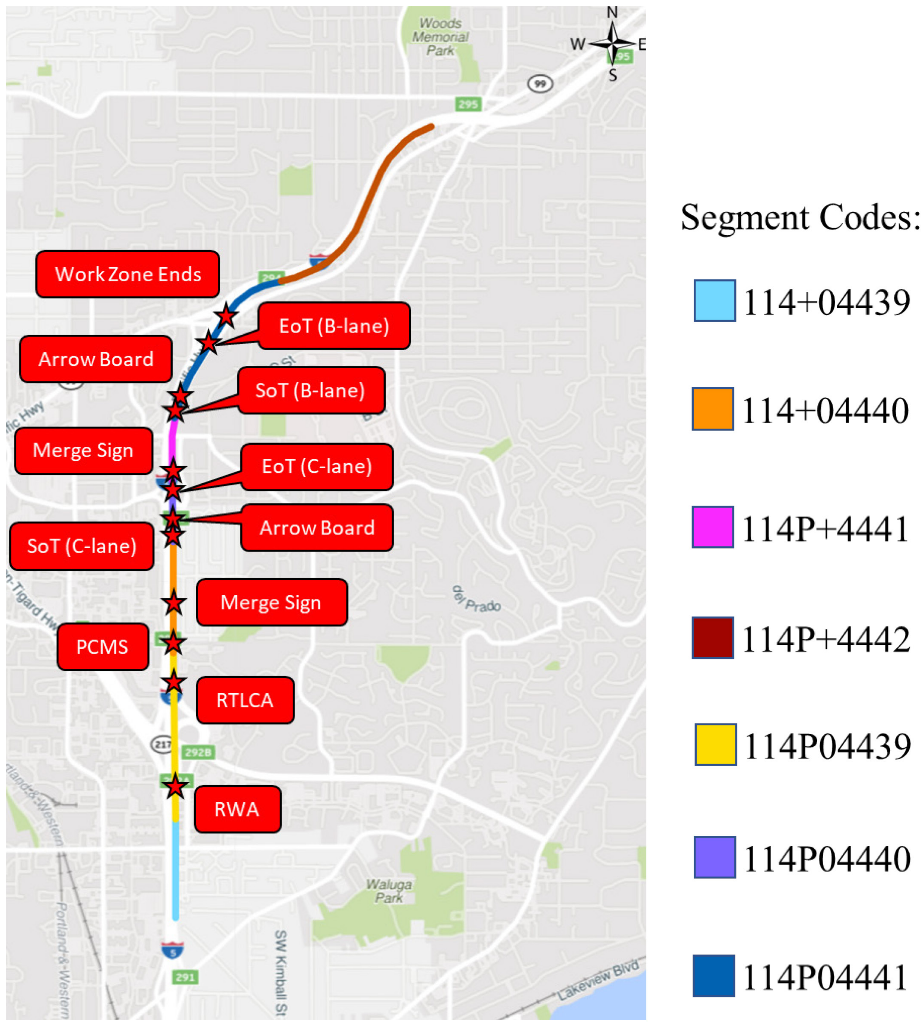
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #11 and #12 on Case Study Project #4

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



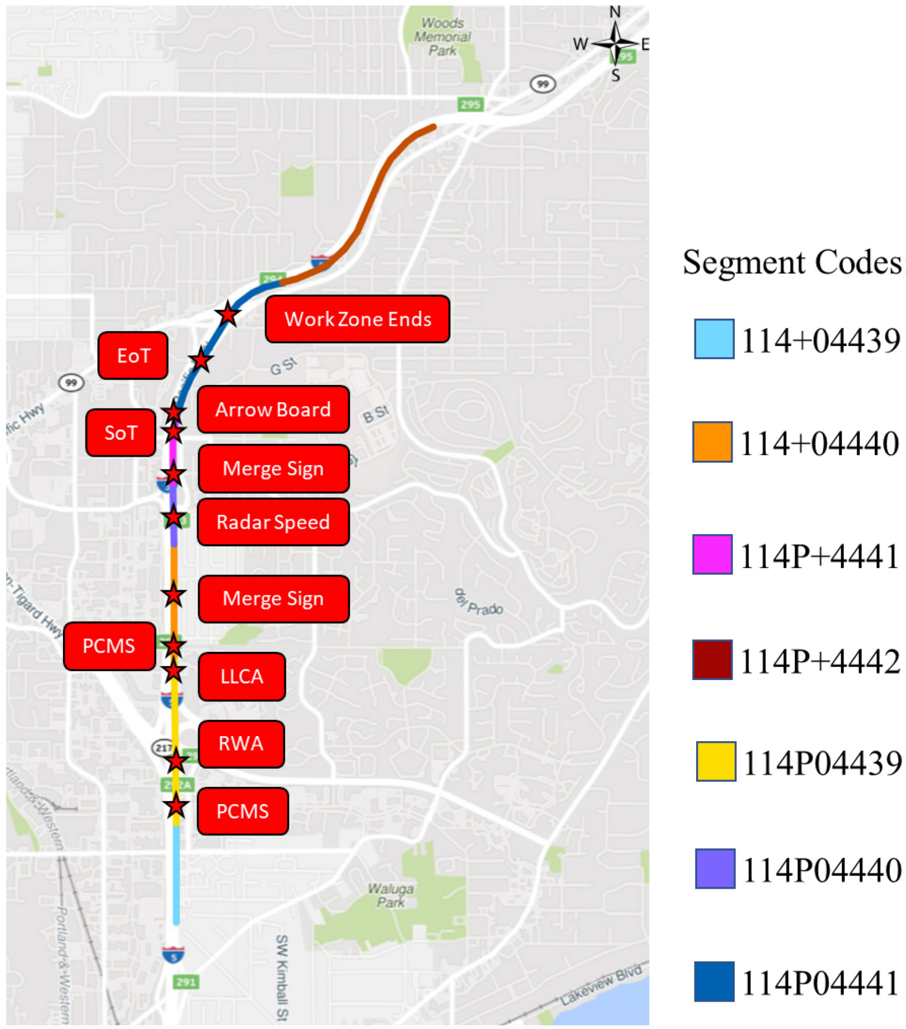
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #13 and #14 on Case Study Project #4

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



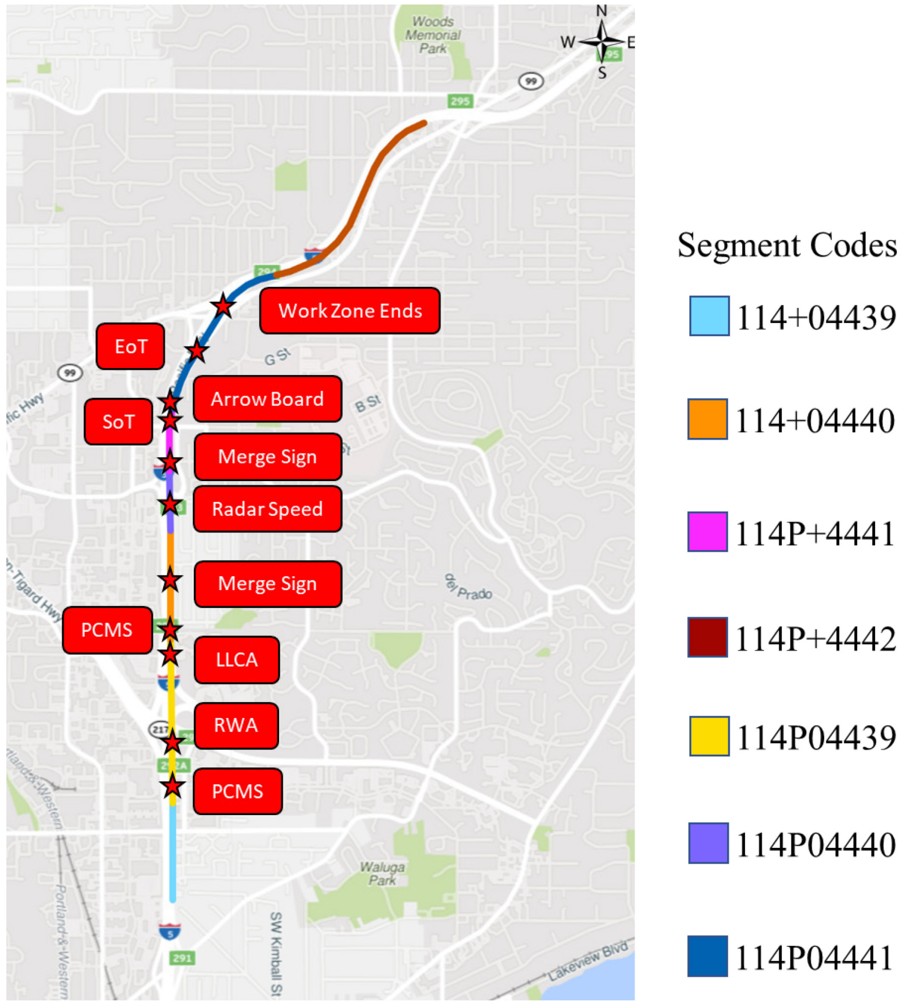
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #15 and #16 on Case Study Project #5

Legend: RWA = Road Work Ahead sign; RTLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



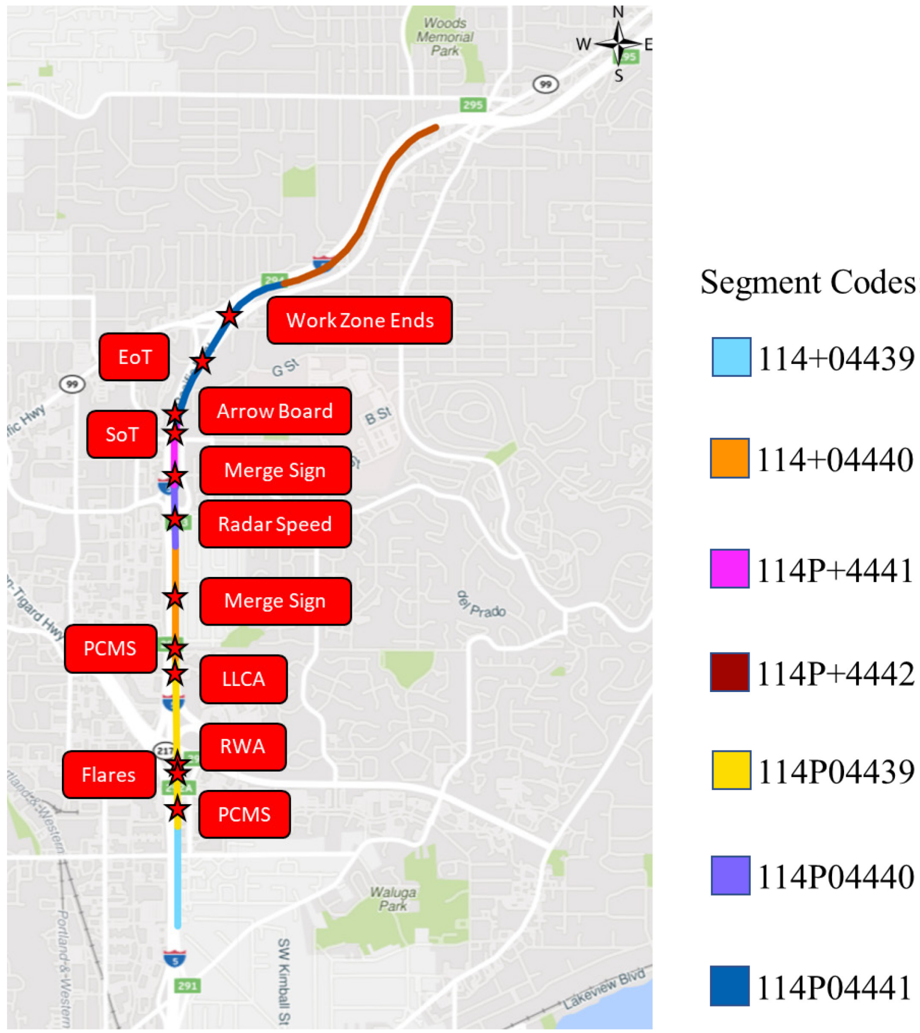
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #17 and #18 on Case Study Project #5

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



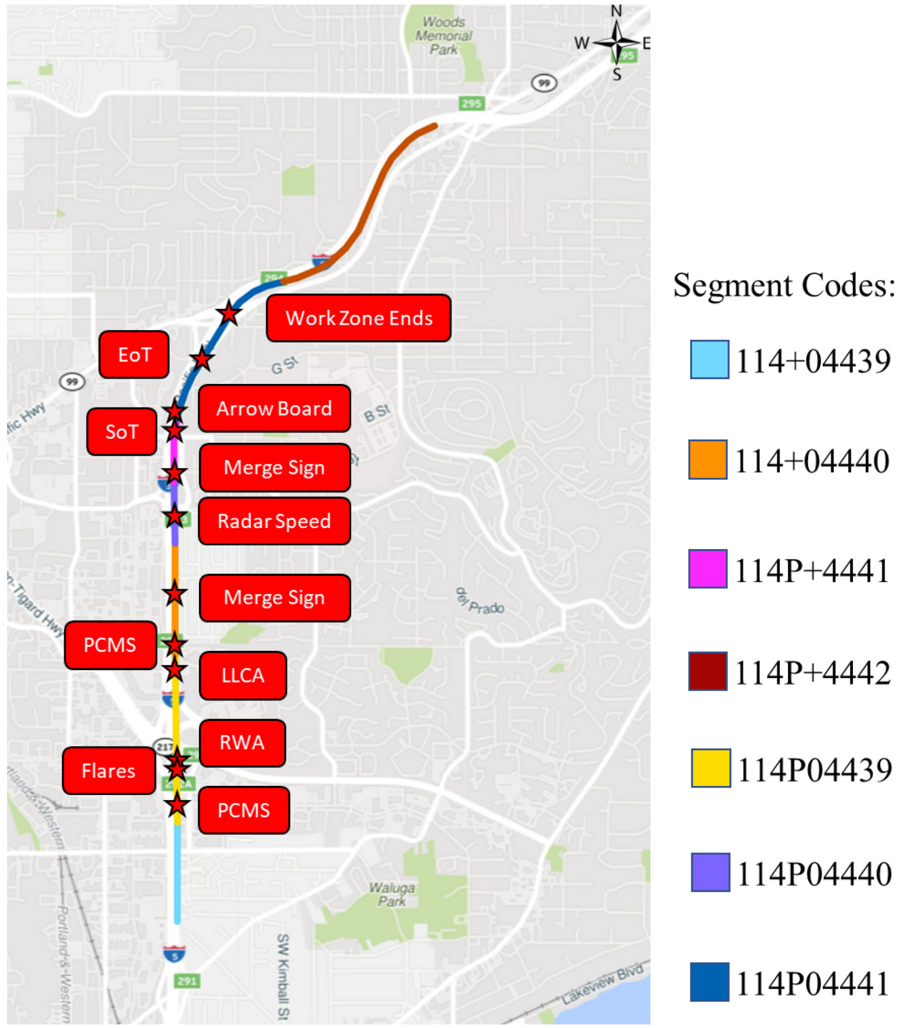
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #19 and #20 on Case Study Project #5

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



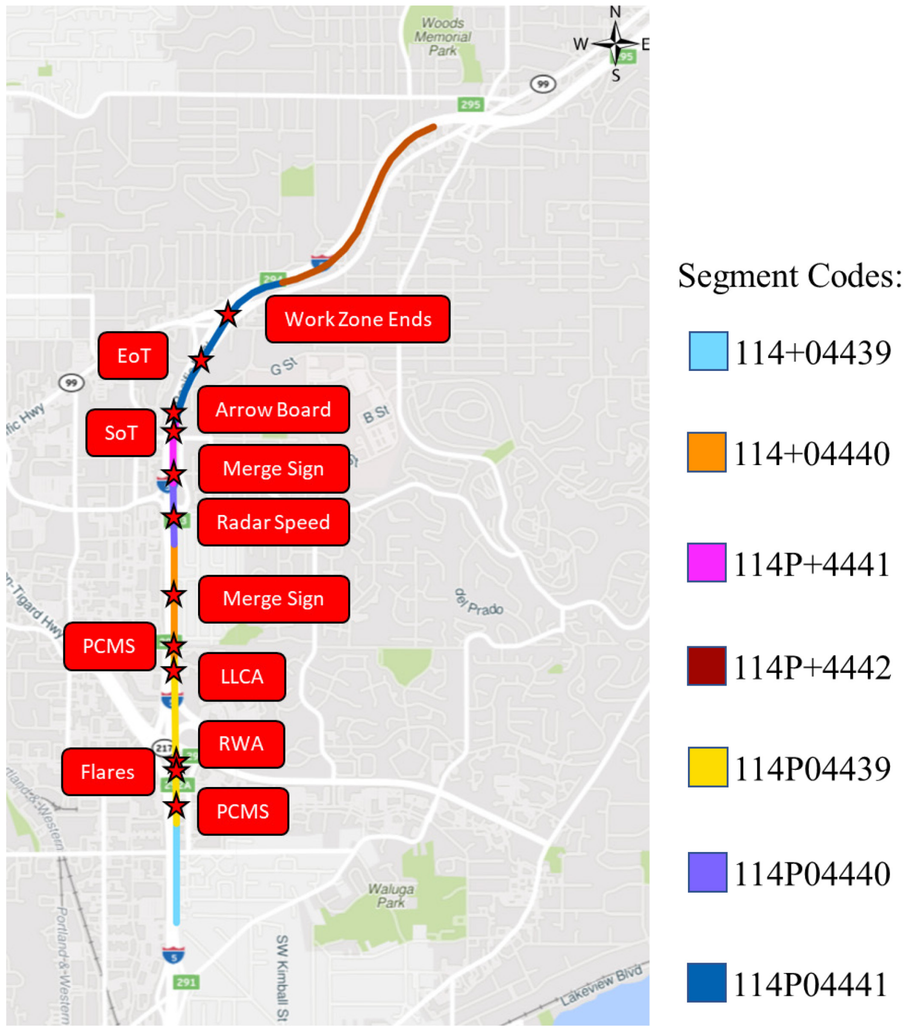
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #21 and #22 on Case Study Project #5

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



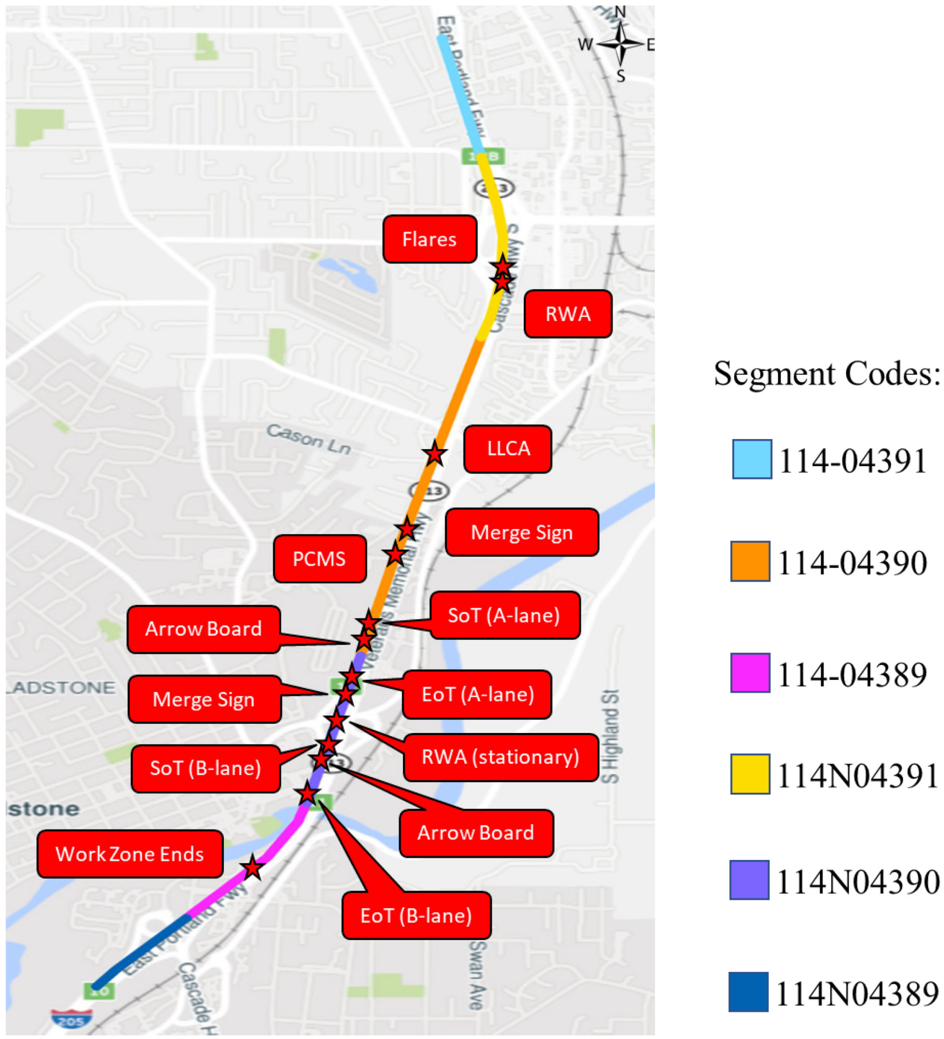
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #23 and #24 on Case Study Project #5

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



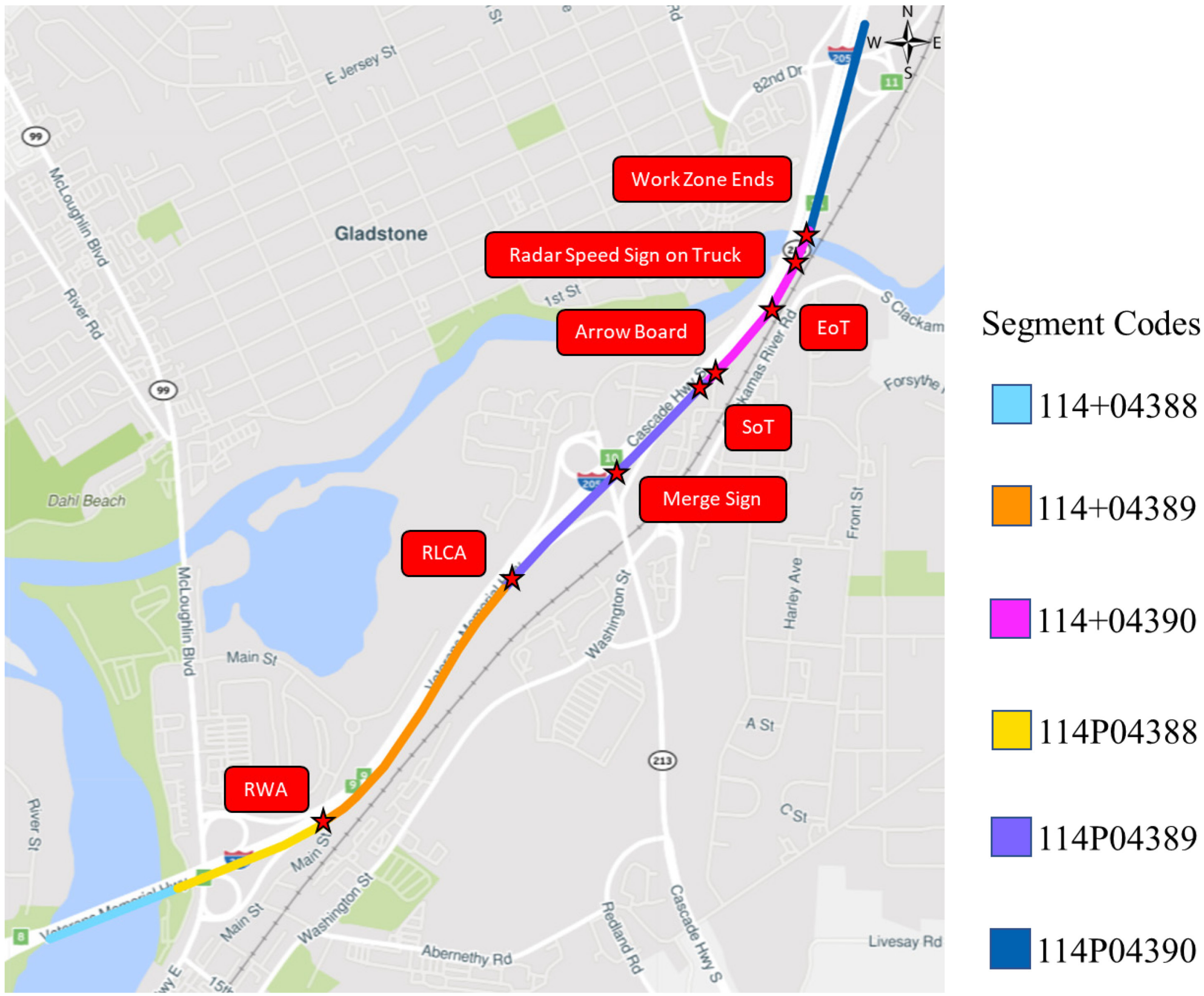
Traffic control measures, RITIS segments, and RITIS segment codes for Observations #25 and #26 on Case Study Project #5

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



Traffic control measures, RITIS segments, and RITIS segment codes for Observations #27 and #28 on Case Study Project #6

Legend: RWA = Road Work Ahead sign; LLCA = Left Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper



Traffic control measures, RITIS segments, and RITIS segment codes for Observations #29 and #30 on Case Study Project #6

Legend: RWA = Road Work Ahead sign; RLCA = Right Lane Closed Ahead sign; SoT = Start of taper; EoT = End of taper

APPENDIX D: CASE STUDY OBSERVATIONS – SPEED TABLES

Summary Of Vehicle Speeds During Observation #1 (Set-Up) On Case Study Project #1 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (no treatment present) (n = 26)			15 minutes after set-up (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	60.5	61.0	1.2	62.7	62.5	2.8	58.9	58.0	1.4
At treatment	61.7	62.0	1.4	63.3	63.0	1.9	59.5	60.0	2.3
Downstream of treatment	57.5	58.0	2.3	58.7	58.0	1.8	55.1	55.0	1.4

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #2 (Set-Up) On Case Study Project #1 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 41)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	60.5	62.0	3.5	60.0	60.0	2.0	59.0	59.0	3.3
At treatment	62.7	63.0	2.2	61.1	61.0	2.1	59.5	60.0	3.6
Downstream of treatment	60.7	61.0	1.1	57.7	57.0	3.1	55.3	56.0	3.5

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #3 (Set-Up) On Case Study Project #2 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 43)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	57.5	58.0	1.7	45.3	46.0	8.3	55.6	57.0	5.6
At treatment	55.9	57.0	2.5	44.5	44.0	7.5	47.9	48.0	4.2
Downstream of treatment	57.8	59.0	3.4	44.3	44.0	11.9	33.9	31.0	3.1

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #4 (Set-Up) On Case Study Project #3 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 12)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	57.5	58.0	1.1	59.9	60.0	0.7	60.7	61.0	1.7
At treatment	55.9	57.0	1.3	56.8	57.0	0.6	58.1	58.0	2.0
Downstream of treatment	56.5	57.0	2.3	56.2	56.0	0.6	57.8	58.0	2.3

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #5 (Set-Up) On Case Study Project #3 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 72)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	62.8	63.0	2.9	63.3	63.0	2.7	64.1	65.0	1.0
At treatment	65.1	66.0	1.5	64.9	65.0	2.0	66.0	66.0	1.5
Downstream of treatment	64.5	65.0	1.0	64.3	64.0	1.9	66.9	67.0	1.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #6 (Set-Up) On Case Study Project #1 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (no treatment present) (n = 36)			15 minutes after set-up (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	61.3	61.0	2.8	61.3	62.0	3.3	63.9	65.0	3.0
At treatment	62.1	62.0	1.7	61.5	63.0	3.3	64.1	65.0	1.9
Downstream of treatment	60.4	60.0	1.5	60.6	61.0	2.4	60.5	62.0	2.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #7 (Removal) On Case Study Project #1 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 29)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	63.1	65.0	4.2	60.4	61.0	2.3	59.4	59.0	2.2
At treatment	63.0	62.0	2.9	60.8	61.0	2.1	58.7	59.0	1.4
Downstream of treatment	60.9	62.0	1.9	58.0	57.0	3.1	56.5	57.0	1.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #8 (Set-Up) On Case Study Project #3 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 128)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	64.7	65.0	1.9	64.4	65.0	1.9	61.3	62.0	1.0
At treatment	65.1	65.0	2.0	63.8	64.0	2.2	58.9	59.0	1.3
Downstream of treatment	64.7	65.0	1.9	62.1	62.0	2.4	56.8	57.0	1.5

n = number of 1-minute intervals of RITIS speed data

Summary of Vehicle Speeds During Observation #9 (Removal) on Case Study Project #3 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 38)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	64.4	65.0	1.5	60.4	60.0	2.6	62.0	62.0	0.0
At treatment	63.1	64.0	1.4	61.0	61.0	2.5	60.0	60.0	0.0
Downstream of treatment	62.2	62.0	0.4	59.9	60.5	2.5	57.0	57.0	0.0

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #10 (Set-Up) On Case Study Project #3 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (no treatment present) (n = 45)			15 minutes after set-up (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	64.8	65.0	1.2	62.0	62.0	1.8	66.3	66.0	1.2
At treatment	63.7	63.0	1.3	62.4	63.0	2.7	65.7	66.0	0.6
Downstream of treatment	64.8	65.0	1.6	62.7	63.0	2.8	66.0	66.0	2.0

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #11 (Set-Up) On Case Study Project #4 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (no treatment present) (n = 92)			15 minutes after set-up (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	70.1	70.0	0.7	69.2	69.5	1.6	68.7	69.0	1.6
At treatment	71.7	71.0	0.9	69.3	70.0	1.9	60.7	62.0	1.8
Downstream of treatment	70.7	71.0	0.8	53.1	63.5	21.1	6.3	6.0	0.8

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #12 (Removal) On Case Study Project #4 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (no treatment present) (n = 15)			During removal operation (no treatment present) (n = 107)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	70.9	71.0	0.7	69.7	70.0	1.8	70.1	71.0	2.7
At treatment	65.1	66.0	3.2	69.2	69.0	1.5	70.2	70.0	0.7
Downstream of treatment	7.3	7.0	0.8	29.1	19.0	23.9	67.9	68.0	1.4

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #13 (Set-Up) On Case Study Project #4 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 54)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	66.4	66.0	0.6	69.4	69.5	1.3	68.8	69.0	0.4
At treatment	66.2	66.0	0.4	67.7	68.0	1.7	64.8	65.0	1.2
Downstream of treatment	66.0	66.0	0.0	68.1	68.0	1.9	61.1	61.0	1.3

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #14 (Removal) On Case Study Project #4 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 39)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	69.0	69.0	0.0	66.6	67.0	1.4	67.6	68.0	0.5
At treatment	63.6	64.0	0.5	62.8	62.0	2.0	66.5	66.0	0.8
Downstream of treatment	54.7	55.0	1.1	60.0	62.0	4.6	64.9	64.0	1.6

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #15 (Set-Up) On Case Study Project #5 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (no treatment present) (n = 109)			15 minutes after set-up (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	64.7	63.0	2.9	62.4	62.0	2.1	62.1	62.0	3.3
At treatment	66.8	68.0	2.6	63.6	64.0	2.2	62.5	62.0	3.0
Downstream of treatment	61.5	61.0	2.1	60.1	60.0	3.0	60.5	61.0	2.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #16 (Removal) On Case Study Project #5 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (no treatment present) (n = 15)			During removal operation (no treatment present) (n = 63)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	63.7	64.0	1.4	65.7	65.0	2.4	65.9	65.0	1.3
At treatment	55.1	55.0	0.8	64.1	66.0	3.5	64.1	63.0	1.9
Downstream of treatment	49.5	50.0	1.4	60.4	62.0	5.0	61.4	61.0	2.9

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #17 (Set-Up) On Case Study Project #5 (Treatment = PCMS)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 105)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	60.0	60.0	3.4	61.2	61.0	2.5	59.9	60.0	1.3
At treatment	60.3	60.0	2.3	60.9	61.0	2.5	60.4	60.0	0.5
Downstream of treatment	59.3	60.0	2.3	57.8	57.0	3.5	58.3	59.0	2.0

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #18 (Removal) On Case Study Project #5 (Treatment = PCMS)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 52)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	62.3	62.0	1.2	65.1	65.0	1.8	67.9	69.0	2.1
At treatment	61.8	62.0	1.4	62.5	63.0	2.6	66.6	68.0	2.9
Downstream of treatment	59.3	60.0	1.8	60.2	61.0	3.2	63.3	65.0	4.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #19 (Set-Up) On Case Study Project #5 (Treatment = PCMS)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 46)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	63.3	63.0	1.8	62.7	62.5	2.7	62.7	62.0	3.2
At treatment	66.7	67.0	1.3	65.0	65.5	2.9	64.7	65.0	1.0
Downstream of treatment	60.5	61.0	1.6	60.7	62.0	3.3	60.5	62.0	2.7

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #20 (Removal) On Case Study Project #5 (Treatment = PCMS)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 59)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	61.5	63.0	3.2	63.3	63.0	1.9	65.4	65.0	2.2
At treatment	53.3	52.0	1.5	60.9	61.0	2.5	62.3	64.0	3.8
Downstream of treatment	51.1	50.0	1.3	58.5	58.0	1.8	60.1	61.0	3.9

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #21 (Set-Up) On Case Study Project #5 (Treatment = Electronic Flares And PCMS)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 65)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	65.1	67.0	3.4	63.0	63.0	2.8	59.8	60.0	3.3
At treatment	63.7	63.0	2.4	64.0	63.0	2.6	65.2	66.0	1.3
Downstream of treatment	59.4	60.0	2.2	61.5	61.0	3.4	62.8	64.0	2.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #22 (Removal) On Case Study Project #5 (Treatment = Electronic Flares And PCMS)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 42)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	69.3	70.0	0.9	66.3	66.0	1.4	63.9	64.0	3.6
At treatment	65.5	66.0	1.1	64.8	65.0	1.4	63.4	62.0	2.5
Downstream of treatment	63.3	63.0	0.7	62.3	63.0	2.2	63.3	62.0	2.7

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #23 (Set-Up) On Case Study Project #5 (Treatment = Electronic Flares And PCMS)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 68)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	63.2	62.0	2.5	63.3	63.0	2.6	64.7	65.0	1.5
At treatment	60.9	62.0	2.4	64.9	65.0	2.7	64.6	64.0	2.0
Downstream of treatment	55.8	56.0	3.6	61.6	62.0	2.4	60.4	60.0	1.5

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #24 (Removal) On Case Study Project #5 (Treatment = Electronic Flares And PCMS)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 58)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	61.3	61.0	0.5	60.3	60.0	2.6	60.3	61.0	1.0
At treatment	61.6	62.0	0.5	58.6	58.0	3.4	56.7	57.0	0.6
Downstream of treatment	59.5	59.0	0.5	58.7	59.0	4.5	56.2	56.0	1.3

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #25 (Set-Up) On Case Study Project #5 (Treatment = Electronic Flares And PCMS)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 101)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	57.7	60.0	5.0	58.4	58.0	3.4	63.1	63.0	1.6
At treatment	60.7	60.0	2.4	58.3	58.0	3.3	62.7	62.0	0.9
Downstream of treatment	55.1	56.0	3.8	56.2	57.0	4.0	60.2	60.0	1.2

n = number of 1-minute intervals of RITIS speed data

Summary of vehicle speeds during Observation #26 (removal) on Case Study Project #5 (Treatment = Electronic flares and PCMS)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 49)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	65.1	65.0	1.8	61.9	62.0	2.8	60.9	61.0	0.8
At treatment	62.9	62.0	1.4	62.1	62.0	3.3	65.5	66.0	0.8
Downstream of treatment	62.3	62.0	1.2	59.0	58.0	4.0	61.7	62.0	2.0

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #27 (Set-Up) On Case Study Project #6 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (treatment present) (n = 27)			15 minutes after set-up (treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	60.5	61.0	0.6	61.2	60.0	1.7	63.1	63.0	1.2
At treatment	59.0	59.0	1.1	58.7	58.0	3.0	62.3	62.0	0.8
Downstream of treatment	59.1	59.0	1.1	57.7	57.0	1.9	57.9	57.0	1.6

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #28 (Removal) On Case Study Project #6 (Treatment = Electronic Flares)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (treatment present) (n = 15)			During removal operation (treatment present) (n = 108)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	65.4	65.0	0.6	62.4	63.0	2.5	66.9	67.0	1.0
At treatment	65.5	66.0	0.6	63.3	63.0	2.1	66.5	67.0	0.7
Downstream of treatment	63.8	64.0	1.7	62.5	62.0	2.0	64.1	64.0	1.2

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #29 (Set-Up) On Case Study Project #6 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before set-up operation (no treatment present) (n = 15)			During set-up operation (no treatment present) (n = 62)			15 minutes after set-up (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	63.6	63.0	1.2	65.1	65.0	1.8	64.3	65.0	1.9
At treatment	64.3	65.0	1.0	65.4	66.0	1.7	65.3	66.0	1.9
Downstream of treatment	64.3	64.0	1.2	65.2	65.0	2.3	67.0	67.0	0.9

n = number of 1-minute intervals of RITIS speed data

Summary Of Vehicle Speeds During Observation #30 (Removal) On Case Study Project #6 (Treatment = Control)

Location	Time period for RITIS speed data								
	15 minutes before removal operation (no treatment present) (n = 15)			During removal operation (no treatment present) (n = 29)			15 minutes after removal (no treatment present) (n = 15)		
	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)	Mean (mph)	Median (mph)	SD (mph)
Upstream of treatment	61.1	61.0	3.0	62.8	62.0	3.1	61.4	61.0	2.8
At treatment	63.1	63.0	3.1	63.5	63.0	2.4	63.2	63.0	1.5
Downstream of treatment	64.7	65.0	2.6	64.8	65.0	2.0	64.7	65.0	1.1

n = number of 1-minute intervals of RITIS speed data