EVALUATION OF RADAR SPEED DISPLAY FOR MOBILE MAINTENANCE OPERATIONS

Final Report

REPORT #OR-RD-16-09

Oregon Department of Transportation

EVALUATION OF RADAR SPEED DISPLAY FOR MOBILE MAINTENANCE OPERATIONS

Final Report

PROJECT ###

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December 2015

Technical Report Documentation Page

1. Report No. OR-RD-16-09	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of Radar Speed Display for Mobile Maintenance Operations		5. Report Date December 2015 6. Performing Organization Code
7. Author(s) John A. Gambatese and Ali Jafarnejad		8. Performing Organization Report No.
9. Performing Organization Name and Address School of Civil and Construction Engineering Oregon State University 101 Kearney Hall Corvallis, OR 97331		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	U.S. Dept. of Transportation Federal Highway Admin. 400 Seventh Street, SW Washington, DC 20590-0003	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract: Roadway maintenance projects often require working during nighttime hours in close proximity to ongoing traffic and may reduce traffic flow to a single lane while work is undertaken. In many cases the work is of short duration and a mobile operation. The Oregon Department of Transportation has conducted several research studies to identify best practices for traffic control during maintenance work. Radar speed signs (RSSs) are a traffic control device that has shown promise for positively affecting driver behavior and reducing speeds. RSSs use radar technology to measure the speed of oncoming vehicles and display the vehicle speed and accompanying messages to the drivers. This research study evaluated the impact of truck-mounted RSSs on vehicle speeds in maintenance work zones and identified best practices for their use as part of mobile and stationary maintenance work operations. The research study includes four case studies on multi-lane maintenance projects in Oregon. On each case study, the researchers conducted two periods of testing: one with the RSS display turned on and one without the RSS display turned on, and recorded vehicle speeds. The research findings indicate that vehicle speeds are typically lower and there is less variation in speeds between adjacent vehicles with the RSS turned on. Based on the findings, the researchers recommend use of truck-mounted radar speed signs during mobile maintenance operations on high-speed roadways.

17. Key Words	18. Distribution Statement
Work Zone, Safety, Radar Speed sign, Maintenance	Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	180	

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

The authors would like to acknowledge the input of the ODOT Research Unit and Technical Advisory Committee. The Technical Advisory Committee members are:

Mike Beam, ODOT
Stephen Brown, ODOT
Timothy Damm, ODOT
Steven Davis, ODOT
Jarod Johnson, ODOT
Jon Lazarus, ODOT Research Unit, Research Coordinator
Ted Miller, ODOT
Dennis Mitchell, ODOT
Duc Phan, ODOT
Ryan Sexton, ODOT
Michael Stinson, ODOT
Michael Strauch, ODOT

The authors would like to thank all of the construction personnel involved in the case study projects for their interest and input in the study and extra efforts made to assist the researchers. Without their input and support, the study activities described in this report would not be possible. Additional appreciation is expressed to Kasim AlOmari and Chuma Nnaji, graduate students in Civil and Construction Engineering at OSU, who assisted with data collection on the case study projects.

DEDICATION

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.

Evaluation of Radar Speed Display for Mobile Maintenance Operations

EXECUTIVE SUMMARY

Roadway work zone activities often expose workers to the possibility of being in close proximity to vehicles travelling at high speeds. Highway maintenance projects typically require workers to reduce traffic flow to a single lane while work is undertaken in an adjacent lane. During lane closures, maintenance operations can place workers on the roadway within a marked work zone. Areas of limited protection create considerable safety risk for both the workers and passing motorists. Inattentive or speeding drivers, careless workers, misplaced cones, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities. Workers conducting mobile highway construction and maintenance operations experience a hazard that is absent on other types of construction sites: high speed traffic flowing just a few feet away from the construction area. This hazard is ever-present and evident by the number of work zone crashes that continue to occur on Oregon and US roads.

Various measures have been taken to increase the level of safety in work zones including the application of speed signs based on radar detection. ODOT is required to follow all applicable rules, regulations, and guidelines for work zone safety, as well as the necessary protective steps to ensure the safety of the construction and maintenance crews on Oregon roadways (ODOT 2014; ODOT 2012a; FHWA 2009). Given the continuing number of crashes in work zones, additional measures are needed to attain the Federal zero fatalities initiative. This goal may be feasible by providing additional warning equipment such as radar speed signs between the hazard of fast flowing traffic and the maintenance/construction work crews or by using equipment outfitted with a radar speed sign for mobile operations.

The present study is designed to quantify the impact of a truck-mounted radar speed sign (RSS) on vehicle speeds in maintenance work zones and identify best practices for their use as part of mobile maintenance work operations. The overall goal of this investigation is to assist ODOT Maintenance in evaluating the benefits and limitations of using a truck-mounted radar speed sign during mobile operations. ODOT Maintenance has procured radar speed signs for use in Regions 1 and 4 and elsewhere around the state. The signs are attached to the back of maintenance trucks, and deployed as part of the traffic control measures during maintenance work. This research study is designed to provide information to ODOT Maintenance personnel on the expected impacts of the radar speed signs and guidance on the use of the signs within maintenance work zones. The research includes observations of the traffic when the truck is moving as part of the maintenance operations. The research focuses on a radar speed sign procured by ODOT Maintenance. The specific objectives for this research study are to:

1. Implement the radar speed sign on multiple Region 1 and 4 maintenance operations that are mobile in nature.

2. Determine the extent to which the radar speed sign is applicable to, and appropriate for, typical mobile maintenance operations.

3. Determine the impact of the presence of the radar speed sign on vehicle speeds as the vehicles pass through the maintenance work zones.

4. Develop recommendations and guidance for ODOT Maintenance regarding use of radar speed signs in mobile maintenance work zones.

To achieve the research goal and meet the stated objectives, seven primary research activities were planned and conducted for the study: (1) Study Initiation; (2) Literature Review; (3) Preliminary Testing and Verification; (4) Implementation and Data Collection; (5) Data analysis and Evaluation; (6) Development of Guidelines for Implementation; (7) Preparation of Draft and Final Reports. The researchers coordinated with ODOT Maintenance in Regions 1 and 4 and selected multiple maintenance operations in order to evaluate the truck-mounted radar speed sign under different conditions and types of operations and to minimize or eliminate potential confounding factors. Three operations in the Portland metropolitan area (Region 1) and one in the Klamath Falls area (Region 4) were selected. The case studies were as follow:

- Case Study #1: I-205 Relamping
- Case Study #2: I-205 Sweeping
- Case Study #3: I-84 (Banfield Expressway) Vactoring
- Case Study #4: US-97 Spraying

For each operation selected, two periods of testing were conducted for comparison: one with the radar speed sign turned on (treatment) and one without the radar speed sign turned on (control). Temporary speed sensors were placed on the roadway pavement in the adjacent travel lanes at various locations throughout the planned work area to measure the speeds of the passing vehicles.

The results of the study provide helpful insights into the impacts of a truck-mounted radar speed sign on vehicle speeds during mobile maintenance operations on high-speed roadways (55-65mph regulatory speed). Overall, the RSS display proved to be effective in reducing vehicle speeds in the work zone compared to when the RSS is not used. This impact occurs for both continuously mobile operations (e.g., sweeping and spraying) and intermittent operations (e.g., relamping and vactoring). The magnitude of impact varies from one project to another depending on multiple factors such as the volume and mix of traffic, roadway location and design, and type of work activity. The quantitative analyses of the speed data from the four case study projects included in this research study reveal the following:

- The amount of decrease in vehicle speed between the Road Work Ahead (RWA) signs and the active work area is greater with the RSS display turned on than without the RSS display turned on. For the case study projects evaluated, 85^{th} percentile speeds decreased approximately 2 to 5 mph (4% - 8%) without the RSS turned on and 3 to 13 mph (5% - 23%) with the RSS turned on.

- Vehicle speed is lower as the vehicles approach and pass by the work equipment with the RSS display turned on than without the RSS display turned on. 85th percentile speeds for the case study projects were approximately 2.0 mph less with the RSS display turned on compared to without the RSS display turned on.

- When comparing the percentage of vehicles travelling above the posted regulatory speed limit ("speeders") at the RWA signs to the percentage of speeders in the work zone during the entire test period, there is typically a decrease in the percentage of speeders between the two locations (i.e., fewer speeders in the work zone). The amount of decrease in the percentage of speeders is greater with the RSS turned on than without the RSS turned on. The percentage decrease ranged from 27% to 48% in the case studies when the RSS was turned on, and ranged from 15% to 36% without the RSS turned on. In addition, the decrease in the percentage of speeders is greater in the vicinity of the maintenance equipment than in other areas of the work zone.

- The mean speed of the speeders in the work zone during the entire test period with the RSS turned on ranged from 59.9 to 61.6 mph, and without the RSS turned on ranged from 59.5 to 62.8 mph. However, the decrease in mean speed from the RWA sign to the work zone is greater with the RSS turn on than without the RSS turned on.

- The difference in speed between adjacent vehicles as the vehicles pass through the work zone is typically less with the RSS display turned on than without the RSS display turned on. For all vehicles, the maximum mean speed difference was approximately 2.0 mph less with the RSS display turned on than without the RSS turned on (approximately 7 mph difference without the RSS turned on and approximately 5 mph difference with the RSS turned on).

- The distance apart between adjacent vehicles as the vehicles pass through the work zone is less with the RSS display turned on than without the RSS display turned on. This result and the result mentioned above related to mean speed difference indicate that with the RSS turned on, on average, there is less distance between vehicles and less speed difference.

- The differences listed above vary depending on the type of work being conducted and type and amount of equipment present.

- Vehicle speed decreases as the vehicles approach the equipment and increases after passing the equipment. This change in speeds occurs both with and without the RSS turned on. The amount of decrease upstream of the equipment is greater with the RSS turned on than without the RSS turned on.

Vehicle speed varies throughout the length of the work zone. At the RWA sign location, vehicles travel at normal highway speeds (Gambatese and Zhang 2014). Passenger cars tend to travel faster than trucks. However, all vehicles begin to slow down as they enter the active work area. There is a gradual decrease in speed to the end of the coned taper. In the work zone, vehicles typically travel at a lower speed when they pass by the work equipment as described above.

After passing the equipment the vehicles typically increase their speed. These results are similar to that observed in previous ODOT studies (e.g., SPR 751 and SPR 769).

The findings of the study enable making recommendations for future practice. The use of truck-mounted RSS displays on mobile equipment during maintenance operations is recommended to help decrease vehicle speeds and speed variability through the work zone. Based on the present case studies, speeds for passenger cars and trucks will be less with the truck-mounted RSS displays present and turned on. The RSS signs should be turned on throughout the work operation. In addition, the display settings on the sign should be determined based on the regulatory speed on the roadway. For example, for a high speed roadway with 55 mph regulatory speed, the following settings are recommended:

- Below 40 mph: no speed or message displayed
- Between 40 mph and 55 mph: display the vehicle's speed
- Above 55 mph: display the vehicle's speed and the message "Slow Down"

The results of this study are promising. A traffic control device that is easy to use, mobile, and multi-functional was found to help slow down vehicle speeds. Lower vehicle speeds, and lower differential speeds between adjacent vehicles, are expected to lead to improved safety on the roadways for motorists and maintenance workers.

Further research to investigate and evaluate motorist reactions based on different sign settings and different messages is warranted. Standardized messages and RSS speed settings should be developed and used in order to make maintenance work zones appear as consistent as possible from region to region throughout the state. In addition, the use of an advisory speed sign with lower speed than the regulatory speed in combination with the truck-mounted RSS display should also be studied further.

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1.0 INTRODUCTION

1.1 BACKGROUND

Roadway work zone activities often expose workers to the possibility of being in close proximity to vehicles travelling at high speeds. Highway maintenance projects typically require workers to reduce traffic flow to a single lane while work is undertaken in an adjacent lane. During lane closures, maintenance operations can place workers on the roadway within a marked work zone. In some cases, workers only have a line of cones and a few feet separating them from passing traffic. Areas of limited protection create considerable safety risk for both the workers and passing motorists. Inattentive or speeding drivers, careless workers, misplaced cones, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities. The severity of crashes has been shown to increase as the speed of passing traffic increases *(Aarts and Schagen 2006)*. Accordingly, maintenance projects on high-speed roadways present an increased risk of serious and/or fatal injuries to workers, motorists, and their passengers.

Workers conducting mobile highway construction and maintenance operations experience a hazard that is absent on many other types of construction sites: high speed traffic travelling within a very short distance from the construction area. This hazard is ever-present and evident by the number of work zone crashes that occur on Oregon and US roads each year. From 2000 to 2014, there was an average of 473 work zone-related crashes each year in Oregon. The number of fatalities associated with the work zone crashes in Oregon from 2009 through 2014 amounted to 4 in 2014, 5 in 2013, 5 in 2012, 9 in 2011, 9 in 2010, and 17 in 2009 (NHTSA FARS database). For comparison, the number of fatalities in work zones nationally was: 579 in 2013, 609 in 2012, 590 in 2011, 586 in 2010, and 680 in 2009. The number of fatalities per year has decreased since 2009 both nationally and in Oregon. Approximately 40% of the work zone crashes in Oregon occur in the transition zone prior to the work area (ODOT 2014). Lastly, ODOT (2012b) reports that, compared to other occupations, the risk of death is seven times higher for roadway workers than for the average worker in all work industries combined.

The National Highway Traffic Safety Administration (NHTSA) maintains the Fatality Analysis Reporting System (FARS), a database of all of the fatal crashes that occur on US roads. This information is available to the general public on the NHTSA website and shows the number of fatalities and incidents with fatalities that occurred within work zones during a specified time period. Furthermore, the incidents and fatalities that occurred within work zones are divided into four categories: (1) construction work zones, (2) maintenance work zones, (3) utility work zones, and (4) work zones that were not identified. Table 1.1 shows the Oregon values for incidents with fatalities that occurred over a period of 14 years (2000-2013). Figure 1.1 illustrates the total number of crashes in Oregon work zones from 2000-2013. As observed in the table and figure, the total number of incidents and fatalities each year varies and is decreasing in recent years.

Table 1.1: Roadway Crashes with Fatalities in Oregon Work Zones (*NHTSA FARS*)

Year	Total Crash Incidents in Work Zones	Incidents with Fatalities				
		Work Zone Type				Total Work Zone Fatalities
		Construction	Maintenance	Utility	Unknown	
2014	Not available	4	-	-	-	4
2013	427	5	-	-	-	5
2012	429	3	1	1	-	5
2011	528	8	-	-	1	9
2010	490	9	-	-	-	9
2009	508	15	2	-	-	17
2008	505	4	1	-	-	5
2007	591	6	1	-	-	7
2006	533	4	1	-	-	5
2005	512	19	-	-	-	19
2004	493	10	-	-	-	10
2003	514	2	-	-	-	2
2002	421	4	-	1	-	5
2001	324	3	1	1	-	5
2000	351	4	1	-	1	6

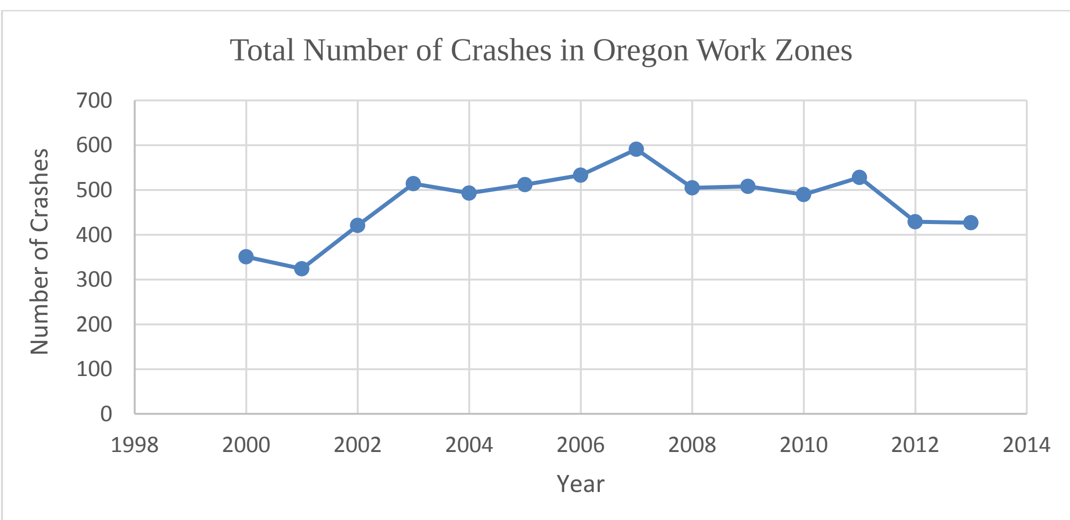


Figure 1.1: Crashes in Oregon Work Zones (*ODOT 2014*)

Table 1.1 indicates that the majority of work zone fatalities over the 14 year period occurred in construction zones. Maintenance zone fatalities represent approximately 10% of all work zone fatalities, while fatalities in utility zones represent a very small portion of all work zone fatalities. There is also a small portion of work zone fatalities that were not categorized by work zone type.

Maintenance operations typically consist of mobile operations over a short duration of time (up to one work shift) such as roadway sweeping, surface patching, line painting, and other mobile operations. Mobile operations are work activities that move along the road either intermittently or continuously as the work takes place. The work might be performed directly from a moving vehicle or equipment, or it may involve workers on foot *(Bryden 2003)*.

Work zone injuries and fatalities can be prevented in many ways. Providing sufficient warning of the work zone to the motorists and providing proper safety training to workers are examples of measures taken to prevent injuries and fatalities. Safety for mobile operations should not be compromised by using fewer or less effective devices simply because the work operation will frequently change its location. For mobile operations to be successful, the advance warning area must move with the work area or be repositioned periodically to provide adequate warning for the motorists *(FHWA 2007)*.

However, the impact of the crashes on the State of Oregon goes beyond the social and emotional impact of the loss of life and injured citizens. The cost associated with each fatal crash can amount to millions of dollars *(Blincoe et al. 2015)*. Additional losses to the public due to road closures, decreased mobility, and increased travel times as a result of crashes in work zones can have a negative impact on the State's economy *(Blincoe et al. 2015)*.

Across the country and in Oregon, various measures have been taken to increase the level of safety in work zones including the application of speed signs based on radar detection. It has been suggested that safety in work zones could also be improved with the application of more automated equipment which would control traffic in work zones without the use of flaggers *(Pigman et al. 2006)*. ODOT is required to follow all applicable rules, regulations, and guidelines for work zone safety, as well as the necessary protective steps to ensure the safety of the construction and maintenance crews on Oregon roadways. As can be seen in Table 1.1, additional measures are needed to reach the Federal goal of zero fatalities (*FHWA 2009b, ATSSA 2008*). This goal may be feasible by providing additional warning equipment such as radar speed signs between the hazard of fast flowing traffic and the maintenance/construction work crews or by using equipment outfitted with a radar speed sign on the back for mobile operations.

In response to these concerns, ODOT Research elected to investigate highway maintenance project safety enhancements. Maintenance projects as described are short-term projects that involve sweeping, drainage cleaning operations, guardrail repair/replacement, and similar operations. These types of projects can be intermittent or continuous. Intermittent mobile operations (such as litter cleanup, pothole patching, or utility operations) often involve frequent stops, and are similar to stationary operations. With operations that move slowly (less than 3 mph), it may be feasible to use stationary signage that is periodically retrieved and repositioned in the advance warning area. Continuously moving mobile operations include work activities in which workers and equipment move along the road without stopping (e.g., mowing, pavement striping, street sweeping, or herbicide spraying), usually at slow speeds. Also, for such operations, workers primarily remain in their vehicles and spend less time on foot on the roadway.

Types of maintenance work where ODOT anticipates using traffic control equipped with a mobile radar speed sign (RSS) primarily includes sweeping and drainage cleaning operations. Sweeping operations are typically continuously moving, and advance along at about 3-5 mph. Drainage cleaning operations are typically not continuously moving, but rather stop-and-go with the work vehicle stopping in front of a drainage inlet for several minutes before proceeding to the next inlet up the highway. Either operation might use a traffic control plan (TCP) "Mobile Operation Lane Closure" or "Mobile Operation Shoulder Closure" depending upon the highway corridor restrictions (e.g., narrow shoulder widths). In both cases, the operations must contain the minimum number of vehicles required by the TCP. Optional roll-up signage is typically not utilized. The advance warning area moves with the work area. Traffic should be directed to pass safely. Parking may be prohibited, and work is typically scheduled during off-peak hours. In addition, vehicles may be equipped with such devices as flags, flashing vehicle lights, truck-mounted attenuators, and appropriate signs. These devices may be required individually or in various combinations, including all of them, as determined necessary.

The present study is designed to quantify the impact of a truck-mounted RSS on vehicle speeds in maintenance work zones and identify best practices for their use as part of mobile maintenance work operations.

1.2 GOALS AND OBJECTIVES

The overall goal of this investigation is to assist ODOT Maintenance in evaluating the benefits and limitations of using a truck-mounted radar speed sign during mobile operations. ODOT Maintenance has procured radar speed signs for use in Regions 1 and 4 and elsewhere around the state. The signs are attached to the back of maintenance trucks, and deployed as part of the traffic control measures during maintenance work. This research study is designed to provide information to ODOT Maintenance personnel on the expected impacts of the radar speed signs and guidance on the use of the signs within maintenance work zones. The study utilizes knowledge gained from prior work zone safety studies that have been conducted by OSU for ODOT over the past 4-5 years and also other researchers and transportation agencies throughout the state in the past few years *(Gambatese et al. 2013; Gambatese and Zhang 2014; 2015)*.

The research focuses on a radar speed sign procured by ODOT Maintenance and attached to the back of a maintenance truck. The specific objectives for this research study are to:

1. Implement the radar speed sign on multiple Region 1 and 4 maintenance operations that are mobile in nature.

2. Determine the extent to which the radar speed sign is applicable to, and appropriate for, typical mobile maintenance operations.

3. Determine the impact of the presence of the radar speed sign on vehicle speeds as the vehicles pass through the maintenance work zones.

4. Develop recommendations and guidance for ODOT Maintenance regarding use of radar speed signs in mobile maintenance work zones.

1.3 RESEARCH SCOPE AND METHODS

To achieve the research goal and meet the stated objectives, seven primary research activities were planned for the study: (1) Study Initiation; (2) Literature Review; (3) Preliminary Testing and Verification; (4) Implementation and Data Collection; (5) Data analysis and Evaluation; (6) Development of Guidelines for Implementation; (7) Preparation of Draft and Final Reports. Each of the planned activities is described in detail below.

Task 1: Study Initiation
This task involved setting up an initial meeting with the ODOT Technical Advisory Committee (TAC) to discuss and affirm the objectives, tasks, and timeline for the study. During the meeting the process for testing the RSS equipment and ODOT mobile maintenance projects/activities to investigate were also determined.

Task 2: Literature Review
For this task, an in-depth review of literature, reports, and procedure manuals germane to the use and testing of RSSs was conducted. Special consideration was given to previous research studies on similar projects conducted by other transportation agencies.

Task 3: Preliminary Testing and Verification
The RSS equipment was tested under controlled conditions. For this task, the truck with the radar speed sign attached was parked in a secure location that is not exposed to public traffic. With the radar speed sign operating, a vehicle was driven multiple times passed the truck at different speeds, including both normal speed and excessive speed. The speed displayed by the RSS was recorded and its accuracy was evaluated.

Task 4: Implementation and Data Collection
This task was the main experimental portion of the study. The researchers coordinated with ODOT Maintenance in Regions 1 and 4 and selected multiple maintenance operations on which to evaluate the radar speed sign under different conditions. The research team examined different types of operations and planned data collection to minimize or eliminate potential confounding factors. Three operations in the Portland metropolitan area (Region 1) and one in the Klamath Falls area (Region 4) were selected. For each operation selected, two periods of testing were conducted for comparison: one with the radar speed sign turned on and one without the radar speed sign turned on. Temporary speed sensors were placed on the roadway pavement in the adjacent travel lanes at various locations throughout the planned work area to measure the speeds of the passing vehicles.

Task 5: Data Analysis and System Evaluation
For Task 5, the data collected from the case studies was analyzed to measure the impacts of the radar speed signs. The evaluation was based on the data collected in Task 4. Statistical analyses of the vehicle data are conducted to compare vehicle speed with and without the presence of the RSS.

Task 6: Develop Guidelines for Implementation
This task involved the development of guidelines for ODOT reference when planning and considering use of an RSS on future maintenance projects.

Task 7: Preparation of Draft and Final Reports
This task entailed compiling all of the research findings into this final report to be published by ODOT.

1.4 BENEFIT

The most significant benefit of the research is expected to be a means for ODOT Maintenance to further improve the safety of maintenance workers and the traveling public during maintenance operations. Additionally, the research is expected to reveal the level of impact of a radar speed sign on vehicle speeds, and how to promote efficient work zone designs for travel through work zones and ultimately maintain a high level of safety and mobility throughout the state.

1.5 IMPLEMENTATION

The research results are provided to ODOT Maintenance for consideration and implementation during future maintenance work. It is expected that the information contained in this document will be implemented by ODOT when developing future work zone safety strategies and planning investments, maintenance operations, and construction activities when considering how to set up and design work zones.

2.0 LITERATURE REVIEW

Work zone speed control has been the subject of many research efforts in the past. Various techniques and procedures have been tested and evaluated; including variation of traditional fixed signing, changeable message displays, radar units with speed sign messages, and a range of electronic devices to sense and display information related to speed *(Pigman et al. 2006)*. A comprehensive review of available literature on work zone traffic control was undertaken and the result of previous studies is presented in this chapter. Standards and practical guidelines for controlling traffic through work zones and providing a safe environment for both workers and motorists have also been reviewed.

The literature cited for the previous research described in both SPR-751 *(Gambatese et al. 2013)* and SPR-769 *(Gambatese and Zhang 2014)* reports is relevant to the present study. For efficiency, portions of the literature review related to work zone traffic control that are provided in the SPR-751 and SPR-769 reports are repeated again in this section of the report.

2.1 TRAFFIC CONTROL DESIGN MANUALS

The selection and specification of traffic control measures and the design of construction or maintenance work zones is addressed and published in the ODOT *Traffic Control Plans Design Manual* and the *Manual on Uniform Traffic Control Devices* (MUTCD). These design manuals provide guidance to traffic control designers to effectively and safely control traffic and reduce speeds within work zones. Summary descriptions of each manual as they pertain to the present research are provided below.

2.1.1 ODOT Traffic Control Plans Design Manual

The ODOT *Traffic Control Plans Design Manual* provides an organized collection of traffic control plan design standards, guidelines, policies, and procedures to be used in the development of a Temporary Traffic Control Plan *(ODOT 2014)*. This manual includes an introduction to Traffic Control Plans (TCP), a list of temporary traffic control devices (TCD), descriptions of traffic control measures (TCM), standard specifications and drawings, traffic control plans designs, and traffic control cost estimating.

Traffic Control Plan:
The principal function of a TCP is to enable safe and efficient movement of road users through or around work zones while protecting workers, incident responders, and equipment. In addition, the TCP is intended to provide for the efficient construction and maintenance of the highway *(ODOT 2014)*. Safety is the primary concern in designing a traffic control plan. ODOT uses the guidance of the *Manual on Uniform Traffic Control Devices* (MUTCD) in the design of TCPs. Mandates within the Oregon Administrative Rules and the Oregon Revised Statutes require the use of the MUTCD as the reference for the specifications of uniform standards for traffic control devices for use upon highways within this state *(ODOT 2014)*.

Work Zone:
The enforceable work zone is defined as starting from the first warning sign, which is usually the "Road Work Ahead" sign, to the "End Road Work" sign or the last traffic control device. Messages displayed on electronic signs or other advance warning signs, such as "Road Work Next XX Miles," are not considered the first warning sign. A work zone is composed of four distinct areas, as showing in Figure 2.1. These areas are the: (1) advance warning area, (2) transition area, (3) activity area, and (4) termination area.

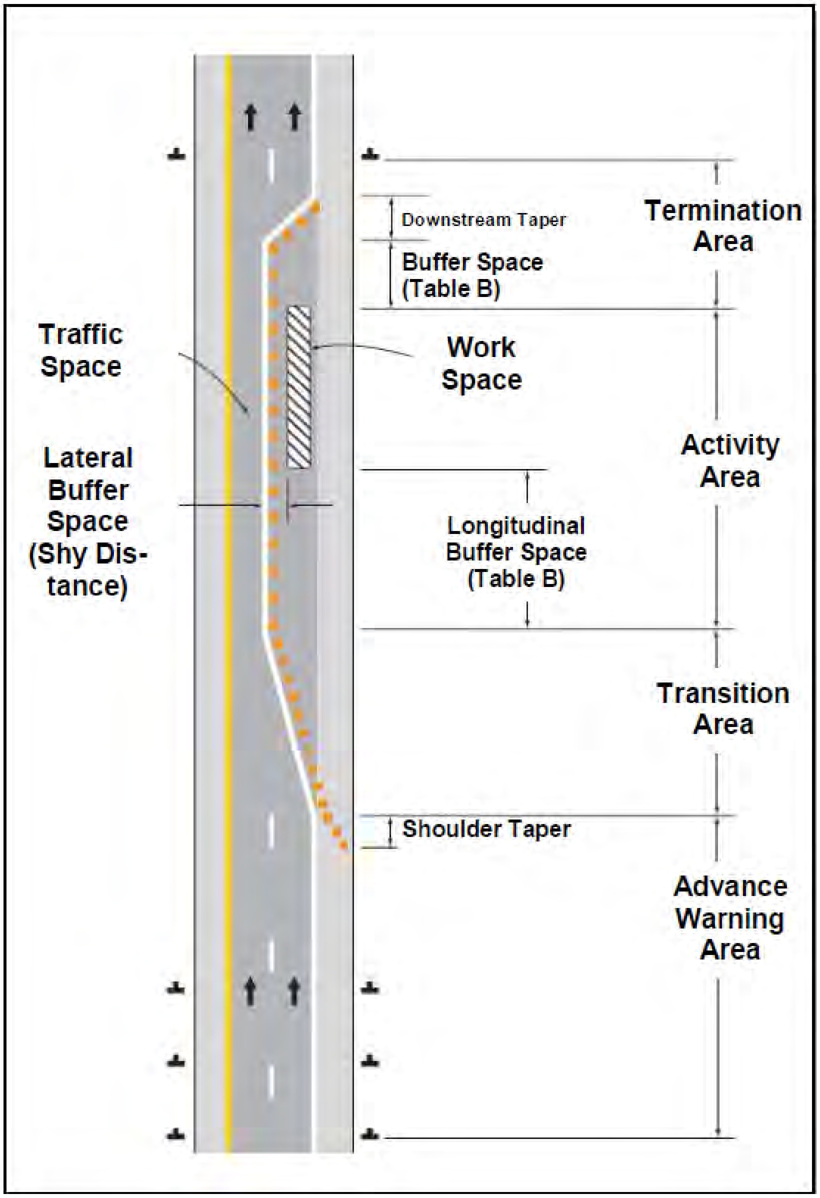


Figure 2.1: Areas in a Work Zone (*ODOT 2014*)

Device Spacing:
Adequate spacing between traffic control devices is needed in order for motorists to see and comprehend the devices at the traveling speed. If the spacing between devices is small, drivers

may not have sufficient time to comprehend and react to the signs. For high speed roadways, the required spacing of channelization devices is speed-dependent. Spacing dimensions, “A”, “B” and “C” are defined in Table 2.1, where dimension A represents the distance between the beginning of taper and the first warning sign, B represents the distance between the first and second warning signs, and C represents the distance between the second and third warning signs.

Table 2.1: Traffic Control Devices Spacing (*ODOT 2014*)

Speed (mph)	A (ft)	B (ft)	C (ft)
20-30	100	100	100
35-40	350	350	350
45-55	500	500	500
55-65 (Fwys)	1,000	1,500	2,640

Traffic Control Devices:
Traffic control devices (TCDs) are used to regulate and guide the traffic and sufficiently warn drivers so that a safe and efficient travelling environment exists for both construction workers and motorists. The five principles of setting up traffic control devices are to: (1) fulfill a need, (2) command attention, (3) convey a clear and simple meaning, (4) command respect from the road user, and (5) give adequate response time *(ODOT 2014)*. FHWA policy requires all TCDs used in a work zone on the National Highway System to be crashworthy. For a TCD to be crashworthy, it must meet the established testing and evaluation criteria of the AASHTO *Manual for Assessing Safety Hardware* (MASH). Work zone traffic control devices are classified into the following four categories *(ODOT 2014)*:

Category 1: Low-mass devices with a known performance history

Category 2: Devices with a higher mass which can pose a greater risk to the public if struck

Category 3: Devices that pose a significant risk to the public if not adequately protected or installed correctly

Category 4: Devices that pose the greatest risk to motorists such as temporary TCDs. These are usually trailer-mounted devices.

The specific traffic control devices employed in a work zone depends on various factors such as the nature and type of work performed, roadway conditions, duration of the work, and traffic conditions (speed, volume, type, etc.). The TCDs that are commonly used on highway maintenance projects are described in detail below.

Tubular and Conical Markers – Tubular and conical markers (tubes and cones) are the most commonly-used channelizing devices for delineating the roadway and directing traffic through a work zone. These devices are effectively used to override existing pavement markings for short-duration applications (less than three days). Figure 2.2 shows tubular markers being used to delineate an edge of a travel lane on the I-84 case study project as part of a prior ODOT study (SPR-751).

Figure 2.2: Tubular Markers on Roadway

Temporary Plastic Drums – Plastic drums (barrels) are the largest, most visible deformable channelization devices. Plastic drums are usually used to delineate travel lanes, identify work areas, construct lane closure tapers, and delineate portable changeable message sign (PCMS) and temporary traffic signal installations *(ODOT 2014)*. Figure 2.3 shows plastic drums in use on the I-84 case study project as part of a prior ODOT study (SPR-751). While designed primarily for channelization, both tubular markers and drums may also be employed for vehicle speed reduction. Channeling the traffic in a certain direction or location may cause reduction in speeds. In addition, tubular markers and drums can be located to narrow down a lane, giving the impression of a tighter driving lane and thus promoting slower speeds.

Figure 2.3: Plastic Drums on Roadway

Type I, II and III Barricades – Barricades are used for several purposes, including delineating temporary signs mounted on temporary sign supports (TSS). Barricades may be placed at regular intervals within a closed lane to remind drivers that the lane is unavailable to them, and placed at the point of closure. Figure 2.4 shows an example of a Type III barricade.

Figure 2.4: Type III Barricade (*ODOT 2014*)

Temporary Signs – Temporary signage is used to convey regulatory, guidance, and warning messages in place of permanent signage during roadway construction and maintenance operations. Figure 2.5 shows several examples of temporary signs.

Figure 2.5: Examples of Temporary Signs (*ODOT 2014*)

Temporary Impact Attenuators – Temporary impact attenuators, also called crash cushions, are crashworthy systems that mitigate the effects of errant vehicles that strike obstacles. When struck by a vehicle, an impact attenuator is designed to lessen the impact of the crash on the traveling vehicle and on the supporting structure. A truck mounted attenuator (TMA) is a mobile impact attenuator attached to a work or shadow vehicle that is used to temporarily protect objects or a work area. One or more TMAs are usually located in advance of an object, work area, equipment, or workers. A TMA should not be used for long-term protection of barriers or other fixed objects. Figure 2.6 shows an example of a TMA attached to the rear of a truck.

Figure 2.6: Truck Mounted Attenuator and Sequential Arrow Board

Sequential Arrow Signs – Sequential arrow signs or arrow boards are large truck- or trailer-mounted lighted signs used to indicate the direction which traffic needs to merge as part of a lane closure. These devices are not to be used to indicate a lane closure. Figure 2.6 above shows an example of a sequential arrow board mounted on top of a truck.

Portable Changeable Message Sign (PCMS) – PCMS's are large, lighted signs used to display programmable, dynamic messages that reflect work zone conditions to be encountered by approaching traffic. PCMS's can be mounted on either a trailer or work vehicle. Figure 2.7 shows an example of trailer-mounted PCMS. Figure 2.8 shows an example of a work vehicle-mounted PCMS.

Figure 2.7: PCMS on Trailer

Figure 2.8: PCMS on Roller

The messages displayed on a PCMS should be complete, independent thoughts. Displaying a message that relies on a second message to complete the thought should be avoided. In practice, one message should be used to describe a situation or condition. A second panel should be used to convey supplemental information, an additional warning, or direction for drivers *(ODOT 2014).*

Radar Speed Trailer - These units use radar technology to measure the speed of oncoming vehicles and display the vehicle speed to the drivers. The vehicle speed is usually displayed along with the regulatory or advisory speed and/or a message alerting the drivers to use caution. Figure 2.9 shows an example of a radar speed trailer.

Figure 2.9: Radar Speed Trailer

Traffic Control Supervisor (TCS) – The traffic control supervisor is a field position employed by the contractor or working as a subcontractor whose primary responsibility is to implement and oversee the Traffic Control Plan (TCP). Examples of the responsibilities included in this role are: inspecting and maintaining the temporary traffic control devices, replacing damaged devices, monitoring traffic flows through the work zone or the effectiveness of a detour, and making recommendations to ODOT and the contractor to improve upon the TCP *(ODOT 2011)*. The TCS must be certified and carry a valid certificate verifying their certification. The person assigned to the TCS role must not be the project superintendent. TCS involvement is typically measured and paid for on a work shift basis. One payment is made for a TCS regardless of length of the work shift.

2.1.2 Manual on Uniform Traffic Control Devices for Streets and Highways *(FHWA 2009)*

The *Manual on Uniform Traffic Control Devices* (MUTCD) provides guidelines for the selection and use of traffic control devices in temporary work zones on streets and highways. In Part 6 of the MUTCD, temporary traffic control is discussed. The primary function of temporary traffic control is to provide for the reasonably safe and effective movement of road users through or around temporary traffic control zones while reasonably protecting road users, workers, responders to traffic incidents and equipment *(FHWA 2009)*. Consideration for road user safety, worker and responder safety, and the efficiency of road user flow is an integral element of every temporary traffic control zone.

The MUTCD states seven fundamental principles of temporary traffic control (TTC). The principles can be summarized as follows (see *MUTCD 2009* for complete description of principles):

1. General plans or guidelines should be developed to provide safety for motorists, bicyclists, pedestrians, workers, enforcement/emergency officials, and equipment.

2. Road user movement should be inhibited as little as practical.

3. Motorists, bicyclists, and pedestrians should be guided in a clear and positive manner while approaching and traversing TTC zones and incident sites.

4. To provide acceptable levels of operations, routine day and night inspections of TTC elements should be performed.

5. Attention should be given to the maintenance of roadside safety during the life of the TTC.

6. Each person whose actions affect TTC zone safety, from the upper-level management through the field workers, should receive training appropriate to the job decisions each individual is required to make. Only those individuals who are trained in proper TTC practices and have a basic understanding of the principles (established by applicable standards and guidelines, including those of this Manual) should supervise the selection, placement, and maintenance of TTC devices used for TTC zones and for incident management.

7. Good public relations should be maintained.

The MUTCD describes the components of temporary traffic control zones, and defines four different sections of the control zone as described above: (1) advance warning area, (2) transition area, (3) activity area, and (4) termination area. The manual also presents traffic control elements recommended for use in each area of the work zone. For example, tapers may be used in both the transition and termination areas. Taper length criteria and the formulas for determining taper length are shown in Table 2.2 and Table 2.3 *(FHWA 2009)*.

Table 2.2: Taper Length Criteria for Temporary Traffic Control Zones (*FHWA 2009*)

Type of Taper	Taper Length
Merging Taper	at least L
Shifting Taper	at least 0.5 L
Shoulder Taper	at least 0.33 L
One-Lane, Two-Way Traffic Taper	50 feet minimum, 100 feet maximum
Downstream Taper	50 feet minimum, 100 feet maximum

Where: L = taper length in feet calculated based on Table 2.3

Table 2.3: Formulas for Determining Taper Length (*FHWA 2009*)

Speed	Taper Length (L) in feet
40 mph or less	$L = (WS^2)/60$
45 mph or more	$L = WS$

Where: L = taper length in feet
W = width of offset in feet
S = posted speed limit, or off-peak 85th percentile speed prior to work starting, or the anticipated operating speed in mph

The MUTCD provides guidelines for improving worker safety. The following list contains the key elements of worker safety and temporary traffic control management that should be considered as indicated by FHWA *(FHWA 2009)*:

- Training – all workers should be trained on how to work next to motor vehicle traffic in a way that minimizes their vulnerability. Workers having specific temporary traffic control responsibilities should be trained in temporary traffic control techniques, device usage, and placement.

- Temporary Traffic Barriers – temporary traffic barriers should be placed along the work space depending on factors such as lateral clearance of workers from adjacent traffic, speed of traffic, duration and type of operations, time of day, and volume of traffic.

- Speed Reduction – reducing the speed of vehicular traffic, mainly through regulatory speed zoning, funneling, lane reduction, or the use of uniformed law enforcement officers or flaggers, should be considered.

- Activity Area – planning the internal work activity area to minimize backing-up maneuvers of construction vehicles should be considered to minimize the exposure to risk.

- Worker Safety Planning – a trained person designated by the employer should conduct a basic hazard assessment for the worksite and job classifications required in the activity area. This safety professional should determine whether engineering, administrative, or personal protection measures should be implemented.

This MUTCD also provides guidelines for using different kinds of signs, including the size and color of signs, and the mounted height of signs. The manual addresses other traffic control devices which are described in previous sections of this report.

One section within Part 6 of the MUTCD is particularly relevant to the present study. Section 6C.01 – Temporary Traffic Control Plans provides guidance on the design of temporary traffic control (TTC) in work zones. The following portions of this section address speed reductions:

> *6C.01-12: Reduced speed limits should be used only in the specific portion of the TTC zone where conditions or restrictive features are present. However, frequent changes in*

the speed limit should be avoided. A TTC plan should be designed so that vehicles can travel through the TTC zone with a speed limit reduction of no more than 10 mph.

6C.01-13: A reduction of more than 10 mph in the speed limit should be used only when required by restrictive features in the TTC zone. Where restrictive features justify a speed reduction of more than 10 mph, additional driver notification should be provided. The speed limit should be stepped down in advance of the location requiring the lowest speed, and additional TTC warning devices should be used.

6C.01-14: Reduced speed zoning (lowering the regulatory speed limit) should be avoided as much as practical because drivers will reduce their speeds only if they clearly perceive a need to do so.

Support:
6C.01-15: Research has demonstrated that large reductions in the speed limit, such as a 30 mph reduction, increase speed variance and the potential for crashes. Smaller reductions in the speed limit of up to 10 mph cause smaller changes in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 10 mph from the normal speed limit has been shown to be more effective.

2.1.3 Oregon Department of Transportation (ODOT) Guideline for Product Review

The ODOT Standard Specifications book is used as a reference in all ODOT projects. All products qualified for use on ODOT projects go through a stringent review process before they may be used. All products must meet ODOT's minimum standard specifications. The ODOT Standard Specifications book includes Section 00225 related to work zone traffic control. This section contains definitions, standards, and requirements for traffic control devices. Standard guidelines for product review outlining what testing must be done and what specifications a product must meet have also been created *(ODOT 2013a; 2015)*.

The present study aims to reduce vehicle speeds by using a radar speed display. Over the last several years, radar speed displays have become a preferred technology for a growing number of safety professionals looking to slow traffic. There may be, however, vast differences between one radar speed display model and another. To use an RSS in a work zone area, the RSS must be MUTCD compliant. The Federal Highway Administration's MUTCD sets the standards for size, shape, dimensions, content, and color of thee displays for use on all Federal roadways, and most states and municipalities have adopted the MUTCD standard as their own.

Section 00225.18 of the ODOT Standard Guideline published in July 2013 indicates that electronic and static signs on radar speed display are required to meet all applicable aspects of the current Manual on Uniform Traffic Control Devices (MUTCD). The following list is a summary of the requirements:

- Be fully compliant with the current version of the MUTCD.

- Be housed in a solid, durable, rectangular metal case, and be finished in a non-reflective black color.

- Be legible from distances, as listed in Table 2.4. (Note: This is an actual field test.)

- Include a properly sized electronic display that accommodates required Panel Displays and "YOUR SPEED" placard.

Table 2.4: Radar Speed Trailer – Product Requirement (*ODOT 2013b*)

Panel Type	**Numeric** Min. Character Height (in.)	**Alpha** Min. Character Height (in.)	**Legibility** Min. Distance (ft)
1	12 inches	8 inches	500
2	18 inches	10 inches	650

- Be capable of displaying two Numeric characters in single row. When posted speed is exceeded, the panel shall be capable of displaying four Alpha characters in two rows.

- Be capable of being mounted at least 7 feet above the pavement to the bottom of the electronic sign.

- Be capable of displaying radar speed within 5 mph resolution in 1 mph step increments at a minimum 1,000 ft range and warning messages in static and flashing modes.

- Provide K-band 24.15 GHz direct sensing, license free (FCC part 15 compliant) radar.

- Provide electronics enclosure meeting weatherproof NEMA-3R.

- Provide speed and event logging with time stamp. Data memory has 60 days circular buffer capacity.

- Have automatic dimming capability. The auto-dimming feature (for nighttime use) shall reduce the full rated light element output by 50%.

- Provide programming display features for exceeding, minimum, and maximum speed limits.

- Provide variable speed display types: stealth, actual, speed limit, flashing, and static numerals.

- Provide amber-colored light elements with a wavelength between 587 nm and 593 nm.

- Have a model number that is unique and only includes manufactured products that meet the requirements listed herein.

- Notify ODOT QPL coordinator immediately if production of any product approved for the QPL has been permanently discontinued.

2.2 RESEARCH ON TRAFFIC CONTROL DEVICES AND RADAR SPEED DISPLAYS

The available literature related to this study is very extensive. Work zone speed control has been the subject of numerous efforts in the past. Many of the speed reduction measures mentioned in this research study have been evaluated in other states. In those studies, some investigated the effect of a radar speed sign alone and others measured its effect in combination with other TCDs. This section of the report provides some noticeable studies related to the present research.

2.2.1 Speed Reduction Effect of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways *(McCoy et al. 1995)*

McCoy et al. *(McCoy et al. 1995)* examined the effectiveness of speed displays at a rural interstate work zone in South Dakota. The speed monitoring display evaluated in this study was placed on a trailer. The trailer was augmented with a “WORK ZONE” warning sign, an advisory 45-mph speed limit sign, and a “YOUR SPEED” sign. The trailer was placed in the median next to the left traffic lane at the beginning of the taper. As motorists approached the merge area, their speeds were displayed on the speed monitoring display. The study revealed that the speed monitoring display reduced mean vehicle speeds by 4 mph (i.e., from 60.5 to 56.5 mph).

2.2.2 Controlling Vehicle Speeds in Work Zones: Effectiveness of Changeable Message Signs with Radar *(Garber and Fontaine 1996)*

In a similar study, Garber and Fontaine *(Garber and Fontaine 1996)* used changeable message signs (CMS) with a radar unit to examine speed reductions at rural interstate work zones in Virginia. If the radar detected a vehicle traveling above a preset speed threshold, the CMS displayed the message "YOU ARE SPEEDING SLOW DOWN". The CMS with radar was tested at two sites in southwestern Virginia and speed data was collected with automatic traffic counters. Statistical t-tests of the speed data collected revealed that motorists driving above the regulatory speed limit reduced their speeds by a significant amount from the beginning of the work zone to the middle and end of the work zone. The researchers found that the mean speed of all traffic was reduced by approximately 0.7 mph at the CMS location. Once inside the work zone, however, this reduction increased to approximately 1.4 mph. Based on the 85^{th} percentile speed reduction of about 8 mph, the researchers concluded that the CMS system, coupled with a radar unit, has an impact on reducing speeds of the fastest segment of the driving population.

2.2.3 Use of Speed Monitoring and Communication Display for Traffic Control *(Wertjes 1996)*

The South Dakota DOT conducted a research study to identify and evaluate a speed monitoring display suitable for use in interstate highway work zones. The laser/CMS display was equipped to capture speeds of on-coming vehicles. The operation studied was a short term pavement repair project on which the laser speed threshold was set at 70 mph. The study indicated a 10% reduction in the number of vehicles traveling greater than 70 mph with the equipment present. Mean speeds decreased up to 2 mph, and the 85^{th} percentile speeds decreased by 1 to 4 mph.

2.2.4 Effectiveness of Changeable Message Signs in Work Zones-Phase II *(Garber and Srinivasan 1998)*

Garber and Srinivasan *(Garber and Srinivasan 1998)* conducted a phase-two research study in three work zones for a period of up to seven weeks in Virginia. In the research, the evaluation of the effectiveness of a CMS with radar for different types of vehicles and different lengths of work zones was also included. Based on the analysis of the speed data collected using automatic traffic counters at the beginning, middle, and end of each work zone, the researchers found that the duration of exposure of the CMS did not have significant impact on its effectiveness and the CMS was equally effective in reducing the speeds of different types of vehicles. The researchers also found that, in longer work zones, drivers who reduced their speeds in response to the CMS frequently had a tendency to speed back up. Therefore, the use of a second CMS was recommended in very long work zones.

2.2.5 Evaluation of Work Zone Speed Reduction Measures *(Maze et al. 2000)*

In 2000, the Iowa DOT sponsored research to evaluate various work zone speed reduction measures *(Maze et al. 2000)*. Through the review of previous research and by conducting a survey the researchers concluded that flagging and police enforcement are the most effective methods to reduce speeds. However, due to limited resources within many agencies, the use of police officers in work zones is infrequent. The researchers suggest that replacing police enforcement by photo-radar enforcement equipment may be more practical and cost-effective for those states with fewer police resources available. Based on the their survey of state transportation agencies in all 50 states plus 13 non-DOT transportation agencies, the researchers concluded that the most effective speed reduction method involved some combination of traffic control devices. In their report, Maze et al. provide a review of the effects of narrowing lane with, drone radar, removable rumble strips, and other TCDs on traffic speed. In most cases the TCDs are effective in reducing mean speeds.

As a part of the research, the researchers described speed monitor displays manufactured by MPH Industries, Inc., which is a producer of speed monitor display that are used in current field research data collection efforts. Similar to the present research, Maze et al. mentioned the possibility of placing the speed monitors on the top of vehicle’s trunk for reducing speeds during temporary works.

2.2.6 Evaluation of Traffic Control Devices for Rural High-speed Maintenance Work Zones *(Fontaine et al. 2000)*

In 2000, the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration cooperated on a research study to evaluate innovative traffic control devices for application in construction work zones to alert drivers and/or workers. The researchers evaluated traffic control devices at short-term rural work zones. Seven devices were tested in eight work zones. The devices evaluated included: portable rumble strips, portable variable message signs (VMSs), radar drones, fluorescent yellow-green worker vests, retroreflective vehicle visibility improvements, fluorescent orange signs, and speed display trailers. A radar activated flagger paddle was evaluated, but on a more limited basis.

The effectiveness of these devices was assessed based on the vehicle speeds in the work zone, the ease of installation and removal of the devices, the impact of the device on vehicle conflicts, and worker comments. Analysis of the data collected revealed that the speed display trailer had the largest impact on speeds. Speed reductions at the speed trailer location were between 2 and 7.5 mph, and reductions within the work zone ranged from 3 to 6 mph. The VMS had a positive benefit in reducing conflicts. The fluorescent orange signs, vehicle visibility improvements, and yellow-green worker vests all acted to improve the conspicuity of the workers.

2.2.7 Efficacy of Radar Speed Monitoring Display in Reducing Vehicle Speed *(Skites 2004)*

Speed monitoring displays are radar-activated signs that dynamically display approaching vehicle speeds. Past studies show that speed monitoring displays with radar have a statistically significant effect in reducing mean speeds and the percentage of drivers exceeding the posted speed limit. The long-term effectiveness of radar speed monitoring displays has been evaluated in some studies. Skites *(Skites 2004)* found that portable trailer-mounted displays are appropriate for temporary speed reduction needs such as work zones. Several independent studies were reviewed and end-user field studies examined in the research. As a result Skites found that the advent of radar and variable message sign integrated technology present a low-cost, easy to implement solution for reducing speeds.

2.2.8 Effect of Speed Photo-radar Enforcement *(Benekohal et al. 2010)*

The Illinois DOT conducted a research study to explore the effect of speed photo-radar enforcement (SPE), also referred to as “automated speed enforcement”. In this research study, an advanced warning sign (shown in Figure 2.10 was placed on roadways with 50 mph regulatory speeds to inform the motorists of the implementation of SPE in the work zone. A self-contained van was used to implement the SPE as shown in Figure 2.11. Figure 2.12 provides a graphical view of how the SPE system works.

Figure 2.10: Special Signs for Speed Photo Enforcement (*Benekohal et al. 2010*)

Figure 2.11: Photo Enforcement Vehicle (*Benekohal et al. 2010*)

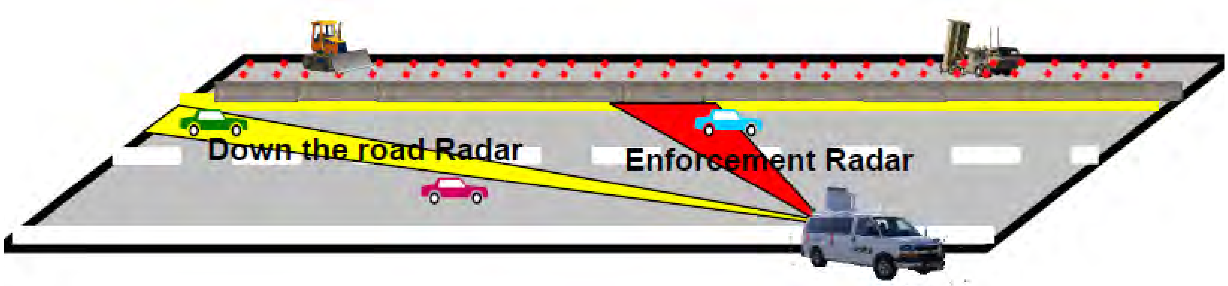


Figure 2.12: Operation of the Photo Enforcement (*Benekohal et al. 2010*)

The speeds of vehicles approaching the photo enforcement van were monitored by two radar systems, a down-the-road radar speed reader and an enforcement radar speed reader. The speed obtained from the down-the-road radar speed reader is displayed on the message board mounted on top of the van. The speed display gives speeding drivers a final chance to reduce speed and comply with the work zone speed limit. The range of a down-the-road radar speed reader is similar to that of a radar speed reader typically used in work zones, which is about 0.25 to 0.5 miles *(Tobias 2011)*.

The enforcement radar speed reader measured the vehicle speed at about 150 feet upstream from the van. If the speed of the vehicle is greater than a specified value, the two onboard cameras are activated to take pictures of the driver and rear license plate of the vehicle. The vehicle owner's address is then determined based on the license plate number, and a ticket is mailed to the address.

The research revealed that the SPE significantly reduced the speeds of cars and trucks by 3 to 8 mph in work zones where the regulatory speed was 50 mph. The percentage of free-flowing vehicles (with headways greater than 4 seconds) exceeding the speed limit at the treatment location was reduced drastically *(Tobias 2011)*. The presence of the SPE system also reduced the speeds of vehicles 1.5 miles downstream of the van location by 2 to 5 mph. Another type of speed photo enforcement equipment is shown in Figure 2.13.

Figure 2.13: Photo Enforcement Equipment

2.2.9 Estimating the Effect of Speed Control Strategies on Speed Distribution in Work Zones with quantile Regression *(Chen and Tarko 2013)*

At the 93rd Transportation Research Board (TRB) annual meeting, a paper was presented describing a study that used quantile regression to evaluate speed data instead of traditional methods *(Chen and Tarko 2013)*. The researchers conducted the study in work zones where the posted speed limit was 45 mph. The researchers concluded that the flexibility of quantile regression allowed for investigating the effects of each traffic control measure on each driver group (slow, average, and fast drivers). The results of the study show that, while a large percentage of all vehicles travelled at greater than the posted 45 mph, police enforcement has more impact on fast drivers than on slow and average drivers. The analyses of the data collected for the present study employed commonly-used statistical analysis techniques that did not include quantile regression.

2.2.10 Effects of Uniform Traffic Officers and Other Speed Management Measures *(Lee et al. 2014)*

In 2014, the State of Vermont Agency of Transportation conducted a research study along with University of Vermont scholars *(Lee et al. 2014)*. The goal of the study was to assess the effectiveness of Uniform Traffic Officers (UTO) and other interventions on maintaining safe travel speeds and to help guide the Vermont Agency of Transportation (VAOT) regarding the provision of proper resource allocation for improving work zone safety. For the purpose of the study, the officers were stationed in marked police vehicles with the blue lights atop the vehicles flashing and parked within project work zones while road workers were active. In Vermont, UTOs do not normally perform enforcement duties and are used primarily for their presence.

Based on the data collected from case studies, the researchers found that there were significant drops in mean speeds and the percentages of speeders in the work zones but the speeds all remained relatively high. The researchers found that the use of UTOs was effective in lowering mean speeds and the proportion of travelers who exceed the speed limit. The presence of UTOs was able to bring the mean speeds to below the work zone speed limit, and also effective in dramatically decreasing the proportion of speeders, in terms of the percent of vehicles who were over the speed limit and those who were going at least 5 mph faster than the limit.

2.2.11 Effectiveness of Countermeasures to Reduce Vehicle Speeds in Freeway Work Zones *(Hildebrand and Mason 2014)*

Hildebrand and Mason *(Hildebrand and Mason 2014)* identified and evaluated supplemental traffic control countermeasures on Canadian roadways that will achieve speed reductions beyond 20 km/h (12.4 mph). The countermeasures tested included combinations of: floating speed zones (FSZ); traffic control person (TCP); narrow lanes; radar speed display board (RSDB); variable message sign (VMS); and a fake police vehicle. The top performing countermeasures were the TCP and FSZ, fake police vehicle and FSZ, and the RSDB and FSZ, which resulted in mean speed reductions of 23 km/h (14.3 mph), 19 km/h (11.8 mph), and 19 km/h (11.8 mph), respectively, and typically with significant reductions in speed dispersion. Differences in driver behavior, roadway design, work zone design, and law enforcement in Canada compared to the US may impact the ability to generalize the research results to US work zones; however, the researchers feel that the differences will be insignificant.

As a part of the study the researchers placed a radar speed display board (RSDB) in advance of the active area to reinforce for the drivers the requirement for a reduction in speed. The display board was equipped with a sign above the display that read “YOUR SPEED” (shown in Figure 2.14).

Figure 2.14: Radar Speed Display Board (*Hildebrand and Mason 2014*)

The premise behind the use of the display was that when motorists believe they are being individually targeted there will be a greater influence on their speed. It is believed that it is very difficult to have motorists drop their speed by more than 20 km/h (12.4 mph) and attempts to do so may increase speed dispersions. The RSDB was programmed to activate and display oncoming vehicle speeds at a specific threshold (70 km/h, 43.5 mph), to begin to flash the oncoming vehicles’ speed at a slightly higher speed (95 km/h, 59.0 mph), and finally, to shut down at an even higher speed (110 km/h, 68.4 mph). The RSDB was used in combination with the 70 and 80 km/h (43.5 and 49.7 mph) single posted FSZ.

Hildebrand and Mason found that a reduction from a regulatory speed of 90 km/h (55.9 mph) to a posted regulatory speed of 70 km/h (43.5 mph) in a work zone on a high-speed roadway is achievable. The results indicate a further reduction in operating speeds when the work zone regulatory speed is posted at 70 km/h compared to the traditional 90 km/h. These further reductions were achieved with the help of a supplemental countermeasure (e.g., fake police vehicle, TCP, RSDB, etc.) and were only used for the short active section of the lane closure. The researchers recommend that road authorities incorporate a provision within work area traffic control layouts that permit posted speed limits of 70 km/h (43.5 mph) in high-speed facility work zones as long as the RSDB or the TCP supplemental countermeasures are used.

2.2.12 Use of Speed Display Trailers in Work Zones *(Sha 2005)*

In this study, the Maryland State Highway Administration Office of Traffic and Safety addressed the use of a Speed Display Trailer (SDT) in work zones, its advantages, and prepared a guideline for its usage. In the study, an SDT was defined as a small device that usually consists of a changeable speed display, a radar speed detector, and a regulatory speed limit or advisory speed sign. Based on previous literature, the SDT was found to be an effective speed reduction measure in work zones. Drivers have shown positive driving behavior toward the speed monitoring display. Set-up and removal of the speed display trailer was easily accomplished. Therefore, the speed display trailer was found to be a cost-effective speed control measure. In their study, the researchers claimed two disadvantages of SDTs. First, the effectiveness of the speed monitor display decreases over time. Second, although an effective speed control countermeasure, speed reductions attained with the SDT are usually less than what is desired.

2.2.13 Evaluation of Radar Speed Display Trailer-Mounted Device for Speed Reduction in Construction Work Zones *(MDT 2006)*

As part of its research program, the Montana Department of Transportation conducted an experimental research study in 2006 in which the researchers investigated the effectiveness of trailer mounted radar speed display devices in reducing speeds in the Bear Canyon construction work zone on I-90. The evaluation consisted of collecting data with automatic traffic recorders (ATR) to determine if the devices are a factor in speed reductions (Figure 2.15). ATR data was collected at evenly spaced distances throughout the work zone crossover (Figure 2.16). ATR speed data was collected prior to initiating the radar speed displays (RSD) to provide baseline data for comparison. The average length of the work zone was 5 miles. Average travel speed (ATS), as determined by the 85th percentile speed data, in the eastbound lanes prior to the placement of the RSD’s was 49 mph, and the average speed after the installation of the RSD’s was 47 mph (rounded to the nearest MPH). Average travel speed in the westbound lanes prior to the placement of the RSD’s was 55 mph, with an average travel speed after the installation of the RSDs of 52 mph. Table 2.5 shows a summary of the 85th percentile speeds at the five ATR placement locations. The speed data revealed that the placement of the RSD’s reduced the average travel speed by 2-3 mph. The researchers suggest that these units be used in other work zones of differing construction types to ascertain their overall efficiency.

Figure 2.15: I-90 Westbound Radar Speed Display Location

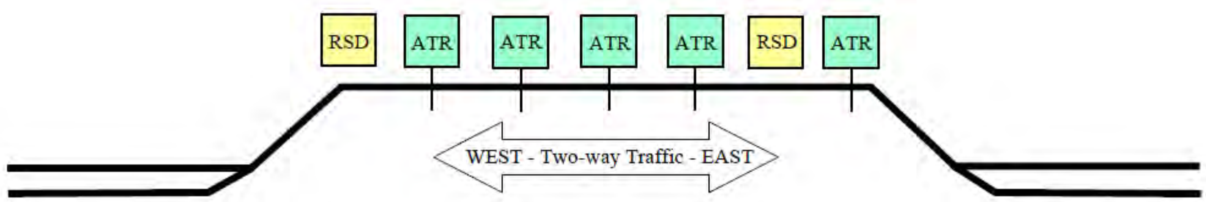


Figure 2.16: Representative Diagram of the I-90 Work Zone Crossover Schematic of approximate Placement of the RSD Units and ATRs *(MDT 2006)*

Table 2.5: 85th Percentile Speeds with and without Radar Speed Trailer (mph) ***(MDT 2006)***

Before	**After**	**Eastbound**	**Before**	**After**	**Westbound**
Speeds without radar trailer	Speeds with radar trailer	Speed limit	Speeds without radar trailer	Speeds with radar trailer	Speed limit
45	43	35	52	51	35
49	47	45	55	51	45
48	48	45	56	54	45
50	48	45	57	50	45
51	51	45	56	54	45

2.2.14 Management of Speed Control in Work Zones *(Sarasua et al. 2006)*

In April 2005, a team of researchers led by Clemson University's Transportation Systems Laboratory embarked on research to better manage speed control in work zones. The research included a literature review and survey of state departments of transportation. A number of devices and strategies were selected for field evaluation: drone radar, changeable message sign (CMS) with radar (CMR), a speed monitoring display (SMD) with CMS, portable rumble strips, and a novel speed activated sign designed by the researchers. For evaluation of the SMD with CMS, the researchers used a V12C-2M alphanumeric sign manufactured by Ingram Technologies. The researchers decided to use the following message sequences:

- STAY ALERT – WORK ZONE
- WATCH SPEED
- YOU ARE SPEEDING

The first message sequence was programmed for continuous display, while the latter two were triggered whenever a vehicle exceeded a preset threshold. Figure 2.17 shows the typical setup with examples of both types of message sequences.

Figure 2.17: Setup Showing Speed Triggered Message and Continuous Message

Data was collected at up to three stations in each work zone studied. The stations were typically positioned before, at, and after the deployed speed reduction measure. The first station was used to collect information about the initial condition of the vehicle speeds. The second station was used to determine the immediate impact of the device on driver speeds. Finally, the third station provided data about the continued impact of the speed reduction measure on observed speeds. Speed data was collected for two conditions—one without any countermeasure and one with a countermeasure—to allow the researchers to determine the effect of the speed control device on driver behavior. Vehicle speeds at the three stations were measured using trigger-engaged speed guns.

After the initial testing, field surveillance of the speed management devices at a variety of different work zone sites on Interstate and State Route highways in South Carolina was done to collect the empirical data needed for evaluation. A statistical analysis of the empirical data was done to quantitatively evaluate the devices. A qualitative evaluation was done as well. Some of the devices were also studied in combination with police enforcement. The results of the analyses show that all of the speed control devices studied during this project have the capability of lowering vehicle speeds.

2.2.15 Evaluation of Radar/CMS Trailers to Reduce Speeds in Work Zones *(Ravani et al. 2012)*

In a study conducted by Caltrans and the California Highway Patrol (CHP) in 2013, the researchers investigated whether trailer-based radar and changeable speed signs that display driver speeds are effective in reducing speeds, as compared to positioning a CHP officer on-site or using only cones and lane closures. Caltrans conducted field experiments to compare the average traffic speeds, volume, and lane distribution at key locations in a work zone with and without the use of the CHP Radar/CMS trailer and a CHP officer parked in a patrol vehicle on-site. Average traffic speeds were collected using iCones—radar speed sensors hidden inconspicuously inside orange traffic barrels—and traffic volume and lane distribution information were captured using video cameras mounted on a mast. Three conditions were evaluated: standard lane closure, lane closure with CMS, and lane closure with CMS plus CHP.

Based on the experimental data collected, Caltrans found that lane closure alone, with no additional equipment deployed, resulted in a reduction of the average traffic speed of 5 to 5.5 mph. Total lane closure plus the Radar/CMS trailer resulted in a reduction of the average traffic speed by 8 to 12.5 mph. Lastly, lane closure plus the Radar/CMS trailer plus the use of a CHP officer in a police vehicle resulted in a total reduction of the average traffic speed of 10.5 to 14 mph, which was a slight improvement over the use of the signs alone in the work zone closure. Based on these results, the use of the CHP Radar/CMS trailer as configured in this study, in combination with an officer, was found to provide for further speed reduction. In the absence of a CHP officer, the CHP Radar/CMS trailer improved the safety in terms of reduced speeds, at least for short duration work zones.

2.2.16 Guidance for Radar Speed Sign Deployments *(Veneziano et al. 2012)*

A team of researchers introduced a guideline for the deployment of radar speed signs. The researchers determined the situations where the use of radar speed signs is applicable, whether the signs have been effective in similar applications, and where such signs should be located. Based on this information, the researchers developed guidance to recommend future applications of radar speed signs. Two levels of guidance were developed: general guidance and location-specific guidance. Location-specific guidance applies to use in school and park zones, work zones, and general street locations such as transition zones, curve warning sign locations, and signal approaches.

The research findings indicate that radar speed signs often achieved their objective of a reduction in speeds. Depending on the application and problem being addressed, changes in speeds ranged from small to significantly large.

Table 2.6 shows a summary of above mentioned research. Other studies have been conducted to evaluate the effectiveness of different types of traffic control devices, including optical speed bars, rumble strips, stepped speed reductions, and more. Given that the scope of the present study does not include these additional devices, further detailed review of literature on these devices is not provided in this report. ODOT is encouraged to conduct future research on other traffic control devices to fully understand their use and effectiveness.

Though the conclusions by previous researchers for various speed reduction strategies are diverse, depending on various factors, it appears that in no case did the deployment of these strategies worsen the existing operational conditions. As a result, it is apparent that the findings of the devices tested as part of the present research are promising

Table 2.6: Summary of Work Zone Radar Speed Sign Results

Study	Application	Locale	Traffic	Speed Limit	Mean Speed Change	General Effectiveness
Radar Speed Trailer						
Pesti and McCoy *(Pesti and McCoy 2001)*	Rural 4-lane divided interstate	Nebraska	38000 (ADT)	55 mph	3 - 4 mph reduction	20 - 40% increase in vehicles complying w/ speed limit Long-term reductions in speeds over 5 weeks
McCoy et al. (McCoy et al. *1995)*	Urban 4-lane divided interstate	South Dakota	9000 (AADT)	55 mph	4 to 5 mph reduction	Before - 74+% speeding After - reduced by 20 - 25%
Carlson et al. *(Carlson et al. 2000)*	Rural 4 lane divided U.S highway Short term work zones (1-12 hours)	Texas	7000 (AADT)	55 mph	2 mph (cars) 3 mph (trucks)	Speeding before versus after: Cars - 5.5 - 7.0% reduction Trucks - 9.6 - 24.4% reduction
Teng et al. *(Teng et al. 2009)*	Interstate and principal arterial	Las Vegas, NV	n/a	45 mph (principal arterial) 55 mph (interstate)	8-9 mph reduction	Size of displayed messages and use of flashing showed significant impact on speeding likelihood and speed reduction
Saito and Bowie *(Saito and Bowie 2003)*	Urban interstates (number of lanes varied)	Utah	n/a	55-65 mph	7 mph reduction	Display appeared to lose effectiveness after one week
Chitturi and Benekohal *(Chitturi and Benekohal 2006)*	Rural 4-lane divided interstate	Illinois	n/a	n/a	4.4 mph reduction (immediate) 6.7 mph reduction (3 weeks)	All speed reductions found to be statistically significant
Fontaine et al. *(Fontaine et al. 2000)*	Rural two and four lane short-term work zones	Texas	n/a	n/a	5 mph reduction	Reduced percent of vehicles exceeding speed limit
Changeable Message Sign-Radar Combination						
Study	**Application**	**Locale**	**Traffic**	**Speed Limit**	**Mean Speed Change**	**General Effectiveness**
Garber and Srinivasan *(Garber and Srinivasan 1998)*	Suburban interstates and primary highway	Virginia	n/a	45 mph (primary) 55 mph (interstates)	Interstate - 5 - 10 mph reduction Primary - 8 - 12 mph reduction	Speed reductions at all sites and exposure durations found to be statistically significant
Garber and Patel *(Garber and Patel 1995)*	Rural 4-lane divided interstate. Three signs used at beginning, midpoint and end of the work zone. Employed messages rather than vehicle speeds	Virginia	8400 - 33000 (AADT)	45 - 55 mph	4 - 17 mph mean speed reduction between 1st and 2nd sign 1 - 3 mph mean speed reduction between 2nd and 3rd sign	6 - 11 mph reduction in 85% speeds between 1st and 2nd sign 2 - 3 mph reduction in 85% speeds between 2nd and 3rd sign
Wertjes *(Wertjes 1996)*	Rural 4-lane divided interstate	South Dakota	4560 (ADT)	55 mph	In advance of taper - 1.7 mph reduction At taper - 1.6 mph reduction End of taper - 0 mph	85th percentile speeds reduced In advance of taper - 68.2 - 66.5 mph At taper - 63.5 - 61.9 mph End of taper - 59.3 - 59.4 mph
Wang et al. *(Wang et al. 2003)*	Rural, 2-lane highway	Georgia	n/a	45 mph	7 - 8 mph reduction	Speed variance decreased significantly following Deployment -- Long term speed reductions between 1 and 3 mph observed
Sorrell et al. *(Sorrel et al. 2007)*	Rural, 2-lane highway and interstate	South Carolina	n/a	45 - 55 mph (two-lane) 45 mph (interstate)	7 - 9 mph reduction (interstate) 5 - 7 mph reduction (two-lane)	85th percentile speeds reduced 6 - 9 mph (interstate), 2 - 4 mph (two-lane)
Post-Mounted Sign						
Study	**Application**	**Locale**	**Traffic**	**Speed Limit**	**Mean Speed Change**	**General Effectiveness**
Maze *(Maze 2000)*	Rural 4-lane divided interstate in advance of a crossover	Iowa	n/a	55 mph	3 mph reduction	85th percentile speeds reduced by 5 mph

2.2.17 ODOT 2013 PCMS Handbook *(ODOT 2013a)*

In September 2013, ODOT published the first edition of its Portable Changeable Message Sign Handbook. The purpose of this handbook is to provide basic information for the safe and effective use of a PCMS. The handbook shows proper setup and delineation for a PCMS and provides a variety of examples of the messages showing on the signs. The handbook recommends that PCMS signs be placed on a straight, flat section of roadway. The sign should be visible from a distance of ½ mile in both daylight and nighttime conditions, and be legible from a minimum of 600 feet at night and 800 feet during daylight conditions. When multiple PCMS signs are needed, the signs should be placed on the same side of the roadway with a minimum distance of 1,000 feet between the signs on freeways. For the messages displayed on the sign, two individual, alternating messages displayed for at least two seconds are necessary. The display time for both panels should be less than 8 seconds. These guidelines are applicable to the case study projects in the present research, and the set-up and operation of the traffic control devices implemented as part of this research study adhered to these guidelines.

2.2.18 ODOT Temporary Traffic Control Handbook

ODOT publishes a handbook for temporary traffic control for operations of three days or less. The handbook is based on Part 6 of the *Manual on Uniform Traffic Control Devices* (MUTCD) and the Oregon MUTCD Supplements. Construction on high speed roadways requires planned traffic control (compared to emergency traffic control and special event traffic control which do not require pre-planned control). Traffic impacts from planned work can be anticipated. In this handbook, ODOT requires that the distance between cones in the taper should equal the posted speed in feet, e.g. 50 mph posted speed = 50 feet between cones. Optional tighter cone spacing in the taper may be used in areas where traffic may intrude into the work zone. Most of the requirements in this handbook are similar to those found in the MUTCD, which is mentioned above.

As with the MUTCD, the ODOT handbook recognizes a difference between short-term and long-term work zones. Long-term work zones are typically considered as those in which the work takes place for a period of greater than three days. If the work takes place for a period of three days or less, it is commonly referred to as short-term. Additionally, a work zone may be mobile or stationary. A stationary work zone is one in which the work takes place at only one location. Highway preservation projects, such as the paving projects evaluated as part of the present research study, are mobile projects where the work takes place at different locations for each work shift. In addition, on a paving project, the construction equipment moves along as the work progresses during each work shift.

3.0 RESEARCH METHODS

This study aims to evaluate the effectiveness of radar speed signs for mobile maintenance operations in order to support the overall goal of assisting ODOT Maintenance with enhancing the safety of motorists and workers in maintenance work zones. As stated previously, the specific objectives are to: implement the radar speed signs on mobile maintenance operations; determine the extent of the applicability of the signs to mobile operations; determine the impact of the signs on vehicle speeds; and develop recommendations and guidance for ODOT Maintenance regarding use of radar speed signs in mobile work zones. The research tasks, described in Section 1 of this report, consisted of collecting field data on three short-term maintenance work zones in the Portland area (Region 1) and one in the Klamath Falls area (Region 4). On each case study project, travel speeds are measured at several locations within the work zones For each operation selected, two periods of testing are conducted: one with the radar speed sign display turned on (treatment) and one without the radar speed sign turned on (control) for comparison.

3.1 TRUCK-MOUNTED RADAR SPEED SIGNS

Radar speed signs, as described in the Literature Review section of this report, use radar technology to measure the speed of oncoming vehicles and display the vehicle speed to the drivers. The vehicle speed is usually displayed along with the regulatory or advisory speed and/or a message alerting the drivers to use caution. For the purpose of this research, a radar speed sign was installed on an ODOT Maintenance truck in each region. The trucks are located in advance of an object, work area, equipment, or workers. For mobile maintenance operations, the truck moves with a low speed (usually 5-10 mph) behind the maintenance equipment used for conducting the work to provide warning to approaching vehicles about the work zone and to advise a decrease in speed.

The radar speed display purchased by ODOT was manufactured by LiteSys, Inc. The display is a 1030F-4W-1 full matrix model with 3 lines of 10-inch characters and 8 characters per line. The display has the capability of showing different messages, plus arrow and chevron functions. The radar speed display is connected to a compact, multi-piece, radar detachable display unit and SpeedView traffic analyzer inside the truck cab. The multi-piece radar display has the ability to show speed in both moving and stationary modes. Building on the capabilities of MPH’s DS-4 ranging radar, the SpeedView can accurately count vehicles once and only once. Its memory can hold more than a year’s worth of traffic data. More information about these two units is provided in Appendix. Figures 3.1 to 3.5 show the different units of the truck-mounted radar speed display.

Figure 3.1: Truck-Mounted Radar Speed Display


Figure 3.2: 1030F-4W-1 Full Matrix Speed Display

Figure 3.3: Radar Speed Display Units inside Truck Cab

Figure 3.4: Radar System Keyboard inside Truck Cab

Figure 3.5: SpeedView Traffic Analysis Unit inside Truck Cab

3.2 TRAFFIC CONTROL PLANS

Traffic control plans (TCPs) are prepared for each work zone operation to provide guidance on mitigating safety hazards in the work zone. The ODOT TCP Design Manual and the MUTCD provide recommendations and guidance for developing TCPs for short-term work zones. TCPs are provided for both stationary and mobile operations in short-term work zones. The following are examples of standard traffic control plans for short-term operations:

- Stationary work on shoulder (non-freeway work) – Figure 3.6
- Mobile operation on shoulder (non-freeway work) – Figure 3.7
- Stationary work lane closure (non-freeway work) – Figure 3.8
- Stationary work on shoulder (freeway work) – Figure 3.9
- Mobile operation on shoulder (freeway work) – Figure 3.10
- Mobile operation lane closure (freeway work) – Figure 3.11

For the case studies included in this research, the work consisted of mobile operations. Therefore, a mobile operation traffic control plan on freeways was used. For each case study, ODOT Maintenance personnel prepared and implemented a project-specific TCP appropriate for the work taking place, as described below.

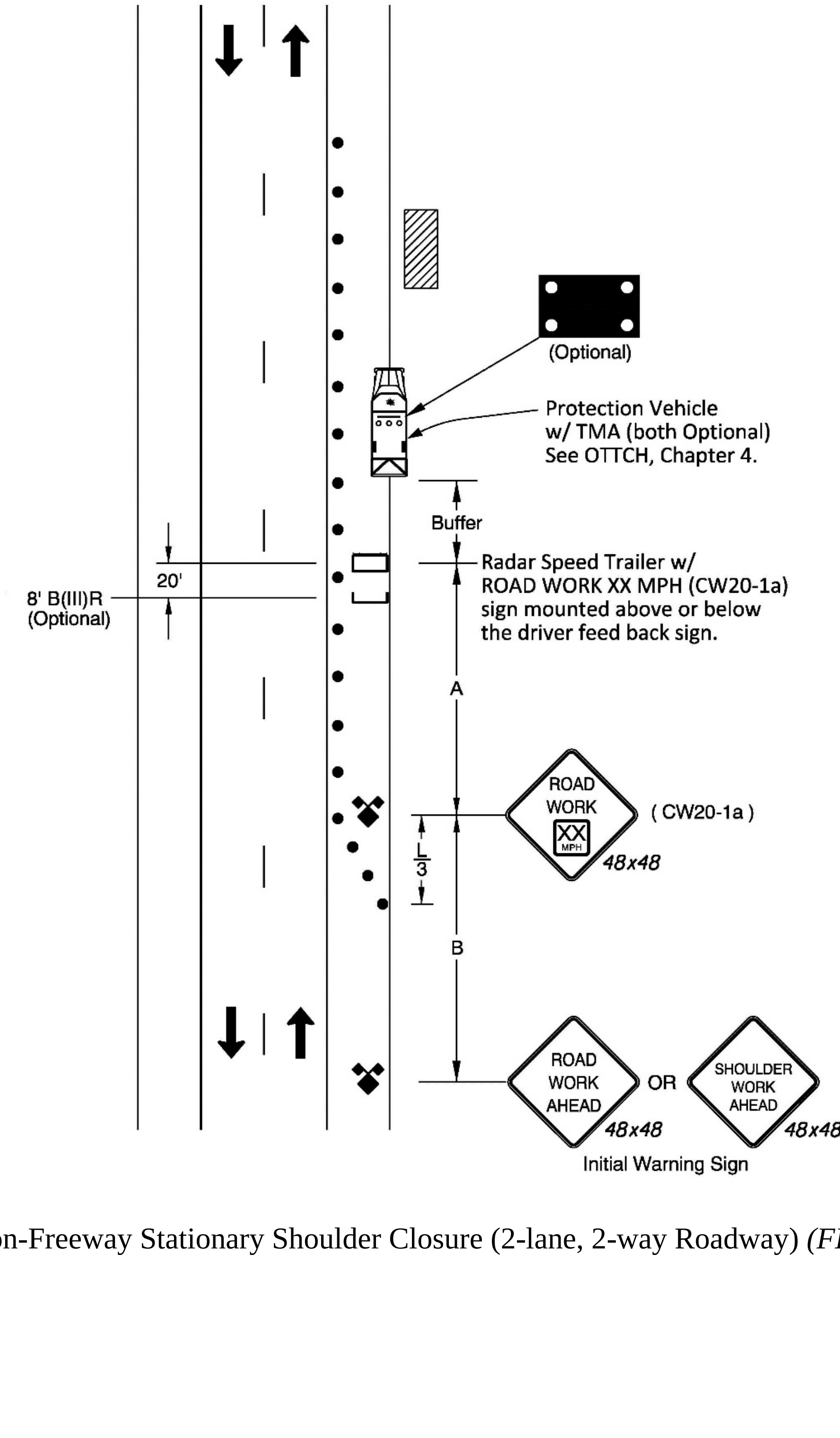
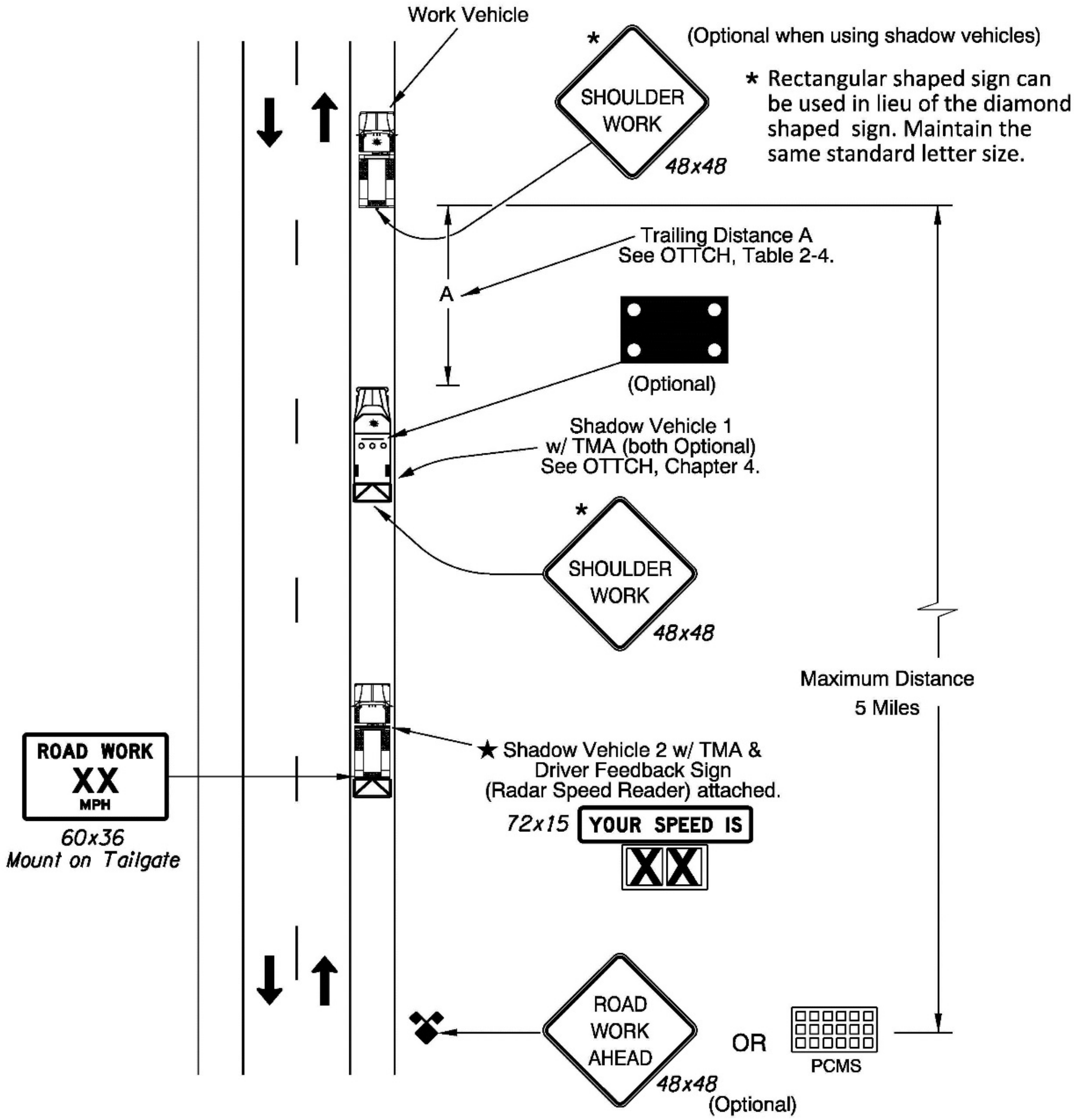


Figure 3.6: Non-Freeway Stationary Shoulder Closure (2-lane, 2-way Roadway) *(FHWA 2009)*



★ 1) The Driver Feedback Sign is integrated into the shadow vehicle.

2) Use the type of radar speed reader for mobile operations which takes into account the speed of the vehicle where it is mounted on and the speed of the vehicle coming towards the radar. If this device is not available, do not use Driver Feedback Sign for mobile operations.

Figure 3.7: Non-Freeway Mobile Operation Shoulder Closure (2-lane, 2-way Roadway) (*FHWA 2009*)

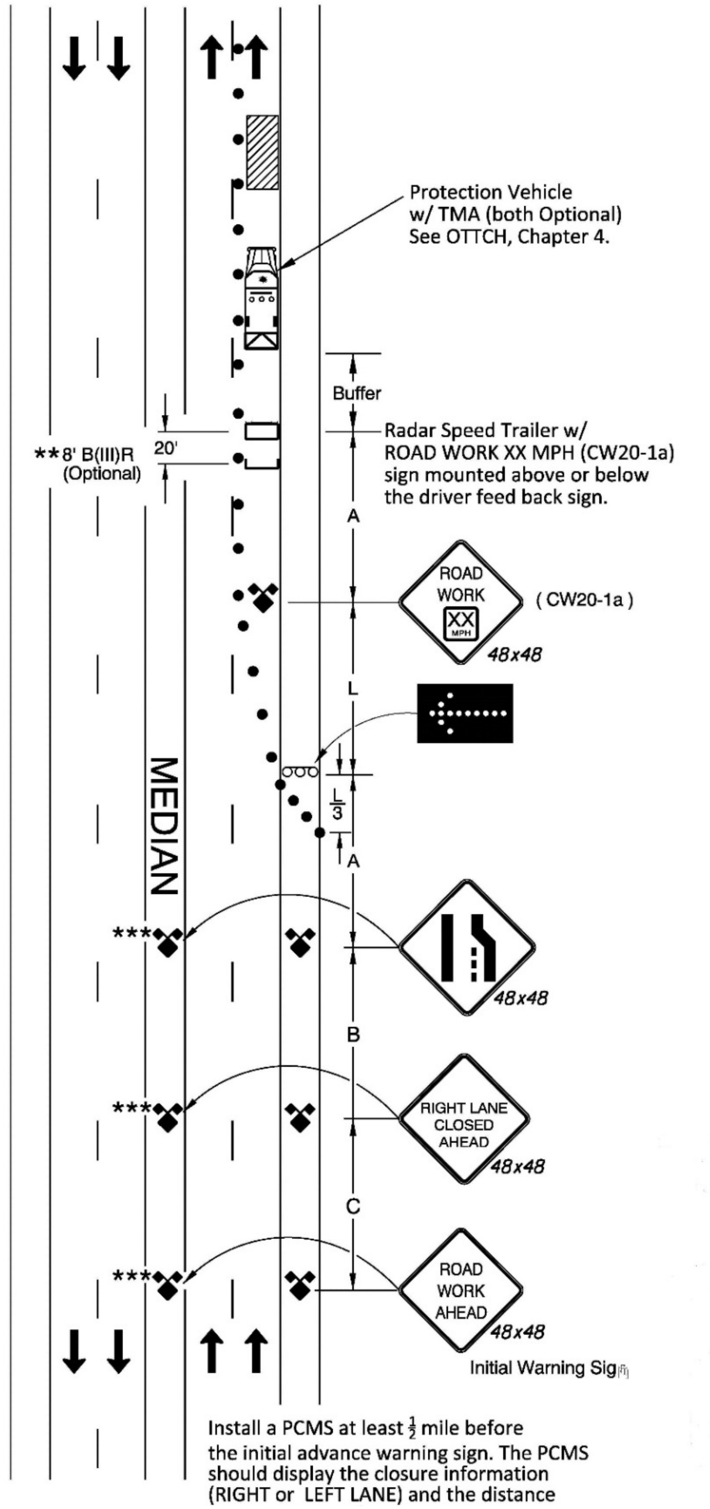


Figure 3.8: Non-Freeway Stationary Lane Closure (Multi-lane, 2-way Roadway) (*FHWA 2009*)

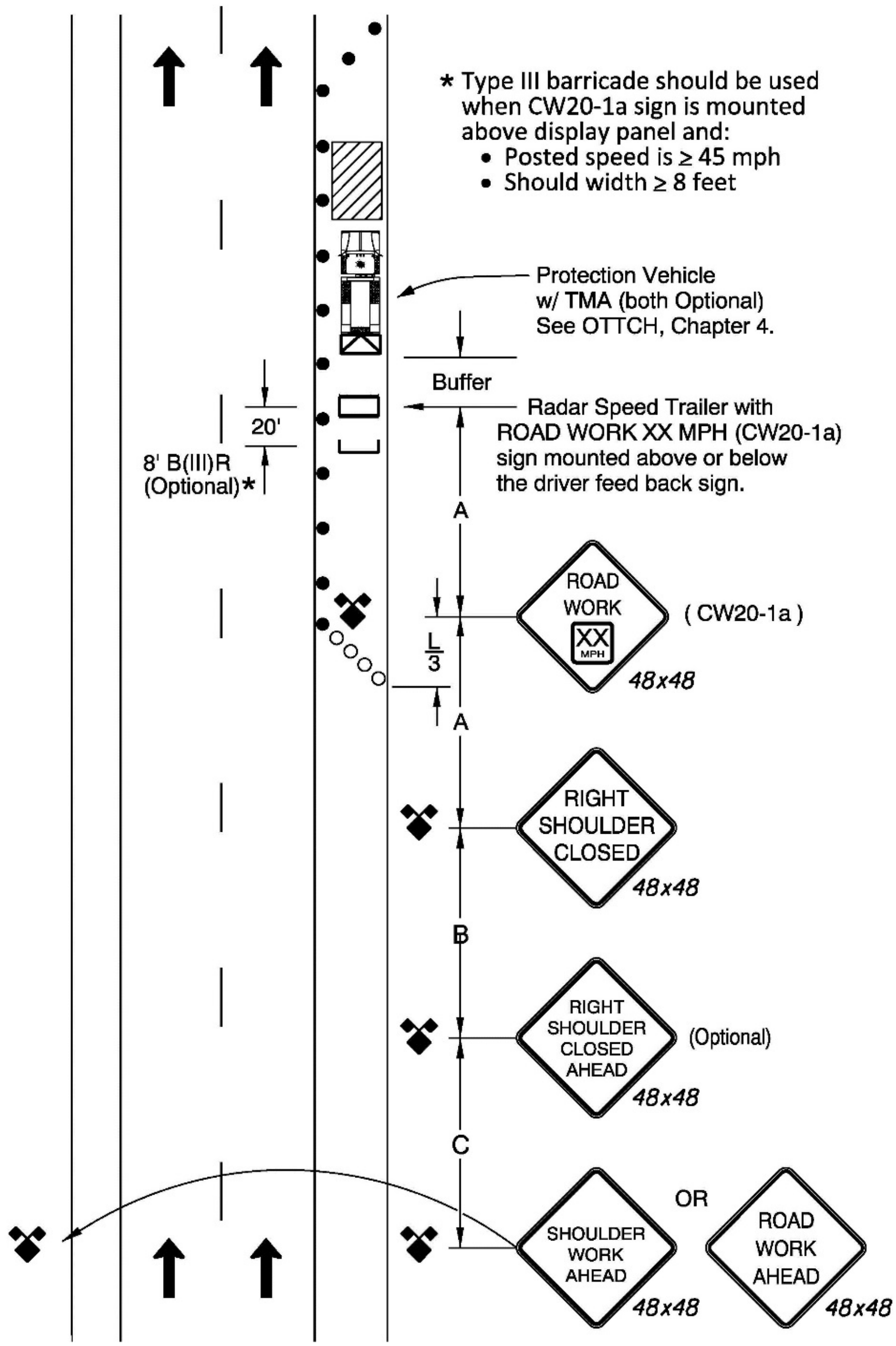


Figure 3.9: Freeway Stationary Work Shoulder Closure (*FHWA 2009*)

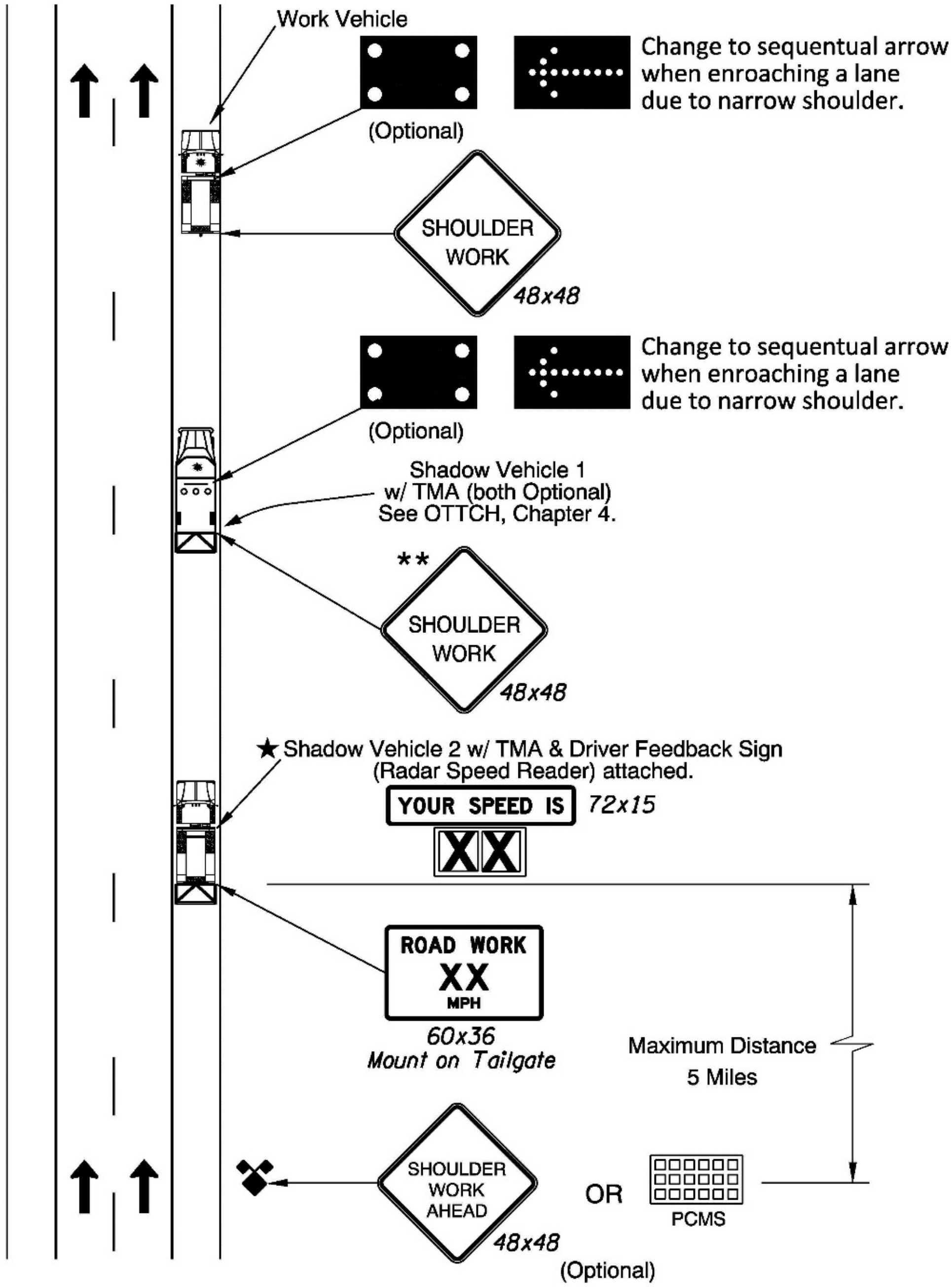


Figure 3.10: Freeway Mobile Operation Shoulder Closure (*FHWA 2009*)

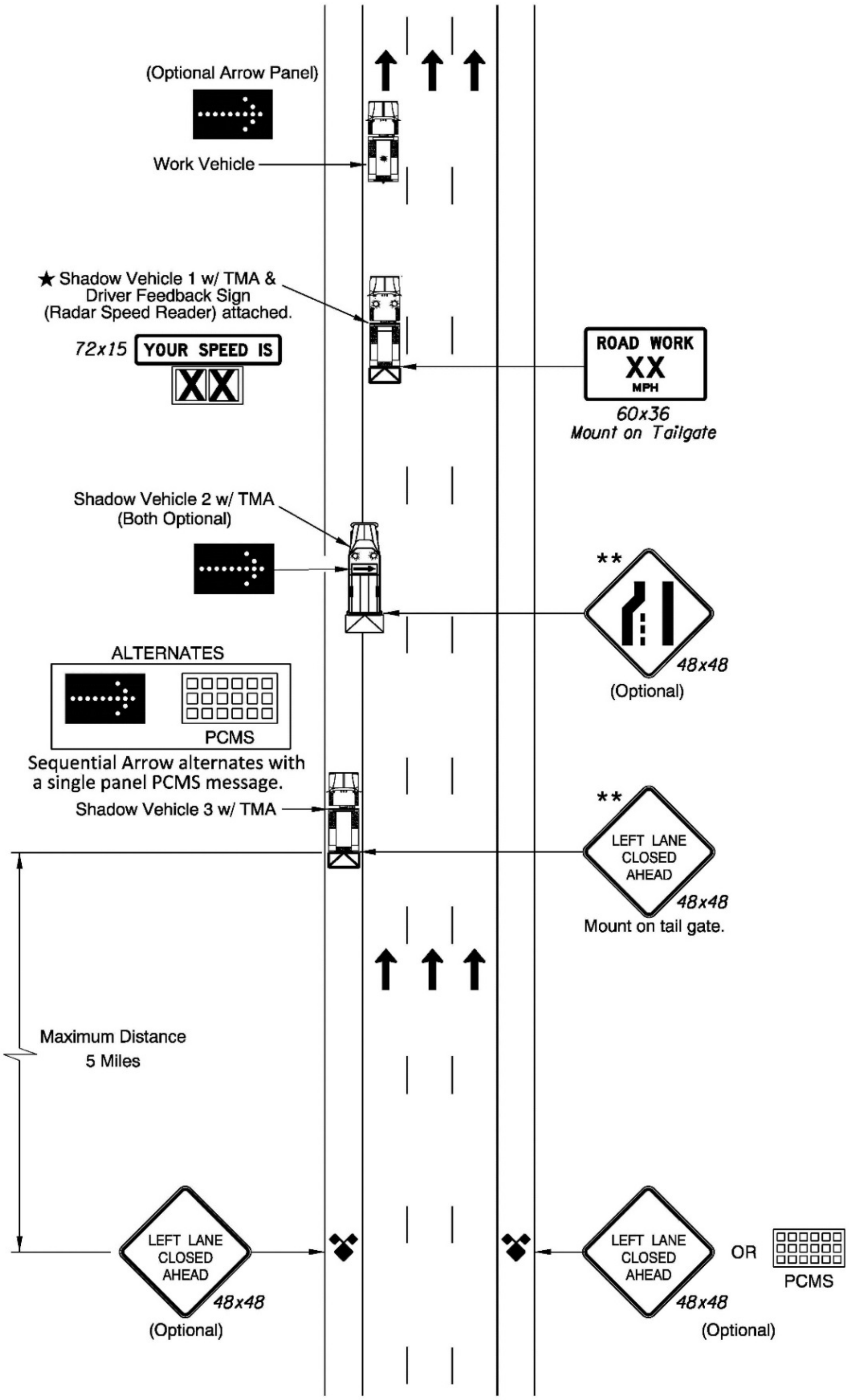


Figure 3.11: Freeway Mobile Operation Lane Closure (*FHWA 2009*)

3.3 DATA COLLECTION

Various types of data were collected from each case study project for analysis. The data collected primarily related to the passing vehicles (vehicle type, speed, length, time of day, etc.). In addition, perspectives of the work crews and general observations made by the researchers related to implementation of the RSS were collected during the case studies. To collect the data, a variety of different pieces of equipment, tools, and resources were used by the researchers, including traffic control analyzers (sensors), a speed gun, and a video camera. Each of these pieces of research equipment is described below.

3.3.1 Traffic Control Analyzer and Placement

NC-200 portable traffic analyzers manufactured by Vaisala were used to collect vehicle data on the roadways. Figure 3.12 shows an example of the traffic analyzer and a cover used to protect it on the roadway.

Figure 3.12: Portable Traffic Analyzer NC-200 (*Vaisala 2012*)

The traffic analyzer is designed to provide accurate traffic counts, speed, and classification (vehicle length) data. The analyzer is placed directly in the traffic lane to measure and record the passing traffic. The sensor utilizes Vehicle Magnetic Imaging (VMI) technology to count the number of passing vehicles and detect vehicle speed and length (Vaisala 2012). Table 3.1 shows the technical specifications of the NC-200 portable traffic analyzer.

Table 3.1: Technical Specifications of Portable Traffic Analyzer NC-200 *(Vaisala 2012)*

Technical Specifications	
Housing Material	Extruded/anodized aluminum
Ultimate Bearing Strength	88,000 psi (607 MPa)
Dimensions	7.125 x 4.625 x 0.5 inches
Weight	1.3 lbs
Operating Temperature	-4 ºF to +140 ºF
Sensor	GMR magnetic chip for Vehicle Magnetic Imaging
Memory	Micor Serial Flash: 3MB
Battery	Lithium-ion rechargeable (can last for up to 21 days without recharging)
Capacity	up to 300,000 vehicles or 21 days per study, whichever occurs first
Vehicle Detection	Detects vehicles between 8 to 120 mph
Accuracy length classification	+/- 4 ft, 90% of the time
Accuracy speed classification	+/- 4 mph, 90% of the time
Accuracy vehicle count determination	+/- 1%, 95% of the time

The traffic analyzer manufacturer suggests that the analyzer be nailed down to the pavement through nail holes on the cover as shown in Figure 3.13. However, for highway maintenance projects, the short duration of use (one night of work) each time the analyzer is used makes it inefficient to nail down the analyzers. Therefore, an alternative method to fix the analyzer on the roadway was used. The analyzers were secured to the pavement using adhesive tape which completely covered the analyzer cover and the analyzer. Figure 3.14 shows an example of how adhesive tape is used to keep the analyzer at the desired location.

Figure 3.13: Placement of Portable Traffic Analyzer using Nails (*Vaisala 2012*)


Figure 3.14: Placement of Portable Traffic Analyzer using Adhesive Tape

The adhesive tape used for this project was Tapecoat M860 Pavement Repair Coating. It is primarily used to repair cracks in concrete and asphalt surfaces. According to the data sheets provided by the manufacturer, Tapecoat M860 is made of a pre-formed, cold-applied, self-adhering material that is impermeable to water and salt *(Tapecoat 2012)*.

To fully understand motorist behavior and vehicle speed through a long mobile operation work zone, 14 portable traffic analyzers were placed on the roadway for each case study. The first two analyzers were placed near the “Road Work Ahead” (RWA) sign to capture vehicle speeds before the vehicles enter the work zone. One analyzer was placed at the beginning of the taper. Other analyzers were placed in the travel lane(s) at different points in the working area. The actual location and spacing of the analyzers in the work zone was dependent on the number of travel lanes, and amount and location of work being performed on the given day or night. Figure 3.15 shows an example of a plan view of the portable traffic analyzer placement for a typical night. The locations of the portable traffic analyzers are indicated with rectangles in the figure.

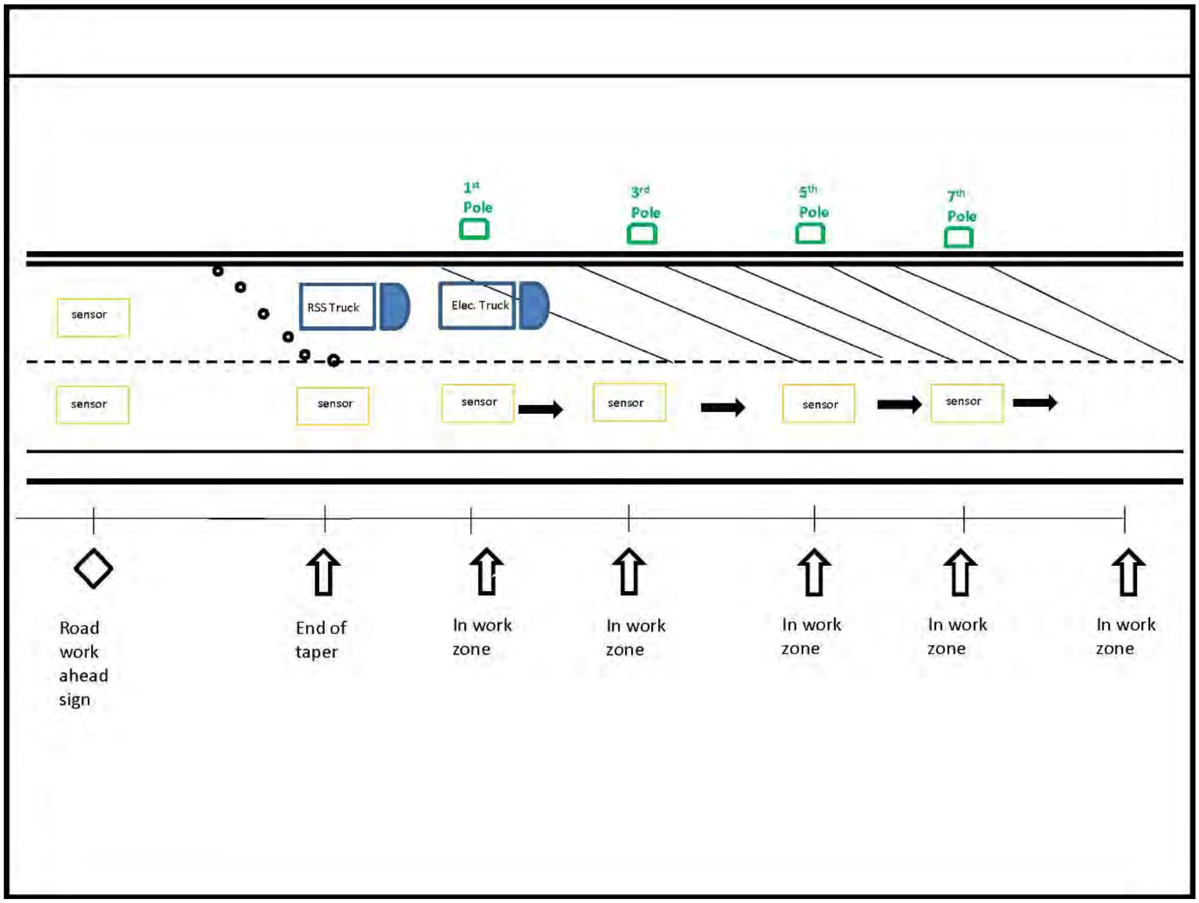


Figure 3.15: Placement of Traffic Control Analyzers (Sensors)

3.3.2 Radar Speed Gun

A radar speed gun was also used to measure and confirm vehicle speeds at specific locations in the work zone. The researchers selected several locations within the work zone to monitor traffic speeds. The researchers held the speed gun for a 5-minute period of time and recorded free flow traffic speeds. Using the speed gun is an auxiliary method to provide supplementary data for further analysis and verification of the speeds recorded by the portable traffic analyzers and radar speed display. The speed gun was also used to spot check the accuracy of the RSS during the operations. Figure 3.16 shows a speed gun used in the research. The accuracy of the speed gun is +/- 1 mph and the speed range is 10-200 mph.

Figure 3.16: Radar Speed Gun

3.3.3 Video Camera

The portable traffic analyzers collect vehicle speed data only at the locations where the analyzers are placed. In addition, there are a limited number of analyzers available. Therefore, vehicle speeds could not be collected using the available analyzers at every location throughout the work zone. The ability to continuously record vehicle speeds throughout the entire work zone is limited using the analyzers. In order to obtain a vehicle's speed profile though the entire work zone, the researchers decided to videotape selected vehicles as they pass through the work zone using a probe vehicle. At selected times during each night of testing, the researchers followed a vehicle though the work zone, driving behind and at the same speed as the vehicle. The researchers selected both cars and trucks to follow. In some cases the vehicle's speed was dictated by the vehicle(s) in front of it (e.g., a car trailing behind a truck driving slowly). While driving, the researchers videotaped the vehicle and documented the location and vehicle speed approximately every 0.5 miles. In addition, the researchers documented the vehicle's speed at significant roadway features, traffic control devices, and when passing construction equipment. Each night of testing the researchers videotaped typically 2 or 3 vehicles travelling through the work zone.

3.4 CASE STUDY PROJECTS

3.4.1 Case Study #1: I-205 Relamping

The I-205 Relamping case study was located in the southbound (SB) direction of I-205, starting near the Sunset Ave. Bridge and continuing for approximately one mile. Figure 3.17 shows the location of the project. The project included replacing the lamps in the light poles located in the median. At the Road Work Ahead sign, the roadway has three lanes, which then reduce to two lanes prior to the work zone area. Because of a very narrow shoulder in the median, the A (left) lane was closed during the work operation to provide a safe work environment. Cones were used to close the lane. As a result, there was only one travel lane (B lane) through the work zone. The selected section of highway was relatively flat and without any sharp curves or steep grades. The posted regulatory speed on this section of roadway is 55 mph.

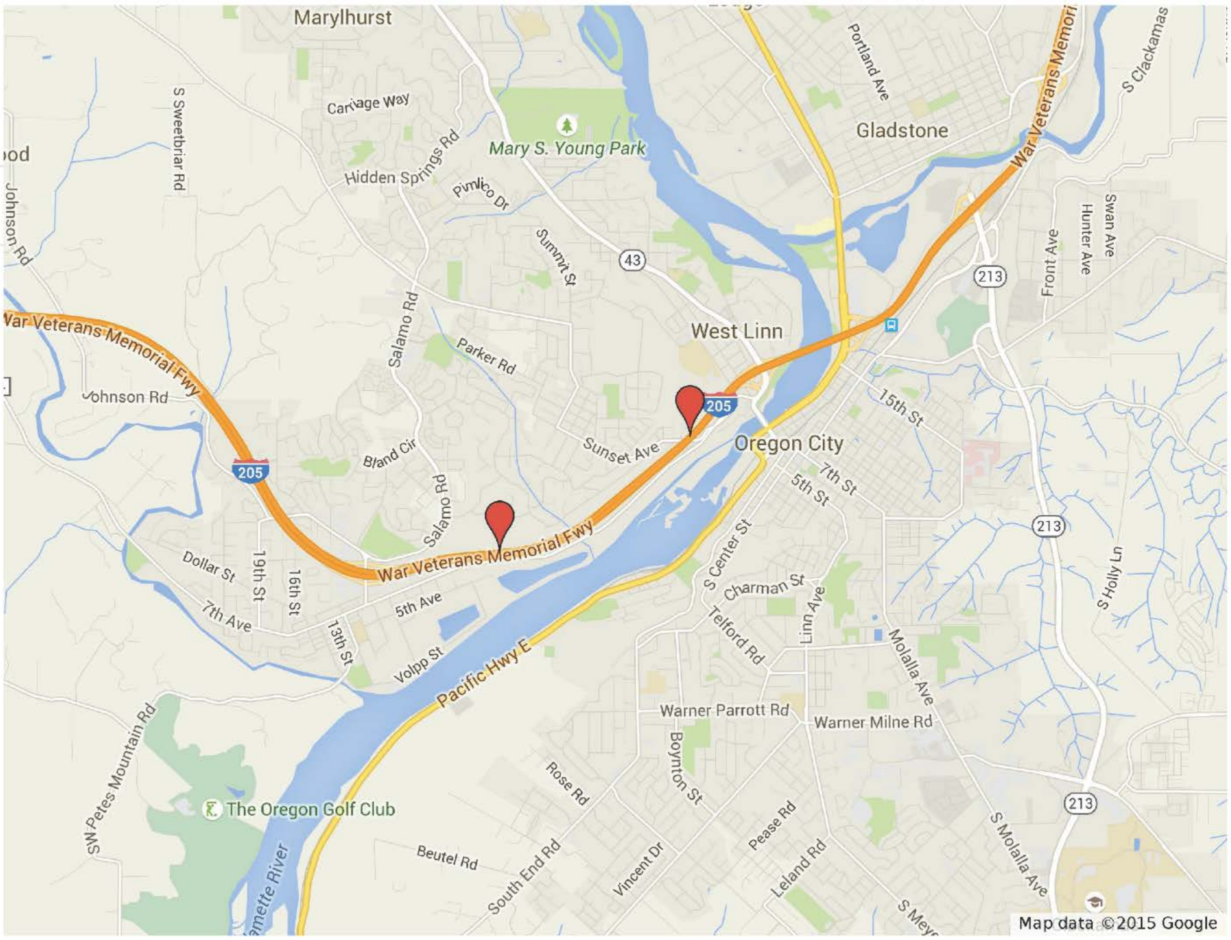


Figure 3.17: Location of I-205 Relamping (Case Study #1)

Two consecutive nights of maintenance work were performed, one without the radar speed sign turned on (Day 1) and one with radar speed sign turned on (Day 2). That is, on the night without the radar speed sign, the sign displayed only arrows directing the vehicles to the adjacent lane as is customarily done. Then, on the night with the sign on, the sign showed the vehicle's speed along with messages for those vehicles traveling over set speed targets. The information displayed on the RSS display was as follows:

- Below 10 mph, the RSS did not display any message
- Between 10 and 55 mph, the RSS showed the vehicle's speed
- Above 55 mph, the RSS displayed the message "Slow Down"

To evaluate the effect of the RSS, the work operation was performed in the same travel direction at the same section of highway and nearly at the same time to decrease the effect of confounding variables. At this location on the roadway, there are 20 light poles in the median of the highway, approximately 260 feet apart. For the first night, odd-numbered poles (poles 1, 3, 5, etc.) were selected to be maintained and on the second night the lamps of even-numbered poles (poles 2, 4, 6, etc.) were replaced. Three sensors were put down near the Road Work Ahead sign, one in each travel lane. One sensor was placed in the travel lane (B lane) at the end of the taper. Lastly, one sensor was placed in the travel lane (B lane) adjacent each pole to be maintained. Therefore, there was a sensor near poles 1, 3, 5, 7, 9, 11, 13, 15, 17, and 19 during the first night (without RSS turned on). As a result, vehicle length and speed were recorded by the 14 sensors through the work zone area. During the entire operation time on the first night, the radar speed sign did not display the vehicle speed. It should be noted that, while the vehicle speed was not displayed to the passing motorists, it was captured by the RSS unit and displayed in the truck cab, and stored in the RSS unit for later analysis.

For the second night the RSS was turned on such that it displayed the recorded speeds to the motorists. The display showed the approaching vehicle speed and/or message as described above. On the second night the even-numbered light poles were selected to be maintained for comparison with the data captured on the first night and minimize the effect of confounding variables. Vehicle length and speed were recorded by three sensors near the Road Work Ahead sign, one sensor at the end of the taper, and 11 sensors at poles 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20.

Maintenance operations started exactly at 22:10 on the first night and at 21:40 on the second night, and lasted approximately three hours each night. The sensors were placed down on the pavement at least 30 minutes in advance of testing to allow time for the sensors to calibrate themselves. Traffic volumes on the two nights were very similar to each other. On the first night, traffic volume was approximately 800 vehicles per hour between 22:00 and 23:00, and then decreased to 485 vehicles from 23:00 to 24:00. After this time, the traffic volume reduced to 330 between midnight until 1:00. On the second night, hourly traffic volume was a little higher than on the first night. It was 835, 530, and 340 vehicles for each hour from 22:00 to 1:00, respectively.

3.4.2 Case Study #2: I-205 Sweeping

The test area for this case study project was located at the same location of Case Study # 1. As shown in Figure 3.18, the location was in the southbound (SB) direction of I-205, west of Oregon City between the Sunset Ave. overpass and 10th Street. The posted regulatory speed on this section of roadway is 55 mph. The operation consisted of sweeping the left (median) shoulder of the highway with a sweeper. This operation differed from the relamping operation in Case Study #1 for a variety of reasons. The relamping operation was an intermittent mobile operation involving frequent short stops near each pole to replace the lamp, but the sweeping was almost entirely a continuously moving mobile operation. Also, unlike during the relamping operation, there was not a complete lane closure during the sweeping operation time. The arrow trucks directed traffic to travel only in the adjacent lane when near the sweeper.

Traffic analyzer sensors were placed on the pavement to record the passing vehicle speed and their length during the operation. A total of 14 sensors in 7 different locations were used to record data in both the fast lane (A lane) and slow lane (B lane). Two sensors were put down upstream of the work zone near the Road Work Ahead sign, and two other sensors were placed at the end of the taper to capture the vehicle characteristics before entering the work zone. Speed and length of the vehicles in the work zone were recorded by the other 10 traffic sensors placed a consistent distance apart at the location of every fifth light pole. There were 20 light poles in the median of the highway from the start point to the end. Two sensors were placed in the A lane and B lane at the first pole, which was approximately the starting location of the sweeping operation. Two sensors were also placed at the end of the work zone near pole 20. In addition, two sensors were located adjacent poles 5, 10, and 15. Figure 3.18 shows the sensor layout for this case study. Each rectangle in the figure represents a traffic sensor with its corresponding ID number.

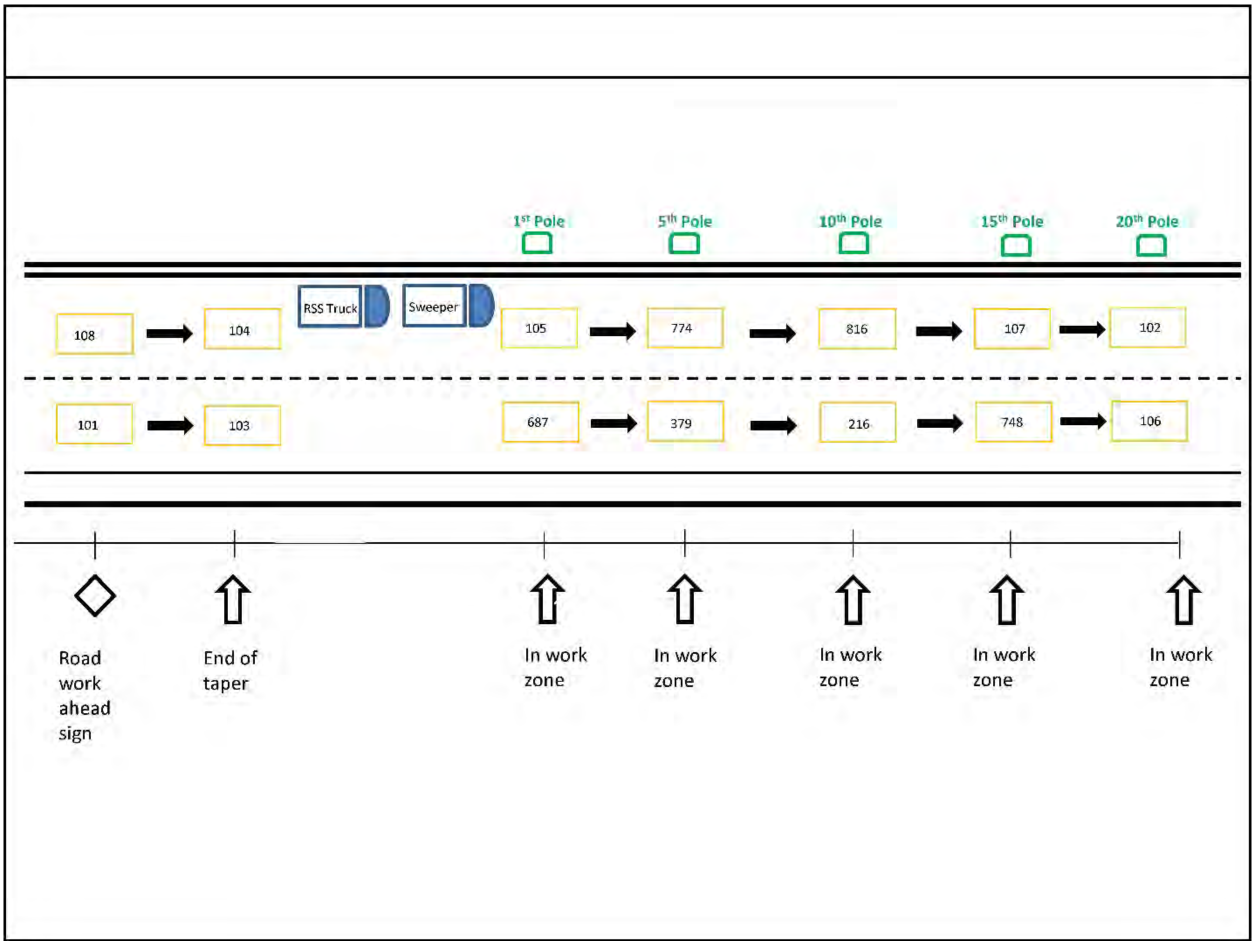


Figure 3.18: Traffic Sensor Layout during Sweeping Operation, SB I-205 (Case Study #2)

For this case study, the information shown to the passing motorists on the RSS display was as follows:

- Below 10 mph, the RSS did not display any message
- Between 10 and 55 mph, the RSS showed the vehicle's speed
- Above 55 mph, the RSS displayed the message "Slow Down"

The maintenance operation took place on March 30, starting at 21:37 and finishing in less than two hours at 23:17. The sweeping was a very quick operation, so both control and treatment tests were performed on one night. The maintenance work was performed twice over the same section of roadway without the RSS displaying the vehicle speeds. Then the work was performed two times over the same section of roadway with the RSS displaying vehicle speeds. The first pass of the sweeper through the work zone took approximately 22 minutes to clean the shoulder of any dust and debris, but the other three passes of the sweeper took approximately 12 minutes since the road was clean and it could travel faster without any stops. There were 10-20 minutes of gap between each sweeper pass for preparation and travel time to return to the starting point of the work zone. During the absence of the sweeper as it was returning to the starting point, there was no presence of maintenance equipment in the work zone and therefore free flow traffic through the work zone. The total test duration for the two passes of the sweeper without the RSS turned on was 35 minutes, which is compared to 23 minutes for the two passes of the sweeper with the RSS turned on. Because of the difference in the total time, the traffic volume during operations without the RSS turned on was twice as much as the volume during the operation with the RSS turned on. More details are provided in the next chapter of the report.

3.4.3 Case Study #3: I-84 (Banfield Expressway) Vactoring

The third case study was performed in the westbound (WB) direction of Interstate 84, between I-5 and I-205 (Banfield Expressway). Figure 3.19 shows the location of the case study. The posted regulatory speed on this section of roadway is 55 mph. The maintenance operation involved vactoring the drains along the right shoulder of the roadway. There was no lane closure during the operation in this case. A truck with an arrow board directed the traffic to the left-hand lanes near the operation. Similar to Case Study #1, it was an intermittent mobile operation involving frequent short stops near each drain to clean the drains. At each drain location, a worker exited his/her vehicle to perform the vactoring operation while standing on the roadway. Two consecutive nights of maintenance operations were conducted: one without the RSS displaying the vehicle speeds (Day 1), and one with the RSS displaying the vehicle speeds (Day 2).

At this location, the highway has three travel lanes in each direction. Because of the limited number of traffic sensors, just the characteristics of traffic passing through the B and C lanes of the work zone were recorded. Twelve sensors were used in this case study to capture data at six different locations along the work zone during each night. Two sensors were located near the Road Work Ahead signs to collect vehicle speed and length before the vehicles entered the work zone. Only every other drain was cleaned each night. For the first night, only odd-numbered drains were selected to be cleaned (similar to odd-numbered poles in Case Study #1), and on the second night the even-numbered drains were selected. As a result, a total of 10 sensors were placed near drains 1, 3, 5, 7, and 9 on the first night, and placed near drains 2, 4, 6, 8, and 10 on the second night in the B and C lanes. Therefore, vehicle behavior including length and speed was recorded by 12 sensors upstream and through the work zone area. During the entire operation time, on the first night the RSS display did not show the vehicle speeds. However, the radar unit was turned on in order to record the approaching vehicle speeds for later analysis. On the second night of testing, the RSS sign displayed the speeds of the oncoming traffic.

For this case study, in addition to the RSS sign or arrow sign, an advisory speed sign was also mounted on the back of the RSS truck or arrow truck (Figure 3.20). The advisory sign included the words “Road Work” and an advisory speed of 45 mph. Additionally, the information displayed on the RSS was as follows:

- Below 40 mph, the RSS did not display any message
- Between 40 and 65 mph, the RSS showed the vehicle’s speed
- Above 65 mph, the RSS displayed the message “Slow Down”

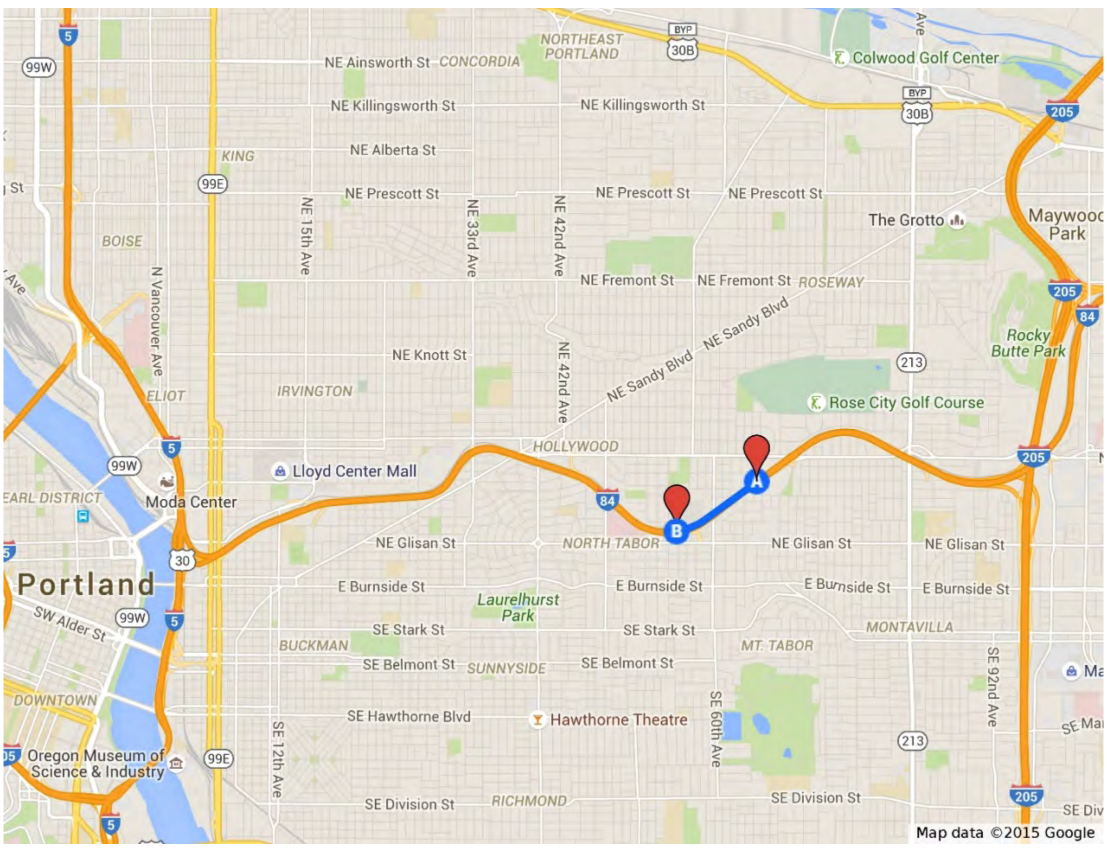


Figure 3.19: Location of I-84 Vactoring Operation, WB I-84 (Case Study #3)

(a) (b)

Figure 3.20: Advisory Speed Sign during (a) First Night of Testing and (b) Second Night of Testing (Case Study #3)

The maintenance operation was conducted from 22:03 to 22:51 on the first night (June 27) and from approximately 21:50 to 23:07 on the second night. The difference between the maximum hourly traffic volumes on each night in the corresponding locations (for example between drain 1 for the first night and drain 2 for the second night) is 19 percent. Total traffic volume recorded by the two sensors near the RWA sign was 1,170 on the first night and 1,316 on the second night for the time period between 22:00 and 23:00. More details on traffic volumes are provided in the next chapter of this report.

3.4.4 Case Study #4: US-97 Spraying

The fourth case study was performed in the northbound (NB) lanes of US-97 in Klamath Falls. Figure 3.21 shows the location of this case study. Similar to the other case study locations, the posted regulatory speed on this section of roadway is 55 mph. The maintenance operation in this case study consisted of spraying the right shoulder of the highway. The RSS was attached to the back of the spray truck. Like case studies #2 and #3, no lane was closed during the maintenance operation in this case. Weed spraying is a continuously moving mobile operation. Also, unlike the previous case studies, the operation took place during the day time and there was no arrow truck or crash truck with attenuator to support the spray truck. The spray truck worked on its own to perform the work.

Similar to the other case studies, the RSS displayed different messages depending on the approaching vehicle speed. The information shown on the RSS display was as follows:

- Below 20 mph, the RSS did not display any message
- Between 20 and 65 mph, the RSS showed the vehicle's speed

- Above 65 mph, the RSS displayed the message “Slow Down”

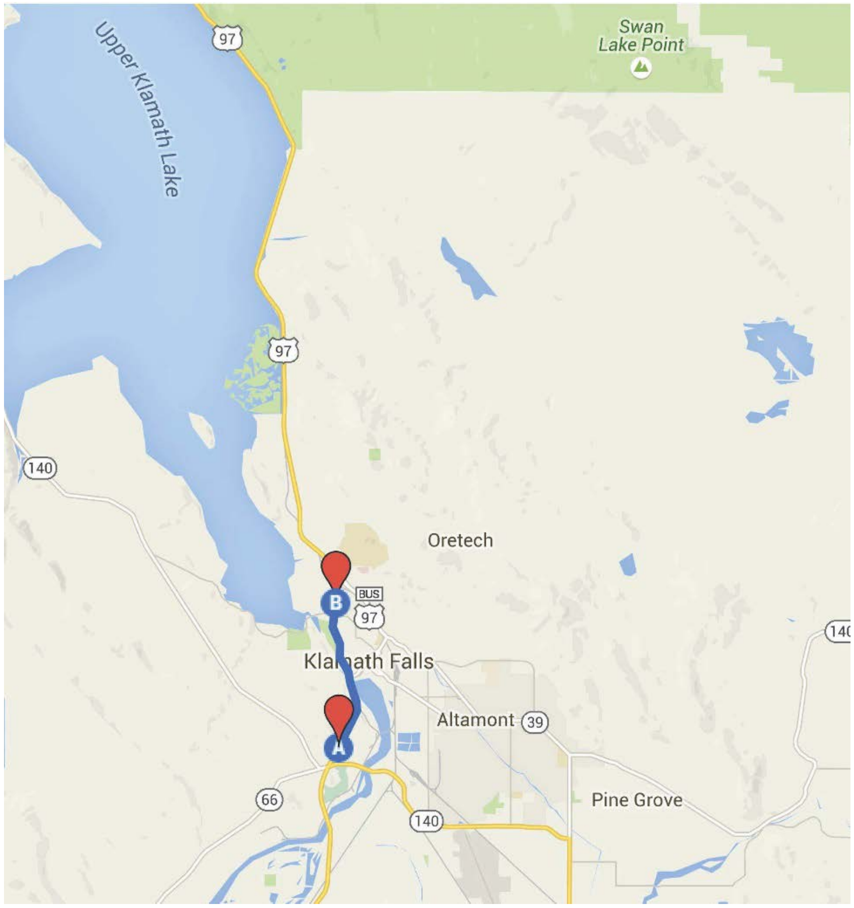


Figure 3.21: Location of Spraying Operation, NB US-97 (Case Study #4)

Vehicle speed, length, and the corresponding time were recorded by 12 sensors located through the work zone and upstream of the work zone. The selected section of highway has two travel lanes in the NB direction. Two sensors were placed near the Road Work Ahead sign and 10 other sensors were put down on the pavement from the start point of the operation to its end point at 5 different locations with approximately the same distance between each sensor location (two sensors at each location, one in the A lane and another in the B lane).

This case study is very similar to Case Study #2 in the Portland region. The maintenance operation without the RSS turned on (control) and with the RSS turned on (treatment) were both completed on the same day. The work started at 08:15 and finished at 11:02 on June 16. Spraying is a fast operation without any stops. First, the spray truck traveled two times through the work zone with a speed of approximately 5-6 miles per hour. The RSS was turned off during these first two passes. Then, the RSS was turned on and the spray truck repeated the same path with the same speed. Each pass of the spray truck took from 26-30 minutes. There were 10-40 minute gaps between each pass for preparation and travel time to return to the starting point of the work zone. Traffic flow went back to the normal free flow speed in the work zone during the absence of the operation truck. The total number of recorded vehicles that passed through the work zone when the RSS was turned off was 309, which is comparable to the 268 vehicles captured by the sensors at the same location during the operation when the RSS was turned on.

3.5 FIRST PRELIMINARY TESTING AND VERIFICATION

Preliminary testing was conducted to test the system under controlled conditions prior to its use in an actual maintenance work zone. For this purpose, the truck with the radar speed display attached was parked in the shoulder of a roadway located near the Corvallis airport. The roadway is used infrequently and the testing was not impacted by any passing traffic. With the radar speed display operating, the following tests were performed:

- Accuracy of RSS at various speeds (20-60 mph) with the truck stationary
- Accuracy of RSS at various speeds (20-60 mph) with the truck moving
- Accuracy of RSS at various speeds (20-40 mph) with multiple vehicles passing the stationary truck at the same time
- Distance upstream of the truck at which the RSS first shows the speed of a vehicle
- Widest angle at which the RSS can record the speed of a vehicle as it passes by the truck

3.5.1 Accuracy of RSS at Various Speeds (20-60 mph) with the Truck Stationary

Three different vehicles were driven passed the truck with the RSS while the truck was parked on the shoulder of the roadway. The three vehicles were driven passed the truck at various speeds (20, 30, 40, 50, and 60 mph). As the vehicles passed by the truck, the accuracy of the RSS was noted. In addition, the researchers verified the actual speed of the passing vehicles with the radar gun. The speeds shown on the RSS were found to be very accurate in this case (stationary mode).

3.5.2 Accuracy of RSS at Various Speeds (20-60 mph) with the Truck Moving

To check the accuracy of the RSS when the truck is moving, the researchers repeated the previous test with the truck moving at both 5 mph and 10 mph. On the first day of testing, the RSS did not operate accurately in the moving mode, and showed the speeds of each vehicle to be 5 mph and 10 mph less than the actual vehicle speeds. Also, when the truck speed was 10 mph, the RSS could not detect and show the passing vehicle speeds that were less than 30 mph. These operational issues were solved by the RSS manufacturer before the case study tests and the repairs verified in two additional subsequent pre-tests. After the corrections were made, the speeds shown on the RSS during the third pre-test were also found to be very accurate in the moving mode.

3.5.3 Accuracy of RSS at Various Speeds (20-40 mph) with Multiple Vehicles Passing the Stationary Truck at the Same Time

The researchers tested the RSS with the truck parked on the shoulder of the roadway and with multiple vehicles passing the truck at the same time. Three cars with different sizes and different speeds (20-40 mph) passed the RSS truck at the same time in adjacent lanes. In general, the RSS displayed the fastest vehicle as long as there was a clear line of sight to the vehicle. The RSS unit also tended to stay fixed on the vehicle in the lane immediately adjacent to the truck, especially if it was the closest vehicle to the truck. Overall, the RSS did a good job reading the speeds of all of the vehicles in all of the lanes.

3.5.4 Distance Upstream of the Truck at which the RSS First Shows the Speed of a Vehicle

The distance upstream of the (stationary) truck at which the RSS display first shows the speed of a vehicle was measured. For the first trial, the distance measured was approximately 2,000 feet. The researchers then repeated the test with all three vehicles several times to find the maximum distance that the RSS can show the speed. The distance measured was approximately 2,260 feet. At this distance, the researchers could see the sign light up, but it was too far away to read the speed and message displayed on the sign.

3.5.5 Widest Angle at which the RSS can Record the Speed of a Vehicle as it Passes by the Truck

The researchers attempted to measure the widest angle at which the RSS can record the speed of a vehicle as it passes by the truck. That is, how far to the side of the truck is the RSS not able to record the vehicle speed accurately. To measure this angle, the researchers parked the truck as far away from the travel lane as possible. Then, the researchers recorded the distance between the end point that the RSS speed disappeared and the corresponding point of RSS in the travel lane (see Figure 3.22). This measurement was difficult to determine due to the additional lag time that the RSS displays the speeds after the vehicle has passed the truck. Based on the average of different distances measured, the angle at which the RSS can no longer record the vehicle speeds was estimated to be approximately 42 degrees (see Figure 3.22). However, further research is needed to more accurately determine this value.

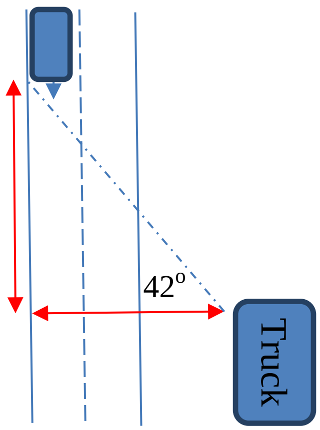


Figure 3.22: Widest angle at which RSS can record vehicle speed (approximate)

3.6 SECOND AND THIRD PRELIMINARY TESTING

Because the radar speed sign did not show the actual speed of approaching vehicles accurately, the RSS vendor was asked to assist with the operation of the RSS and make sure that the equipment was working properly. A second pre-test of the equipment was then conducted. Following the second test, it was determined that a new part was needed for the system. The vendor installed the new part and a third pre-test was then conducted. Similar to the first preliminary test, the equipment was tested in both stationary and moving modes. The accuracy of radar speed sign was tested with the truck located in the shoulder of roadway and moving at the speeds of 5 and 10 miles per hour. In addition, the RSS display was set to show a warning message if the speed of the approaching vehicle was more than 45 mph. The researchers drove past the truck at speeds of 20, 30, 40, and 50 mph. The vehicle speeds were also recorded by a radar speed gun to check the accuracy of the RSS. The RSS was found to be very accurate and worked well when the truck speed was 5 mph. It displayed the speed of the vehicle correctly at 20, 30, and 40 mph. For the 50 mph speed, it correctly showed the constant “Slow Down” warning as programmed.

When the truck speed was 10 mph, the RSS did not display any speed or message when the approaching vehicle speeds were 10 mph or 20 mph. For the trial with the vehicle speed equal to 40 mph, the RSS displayed the actual speed correctly. For the trial with vehicle speed more than 50 mph, it correctly showed the constant warning sign of “Slow Down”.

The researchers also tested the RSS with the truck moving and multiple vehicles passing it at the same time. This tested involved the truck moving in the shoulder of the roadway at 5 mph. Three cars with different sizes and different speeds passed the RSS truck at the same time. In the first trial, a minivan with the speed of 20 mph was driven in the lane closest to the moving truck lane and two passenger cars with smaller size were driven at speeds of 30 mph and 40 mph in the two adjacent lanes at the same time. The RSS displayed the vehicle’s (minivan’s) speed in the nearest lane which was 20 mph. For the next trial, the researchers changed the position of the minivan from nearest lane to farthest lane from the moving truck. Again the speeds of the passing vehicles were 20, 30, and 40 mph respectively (20 mph in the adjacent lane to the moving truck and 40 mph in the farthest lane). For this trial, the RSS was able to record the speed of the farthest vehicle even though it was driven in the farthest lane from the equipment.

At the end of the test the researchers downloaded the recorded data from the RSS unit. The equipment provides a summary of speeds in an Excel CSV file as showed in Table 3.2. As can be seen in the table, the columns contain 5 mph interval groups which show the speed of the approaching vehicles, and time groups in 5 minute increments are displayed for each row. The table also contains the median and maximum speed in each time interval. Ignoring the speed interval of 0-5 mph (as directed by the RSS vendor), the recorded speeds are consistent with the actual speeds. Following the tests, the vendor made further adjustments in the system such that vehicle speeds are recorded every second and not grouped into mph and time ranges.

Table 3.3.2: Sample of Data from RSS Unit

me	03050025.CSV													
aded:	2/12/2015 14:09													
.	0165R-0305													
	2/12/2015 13:16													
	2/12/2015 14:09													
	VDSR													
	Total	0_5	6_10	11_15	16_20	21_25	26_30	31_35	36_40	40_45	46_50	51_55	Median	Max
2015 25	0	17	0	0	7	10	0	0	0	0	0	0	15	24
2015 30	0	30	0	0	0	2	10	5	10	3	0	0	20	42
2015 35	0	13	0	0	0	0	1	1	2	5	6	0	30	50
2015 40	0	13	0	0	0	0	0	0	8	5	0	0	35	42
2015 45	0	17	0	0	0	0	0	0	2	2	9	4	35	51
2015 50	0	12	0	0	2	6	3	1	0	0	0	0	15	31
2015 55	0	7	0	0	1	4	0	2	1	0	0	0	15	38
2015 00	0	8	0	0	1	1	3	1	1	3	0	0	20	44
	0	118	0	0	11	23	17	10	24	18	15	4	16	51

3.7 SENSOR DATA ADJUSTMENT

Tests of the accuracy of the traffic analyzers were conducted to calibrate the analyzers and determine how far off the speeds recorded by the analyzers were from the actual vehicle speeds. Having this information then allows for adjusting the speeds recorded during each case study to the actual vehicle speeds.

To conduct the testing, the 14 sensors used for the data collection in the case studies were placed on a roadway in the center of the lane approximately 2 feet apart in a straight line during the first preliminary test. Figure 3.23 shows the layout of the sensors for pre-testing. The researchers then drove over the sensors multiple times at different speeds. In addition, the researchers recorded the vehicle speed at the sensor location using the RSS unit and radar speed gun in order to verify the actual speed of the vehicle. The researchers drove over the sensors three times at each of the following speeds: 20 mph (average of 21,19, and 20 mph), 29.67 mph (average of 29, 30, and 30 mph), 40 mph (average of 40, 40, and 40 mph), 48.67 mph (average of 46, 50, and 50 mph), and 58.67 mph (average of 60, 57, and 59 mph). The data collected from the portable traffic analyzers was downloaded for analysis. Figure 3.24 shows the results of this testing. The figure shows the average of three actual speeds recorded at each of the test speeds for each sensor (identified by the sensor number).

Figure 3.23: Sensor Layout for Sensor Testing

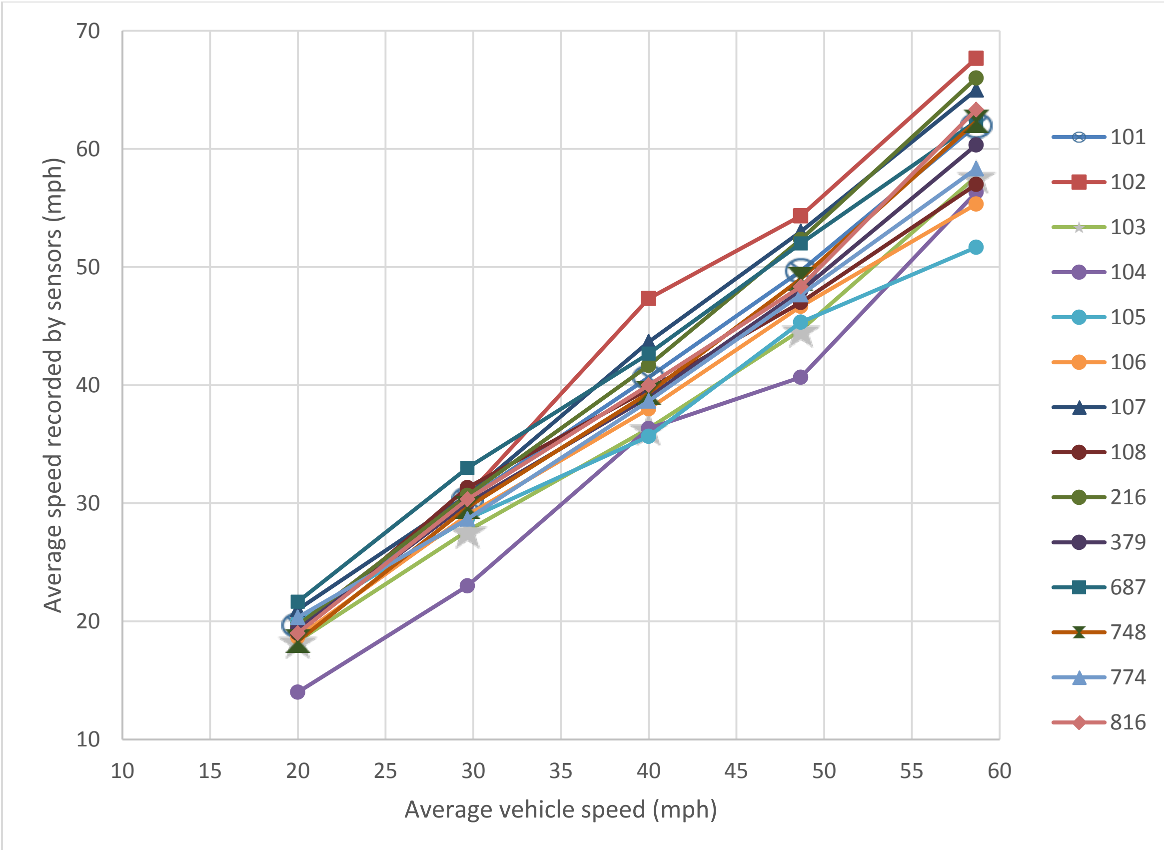


Figure 3.24: Sensor Testing – Average Speed Recorded by Sensors

Figure 3.25 displays the difference between the average speed recorded by the sensor and the average actual speed of the vehicle. The x-axis represents the average of the actual vehicle speed. Each line represents data from one sensor. The last three digits of the sensor serial number are used here to identify the different sensors. As seen in the figure, for most sensors, the difference in speed becomes larger as the vehicle speed increases. Sensors #102, #104, #105, and #107 produced significantly more inaccurate results than the other 10 sensors.

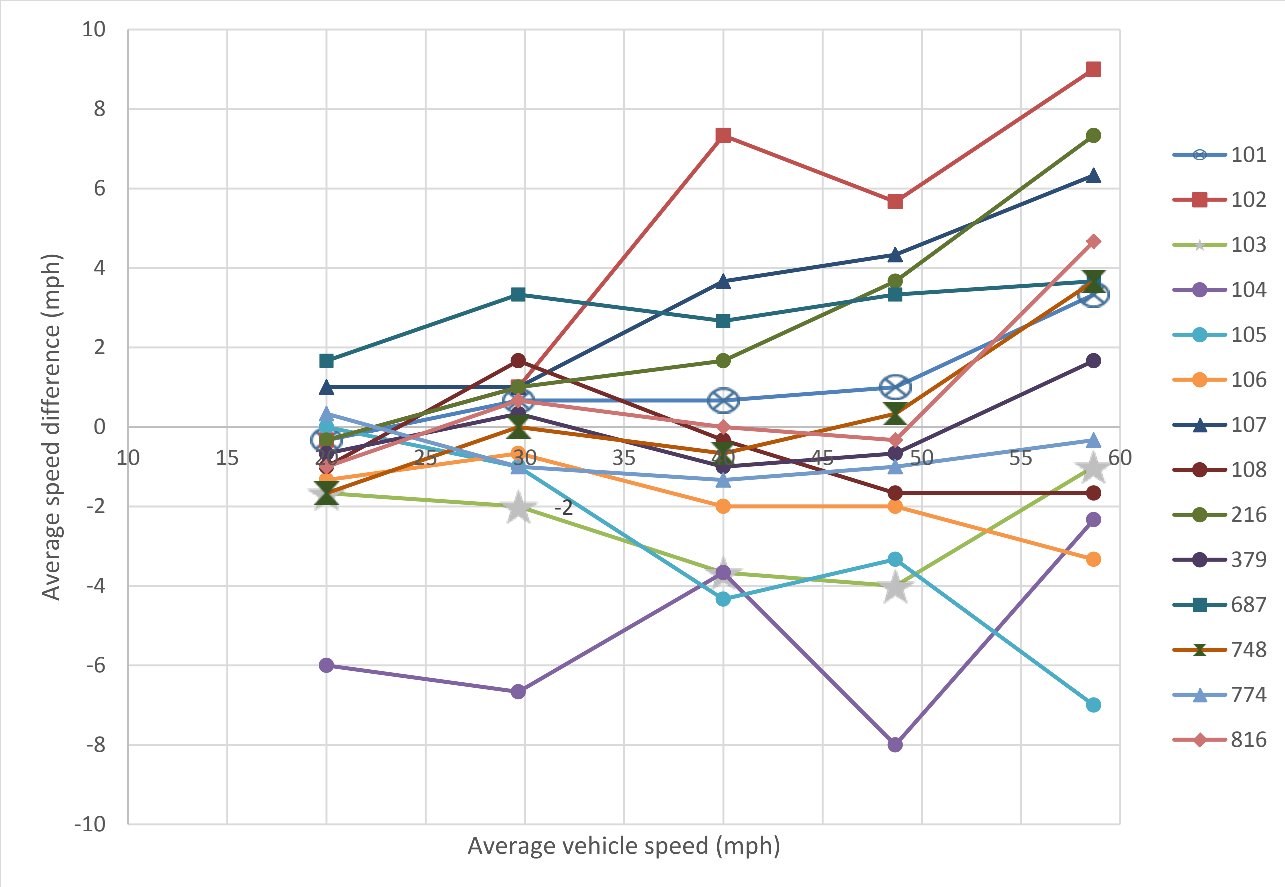


Figure 3.25: Sensor Testing – Average Speed Difference from Actual Speed

The final adjustment for each sensor is based on the regression lines from the average recorded speed vs. actual speed calculated. The result for sensor #101 is shown in Figure 3.26. The full set of results is provided in the Appendix. The equations used for final adjustment are presented in Table 3.3. In the table, the variable x represents the speed recorded by the sensor, and the variable y is the adjusted speed to use in the analysis.

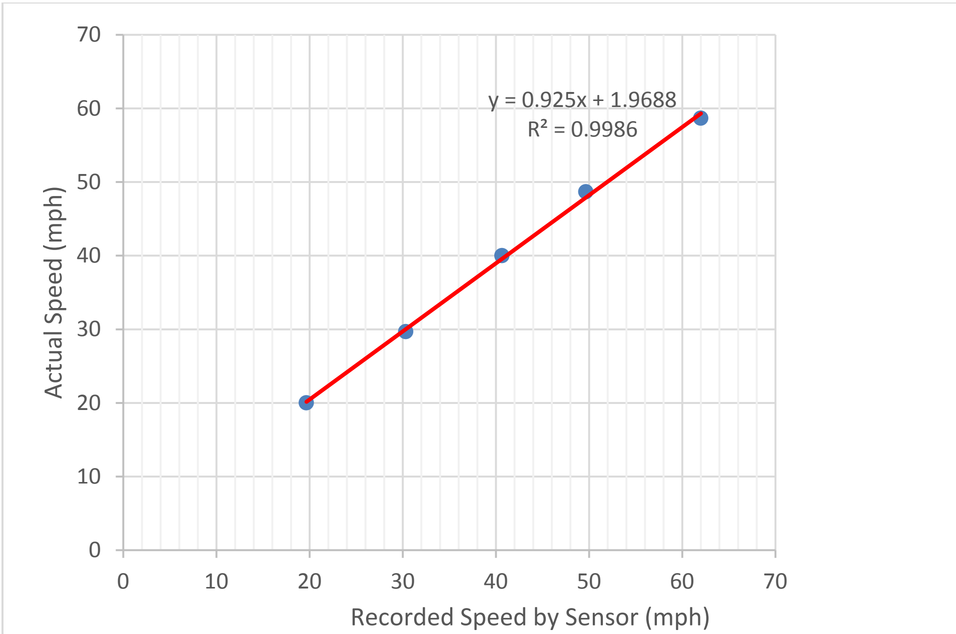


Figure 3.26: Average Recorded Speed vs. Actual Speed for Sensor #101

Table 3.3: Sensor Data Adjustment Equations

Sensor ID	Adjustment Equation
101	y = 0.925x + 1.9688
102	y = 0.7981x + 4.3357
103	y = 0.9999x + 2.4693
104	y = 0.9242x + 7.9166
105	y = 1.1991x - 4.0864
106	y =1.0575x - 0.2918
107	y = 0.8719x + 2.1968
108	y = 1.0436x - 1.0918
216	y = 0.8408x + 4.03
379	y = 0.9604x + 1.6262
687	y = 0.9594x - 1.2157
748	y = 0.8946x + 3.8558
774	y = 1.0127x + 0.1762
816	y = 0.8956x + 3.3969

4.0 RESULTS AND ANALYSIS

Following data collection on each case study project, the researchers downloaded the vehicle data from the traffic analyzers for analysis. This section of the report presents the data recorded along with the analyses for each case study. In order to maintain clarity between the case studies, both the results and the analyses are presented in this section for each case study. With all of the traffic analyzers used and the multiple periods of testing, a very large amount of data was collected on each case study. In addition, multiple quantitative analyses are conducted on each case study. As a result, the number of tables and figures generated for each case study is quite extensive. Therefore, in the body of the report, only representative tables and figures are provided in order to clearly and efficiently communicate the results and findings of each case study. All of the tables and figures created as part of the analyses are provided in the Appendix for further detail and reference if needed.

For all of the case study data presented below, the data has been adjusted to take into account the error in the traffic analyzers as described in the previous section of this report. Additionally, analyses are only conducted within each case study; analytical comparisons between different case studies are not made. The differences in site conditions, vehicle distribution, test layout, and maintenance work operations between each case study limit confidence in the comparisons due to the confounding factors.

4.1 CASE STUDY #1: I-205 RELAMPING

Figure 4.1 presents the recorded traffic volumes during the testing period on each day of testing (Day 1 without the RSS turned on and Day 2 with the RSS turned on). Total traffic volumes decreased during the course of the testing. However, total traffic volume was similar on both days of testing. In addition, the percentage of cars (vehicles < 25 feet in length) and percentage of trucks (vehicles > 25 feet in length) are approximately the same for each day. Based on the volumes measured each day, no impact on the comparison between Day 1 speeds and Day 2 speeds is anticipated.

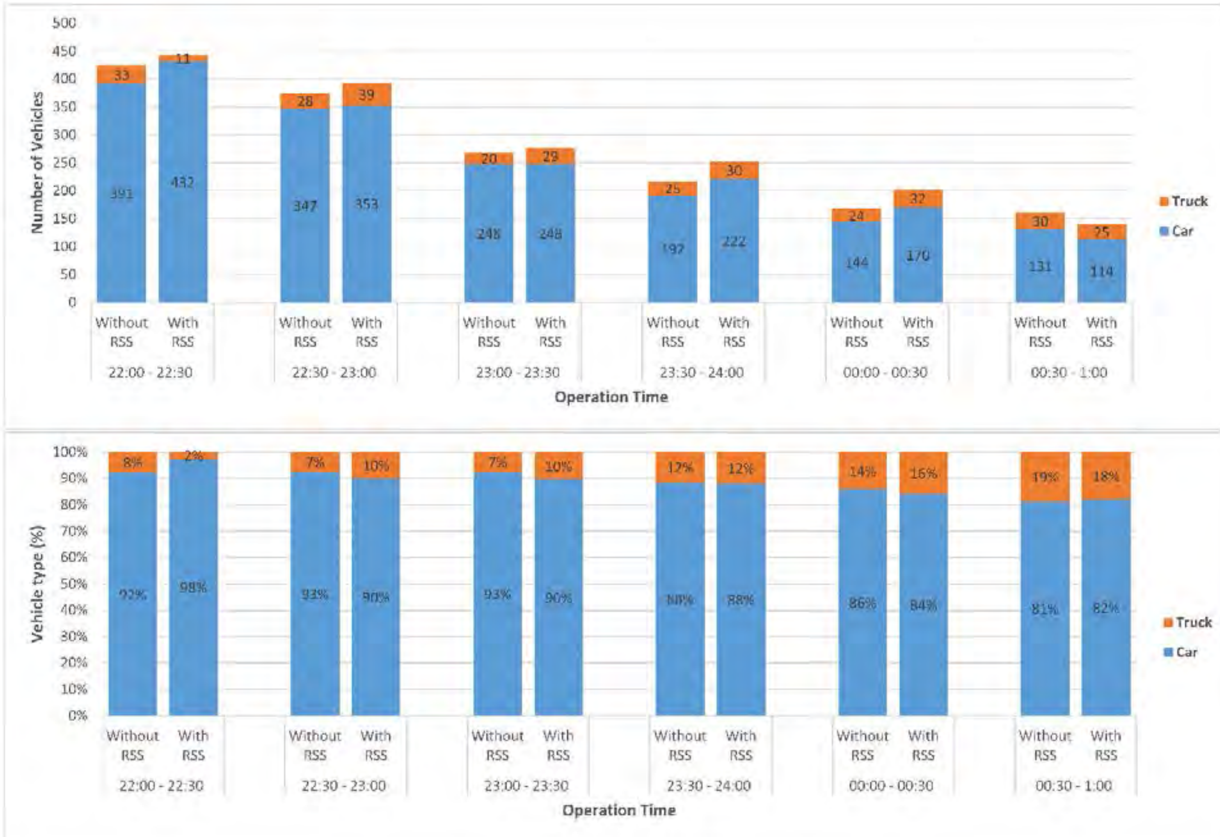


Figure 4.1: Traffic Volume, I-205 Relamping Case Study

Table 4.1 presents a summary of the vehicle speeds recorded for all vehicles at the Road Work Ahead (RWA) sign location on Day 1 without the RSS turned on. For this table, the values represent the data downloaded from the sensors in both the A and B lanes. 85th percentile speed for the entire work period was 65.5 mph. This value ranged from 66.9 mph down to 64.0 mph throughout the test period.

Similarly, Table 4.2 shows a summary of the vehicle speeds over the same period recorded in the work area, specifically at Pole #5. The 85th percentile speed decreased to 57.3 mph at this location.

Table 4.1: Hourly Summary of Vehicle Speed, I-205, Relamping, Without RSS (Day 1), RWA

	Time						
Vehicle Speed (all vehicles)	**Total**	22:00-22:30	22:30-23:00	23:00-23:30	23:30-24:00	00:00-00:30	00:30-01:00
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%
25-29	0.1%	0.0%	0.2%	0.0%	0.4%	0.5%	0.0%
30-34	0.2%	0.2%	0.2%	0.6%	0.0%	0.0%	0.0%
35-39	0.6%	0.6%	0.5%	1.1%	0.4%	0.9%	0.5%
40-44	2.9%	2.2%	2.1%	2.9%	4.6%	1.9%	5.7%
45-49	11.8%	9.4%	12.4%	10.6%	14.2%	14.0%	13.7%
50-54	24.1%	28.3%	20.0%	24.1%	20.3%	27.4%	23.2%
55-59	26.4%	27.0%	26.4%	25.2%	26.1%	30.2%	23.7%
60-64	18.3%	16.7%	19.7%	19.8%	19.9%	12.1%	21.8%
65-69	7.7%	8.1%	8.5%	6.6%	8.0%	7.0%	7.1%
70-74	4.5%	5.0%	6.2%	4.9%	2.7%	3.3%	2.8%
>=75	3.1%	2.4%	3.7%	4.3%	3.4%	2.8%	1.4%
Total # of vehicles	2012	540	436	349	261	215	211
Average speed	57.5	57.6	58.3	57.7	57.1	56.7	56.7
St. Dev.	8.3	7.7	8.7	8.9	8.5	7.9	7.7
85th percentile	65.5	65.8	66.9	65.8	64.9	64.0	64.0
Min	24.5	30.6	24.5	31.6	25.1	28.5	36.5
Max	94.7	86.1	86.1	92.8	94.7	89.5	90.9
Range	70.3	55.5	61.7	61.2	69.6	61.0	54.4

Table 4.2: Hourly Summary of Vehicle Speed, I-205, Relamping, Without RSS (Day 1), Pole 5

	Time						
Vehicle Speed (all vehicles)	**Total**	22:00-22:30	22:30-23:00	23:00-23:30	23:30-24:00	00:00-00:30	00:30-01:00
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.3%	0.5%	0.3%	0.4%	0.0%	0.0%	0.0%
25-29	0.9%	0.2%	1.6%	2.3%	0.9%	0.0%	0.0%
30-34	2.9%	1.7%	5.6%	3.0%	3.8%	1.7%	0.0%
35-39	8.0%	5.1%	11.0%	15.5%	6.6%	3.5%	3.1%
40-44	16.5%	12.8%	24.7%	16.2%	20.2%	9.9%	10.1%
45-49	21.3%	25.5%	21.5%	18.1%	27.7%	12.8%	15.7%
50-54	25.5%	26.3%	19.9%	24.2%	21.1%	36.6%	32.7%
55-59	15.9%	18.3%	9.9%	14.7%	15.0%	19.8%	22.6%
60-64	6.0%	7.0%	4.3%	4.5%	2.8%	9.9%	9.4%
65-69	1.8%	2.2%	0.5%	0.8%	0.9%	4.1%	3.8%
70-74	0.4%	0.0%	0.3%	0.0%	0.0%	1.7%	1.3%
>=75	0.5%	0.5%	0.3%	0.4%	0.9%	0.0%	1.3%
Total # of vehicles	1596	415	372	265	213	172	159
Average speed	49.4	50.5	46.7	47.6	48.4	52.8	53.3
St. Dev.	8.1	7.5	8.1	8.3	7.6	7.6	7.4
85th percentile	57.3	57.3	55.3	55.3	55.5	60.5	60.5
Min	22.9	22.9	25.0	25.0	26.0	32.3	38.6
Max	83.4	78.2	75.1	80.3	77.2	73.0	83.4
Range	60.5	55.3	50.1	55.3	51.1	40.7	44.9

Similarly, Tables 4.3 and 4.4 provide vehicle speed data during the testing on Day 2 with the RSS turned on. Table 4.3 shows the speeds collected at the RWA signs, and Table 4.4 shows the data in the work area at Pole #6. During the early hours of testing on Day 2, queuing occurred in the travel lane adjacent much of the initial work area. As seen in the Table 4.4, the queuing diminished by about 23:00. When observing the work zone, there was no evidence of the root cause for the queuing.

Table 4.3: Hourly Summary of Vehicle Speed, I-205, Relamping, With RSS (Day 2), RWA

	Time						
Vehicle Speed (all vehicles)	**Total**	22:00-22:30	22:30-23:00	23:00-23:30	23:30-24:00	00:00-00:30	00:30-01:00
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	0.3%	0.3%	0.7%	0.3%	0.0%	0.4%	0.0%
35-39	1.0%	1.0%	1.1%	0.6%	0.9%	1.2%	1.3%
40-44	3.3%	3.7%	1.6%	3.3%	2.7%	3.6%	5.9%
45-49	8.3%	7.5%	9.1%	7.7%	7.4%	9.9%	9.3%
50-54	22.8%	22.6%	23.2%	22.8%	19.0%	22.5%	28.4%
55-59	21.9%	19.7%	19.6%	23.7%	24.6%	23.7%	22.9%
60-64	21.1%	21.4%	23.5%	19.3%	22.3%	21.3%	16.5%
65-69	11.3%	11.1%	11.2%	12.8%	13.1%	9.9%	8.9%
70-74	6.3%	7.7%	6.2%	5.3%	7.1%	5.1%	5.1%
>=75	3.6%	4.9%	3.9%	4.2%	3.0%	2.4%	1.7%
Total # of vehicles	2177	575	439	337	337	253	236
Average speed	58.7	59.2	58.8	59.0	59.3	57.8	56.7
St. Dev.	8.7	9.2	8.6	8.9	8.1	8.7	8.1
85th percentile	67.6	68.8	67.6	67.6	68.2	66.5	65.8
Min	27.9	27.9	30.6	34.5	38.0	30.5	35.2
Max	93.8	91.8	87.0	93.8	79.7	91.7	77.5
Range	65.9	64.0	56.4	59.3	41.6	61.2	42.2

Table 4.4: Hourly Summary of Vehicle Speed, I-205, Relamping, With RSS (Day 2), Pole 6

	Time						
Vehicle Speed (all vehicles)	**Total**	22:00-22:30	22:30-23:00	23:00-23:30	23:30-24:00	00:00-00:30	00:30-01:00
MPH							
< 10	0.1%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	2.0%	7.0%	1.0%	0.0%	0.0%	0.0%	0.0%
15-19	13.9%	34.6%	20.8%	0.0%	0.0%	0.0%	0.0%
20-24	18.4%	38.7%	34.7%	0.0%	0.0%	0.5%	0.0%
25-29	5.7%	14.2%	7.8%	0.0%	0.4%	0.0%	0.8%
30-34	2.9%	5.2%	4.6%	0.7%	0.8%	1.0%	1.6%
35-39	3.1%	0.0%	5.9%	5.1%	2.4%	3.9%	0.8%
40-44	6.6%	0.0%	8.8%	12.3%	5.6%	8.7%	8.6%
45-49	10.0%	0.0%	7.3%	15.6%	15.6%	20.8%	13.3%
50-54	14.4%	0.0%	6.1%	27.5%	25.2%	28.0%	19.5%
55-59	14.1%	0.0%	2.2%	26.1%	28.4%	23.7%	31.3%
60-64	5.8%	0.0%	0.7%	6.9%	14.0%	10.1%	17.2%
65-69	2.1%	0.0%	0.0%	5.1%	5.6%	1.4%	3.9%
70-74	0.5%	0.0%	0.0%	0.7%	1.2%	0.5%	2.3%
>=75	0.3%	0.0%	0.0%	0.0%	0.8%	1.4%	0.8%
Total # of vehicles	1715	445	409	276	250	207	128
Average speed	39.4	21.4	29.7	52.2	54.5	52.5	55.1
St. Dev.	16.6	4.6	12.0	7.5	7.9	8.0	8.3
85th percentile	57.3	26.0	45.9	58.4	61.5	59.4	62.6
Min	8.3	8.3	10.4	32.3	28.1	24.0	26.0
Max	87.6	34.4	62.6	74.0	85.5	87.6	80.3
Range	79.3	26.1	52.2	41.7	57.4	63.7	54.3

The traffic analyzers also provide the opportunity to view the vehicle speeds at various locations within the work zone. Figure 4.2 shows how the 85th percentile speed changed from the RWA signs to the end of the work zone at Pole #20 for both cases (with and without RSS turned on). The speeds shown are only those recorded during the time in which the work operation took place. As noted earlier, the posted regulatory speed limit at this location is 55 mph. For much of the work zone, the speeds with the RSS turned on were lower than without the RSS turned on. The difference will be impacted by the queuing that occurred on Day 2 with the RSS turned on which slowed down the vehicle speeds in the work area.

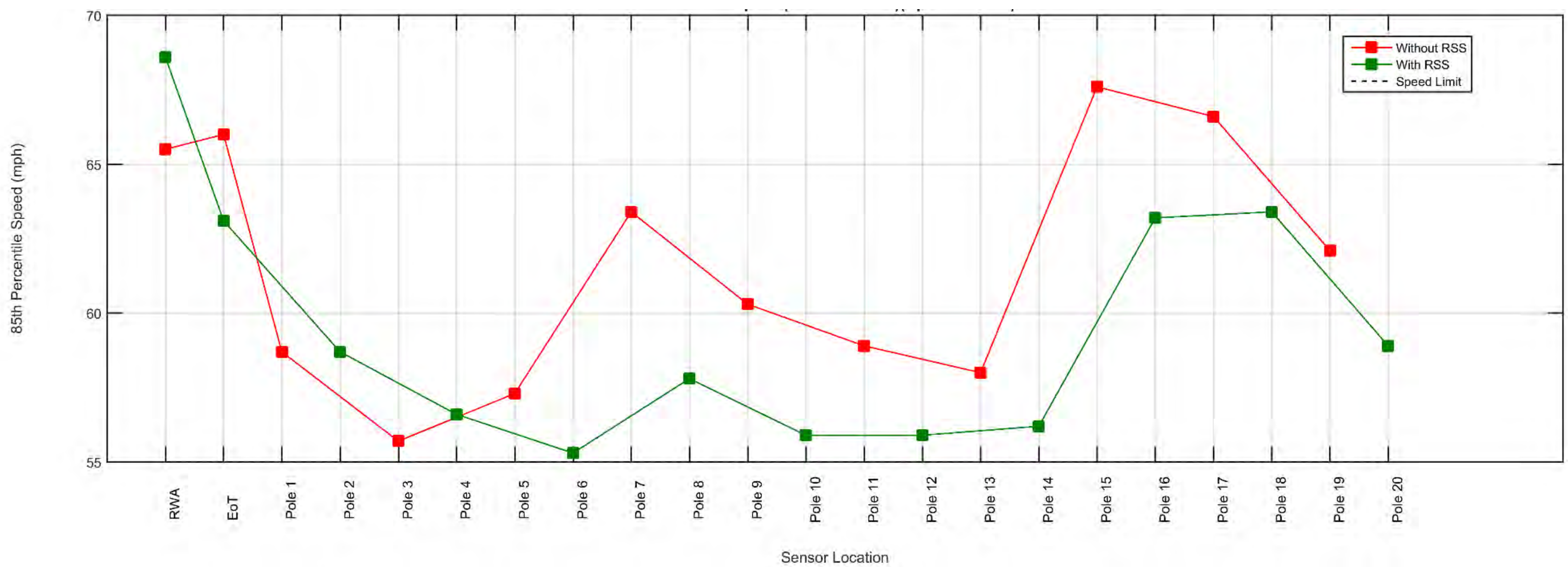


Figure 4.2: Vehicle Speed (85th percentile) at Different Locations during Operation Time, I-205, Relamping

It is likely that the speed in the work zone, at least in the initial portion of the work zone, depends on the speed of the vehicles prior to the work zone. Figure 4.3 shows the 85th percentile speeds at the RWA signs throughout the work period on each day of testing compared to the 55 mph speed limit. The figure shows that on Day 2 of the testing with the RSS turned on, the 85th percentile speed was consistently higher than on Day 1 without the RSS turned on over the course of the testing time period. This difference should be taken into consideration when comparing the speeds between Day 1 and Day 2.

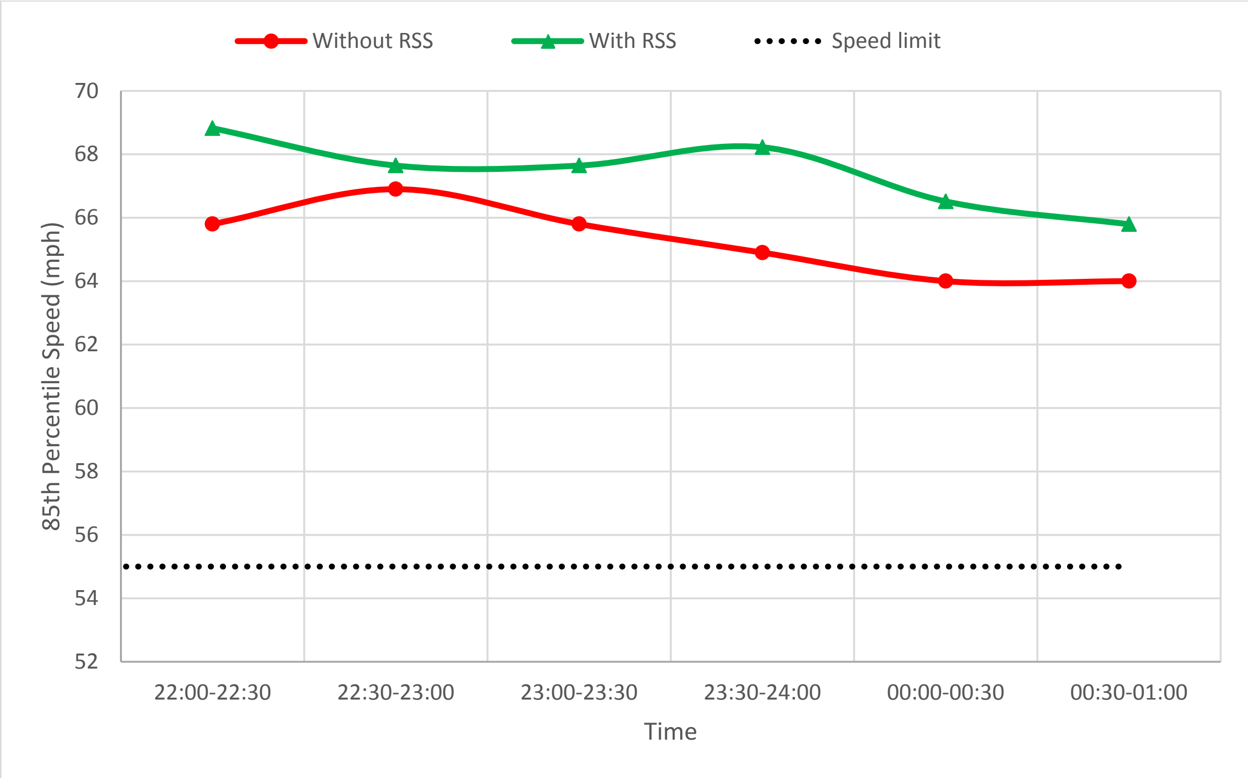


Figure 4.3: Vehicle Speed (85th Percentile) at RWA during Operation Time, I-205, Relamping

As part of the data analysis, comparisons were made between the vehicle speeds on each day at specific locations. Figure 4.4 shows a comparison of 85th percentile speeds at Pole #5 (without RSS turned on) to that at Pole #6 (with RSS turned on). Work was performed at odd-numbered poles on Day 1 without the RSS turned on and at even-numbered poles with the RSS turned on. Poles #5 and #6 were selected for illustration; similar charts showing comparisons between adjacent poles are provided in the Appendix. Recall that queuing occurred early in the work period on Day 2 with the RSS turned on. The lower speeds associated with the queuing are reflected in the figure from approximately 22:00 to 23:00.

Figure 4.4 also shows that the vehicle speeds are lower when adjacent the work equipment. For example, between 23:30 and 24:00 on Day 1 without the RSS turned on, the work took place at Pole #5. At this time, the 85th percentile speed was approximately 55 mph, the same as the posted regulatory speed limit. On the second day of testing (with the RSS turned on), the work on Pole #6 took place earlier in the evening. From 23:30-24:00 on Day 2 there was no work going at Pole #6 and the 85th percentile speed was approximately 62 mph, which was higher than on the prior day at the adjacent Pole #5.

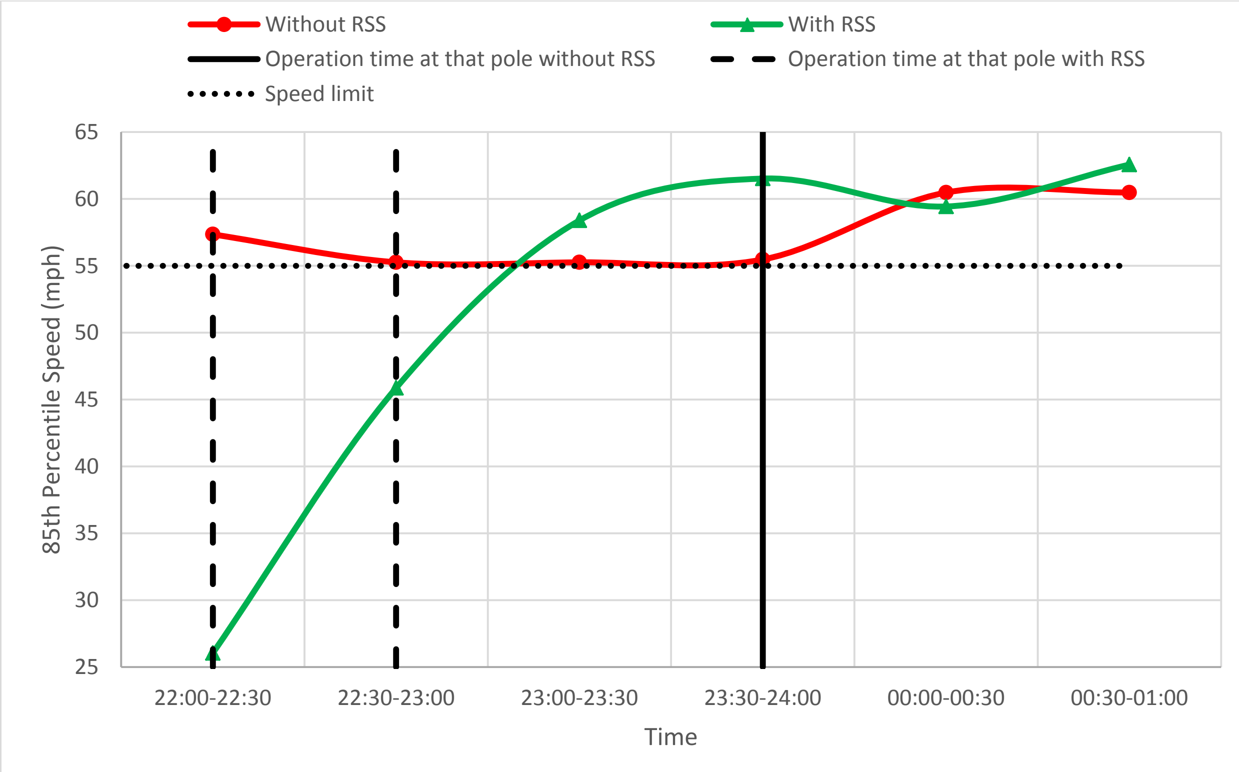


Figure 4.4: Vehicle Speed (85^{th} Percentile) at Pole 5 (Without RSS) and Pole 6 (With RSS) during Operation Time, I-205, Relamping

The effect of the presence of the work equipment on vehicle speeds is illustrated in Figure 4.5. This figure shows the speeds recorded at different locations throughout the work zone while the workers were located at Pole #6 on Day 2 (with RSS turned on). Similar graphs are provided in the Appendix for other poles. Vehicle speeds were quite slow at Poles #2 and #4 due to the queuing that took place.

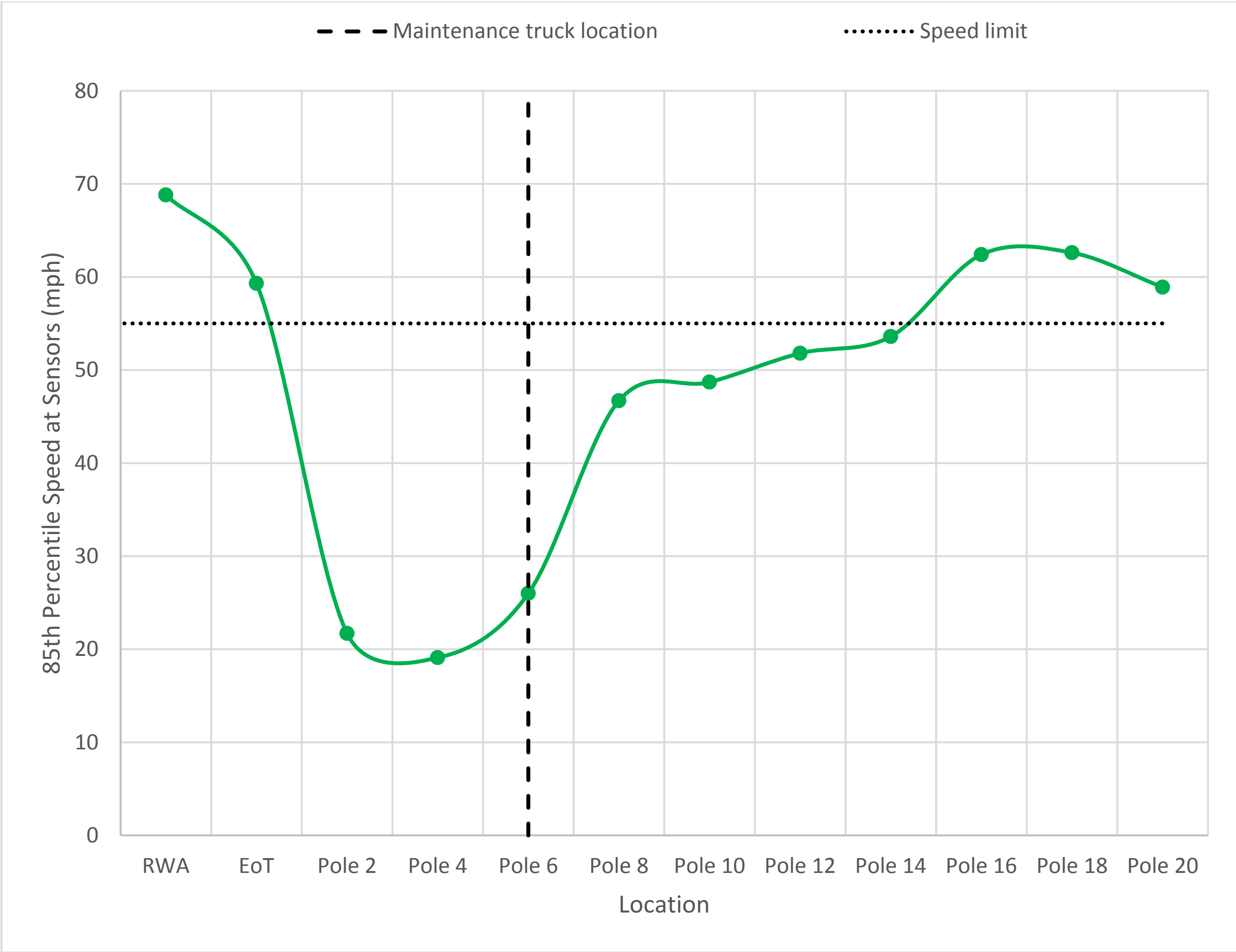


Figure 4.5: 85th Percentile Speed at Different Distances from the Work Operation, I-205, Relamping, With RSS (Day 2), Pole 6

The vehicle speed data collected provided an opportunity to calculate the amount of decrease in speed from the RWA signs to the work zone for both days of testing. The speeds in the work zone (WZ) were those recorded by all of the traffic sensors adjacent all of the light poles. Table 4.5 shows this comparison. For all vehicles, mean speed decreased from 57.5 mph at the RWA signs to 52.7 mph in the work zone, an 8.31% decrease, on Day 1 without the RSS turned on. On Day 2 with the RSS turned on, the amount of decrease for all vehicles was greater at 23%. When analyzing cars and truck separately, similar results were found: the percentage decrease in mean speed was greater with the RSS turned on.

Table 4.5: Percentage of Vehicle Speed Decrease in the Work Zone Area, I-205, Relamping

Type of vehicle	Mean speed (mph) without RSS (Day1) at RWA	Mean speed (mph) without RSS (Day1) in WZ	Decrease in mean speed (%) without RSS (Day1)	Mean speed (mph) with RSS (Day2) at RWA	Mean speed (mph) with RSS (Day2) in WZ	Decrease in mean speed (%) with RSS (Day2)
All Vehicles	57.5	52.7	8.31%	59.1	45.7	23%
Passenger Cars	57.9	52.7	9.07%	59.2	45.3	24%
Trucks	53.5	53.2	0.49%	57.8	50.3	13%

Table 4.6 shows an additional comparison of mean speeds, this time just comparing the speeds within the work zone. For all vehicles, the mean speed in the WZ on Day 1 without the RSS turned on was 52.7 mph and the mean speed in the WZ on Day 2 with the RSS turned on was 45.7 mph, a difference of 7.0 mph. This difference was found to be statistically significant ($p < 0.0001$). Similar statistically significant results were found for cars and for trucks: mean speeds throughout the work zone were less with the RSS turned on. For this case study, the amount of difference was more for cars (7.4 mph) than for trucks (3.0 mph).

Table 4.6: Effect of Radar Speed Sign on Vehicle Speed, I-205, Relamping

Type of vehicle	Mean speed (mph) without RSS (Day1) in WZ	Mean speed (mph) with RSS (Day2) in WZ	Difference in mean speed in WZ (mph)	p-value
All Vehicles	52.72	45.72	7.00	< 0.0001
Passenger Cars	52.65	45.27	7.38	< 0.0001
Trucks	53.24	50.27	2.97	< 0.0001

Expanded comparisons of the vehicle speeds are shown in Tables 4.7 and 4.8. These tables show the speed data at Poles #5 and #6. Similar tables for other adjacent poles are provided in the Appendix.

Table 4.7 summarizes the data during the entire period from 22:00-01:00. On Day 1, the operation time was from 22:00-01:00, while on Day 2 it was from 22:00-24:00. Therefore, Table 4.7 includes some free flow vehicle speeds (without the work operation taking place) for one hour from 24:00-01:00 on Day 2. The free flow speeds are typically higher, therefore increasing recorded speeds for Day 2. Table 4.8 summarizes the data for only the time periods when the work operation took place on both days, and presents a more accurate representation of the impact of the operation on vehicle speeds. As seen in Table 4.8, the mean and 85th percentile speeds are less with the RSS turned on. It should be noted, however that the standard deviation was found to be greater with the RSS turned on. There was greater variation in speeds amongst all vehicles over the duration of the work period with the RSS turned on.

Table 4.7: Volume, 85th percentile, Mean, and Standard Deviation Speed for Different Types of Vehicles, I-205, Relamping, Pole 5 (Without RSS) and Pole 6 (With RSS), 22:00-01:00

Test Day	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Day 1 (without RSS)	1448	57.3	49.6	8.1	148	54.2	47.3	8.0	1596	57.3	49.4	8.1
Day 2 (with RSS)	1590	57.3	39.2	16.8	125	53.2	42.8	12.6	1715	57.3	39.4	16.6

Table 4.8: Volume, 85th percentile, Mean, and Standard Deviation Speed for Different Types of Vehicles, I-205, Relamping, Pole 5 (Without RSS) and Pole 6 (With RSS), Operation Time*

Test Day	Passenger Cars				Trucks				Total Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Day 1 (without RSS)	1448	57.3	49.6	8.1	148	54.2	47.3	8.0	1596	57.3	49.4	8.1
Day 2 (with RSS)	1299	56.3	35.9	16.5	81	50.0	38.8	13.0	1380	55.3	36.0	16.3

*: For Day 1 the operation time was from 22:00-01:00 and for Day 2 it was from 22:00-24:00

Analyses were also conducted that focused on the difference in speed between adjacent vehicles and the distance between adjacent vehicles as the vehicles passed through the work zone. The speed difference between adjacent vehicles is a concern if the difference is large. A faster vehicle approaching a slower vehicle may increase the risk of rear-end crashes. Slow vehicles relative to other nearby upstream vehicles may also create a "shock-wave" effect in the work zone and possible queuing if extremely slow. In addition, a vehicle that travels too closely behind another vehicle (tailgating) creates a rear-end crash hazard. The concern is important for small distances between vehicles where reaction time is a concern. When the distance is large and sufficient time is available to react to the actions of preceding vehicles, there is less of a chance of a collision.

For this analysis, the researchers calculated the speed difference and distance between adjacent vehicles, and then made statistical comparisons to determine whether the RSS display had an impact on the speed difference and distance apart. Speed difference is calculated as the difference in speed between a vehicle and the vehicle in front of it. A positive value for speed difference indicates that the vehicle is travelling at a faster rate of speed than the vehicle in front of it. A negative value for speed difference indicates that the vehicle is travelling slower than the vehicle in front of it.

Similarly, the distance from previous vehicle is defined as how far a vehicle is behind the vehicle in front of it. The traffic analyzers record a vehicle's speed and the time in which the vehicle passes over the analyzer. The distance from previous vehicle is calculated by multiplying the speed of the vehicle in front times the time difference between vehicles.

Figure 4.6 shows the speed difference for vehicles passing Pole #5 during the work operation time on Day 1 without the RSS turned on. Each dot in the figure represents one vehicle. As seen in the figure, the speed differences vary significantly, with a range of approximately -20 mph to +20 mph, and no particular trend in the data is visible.

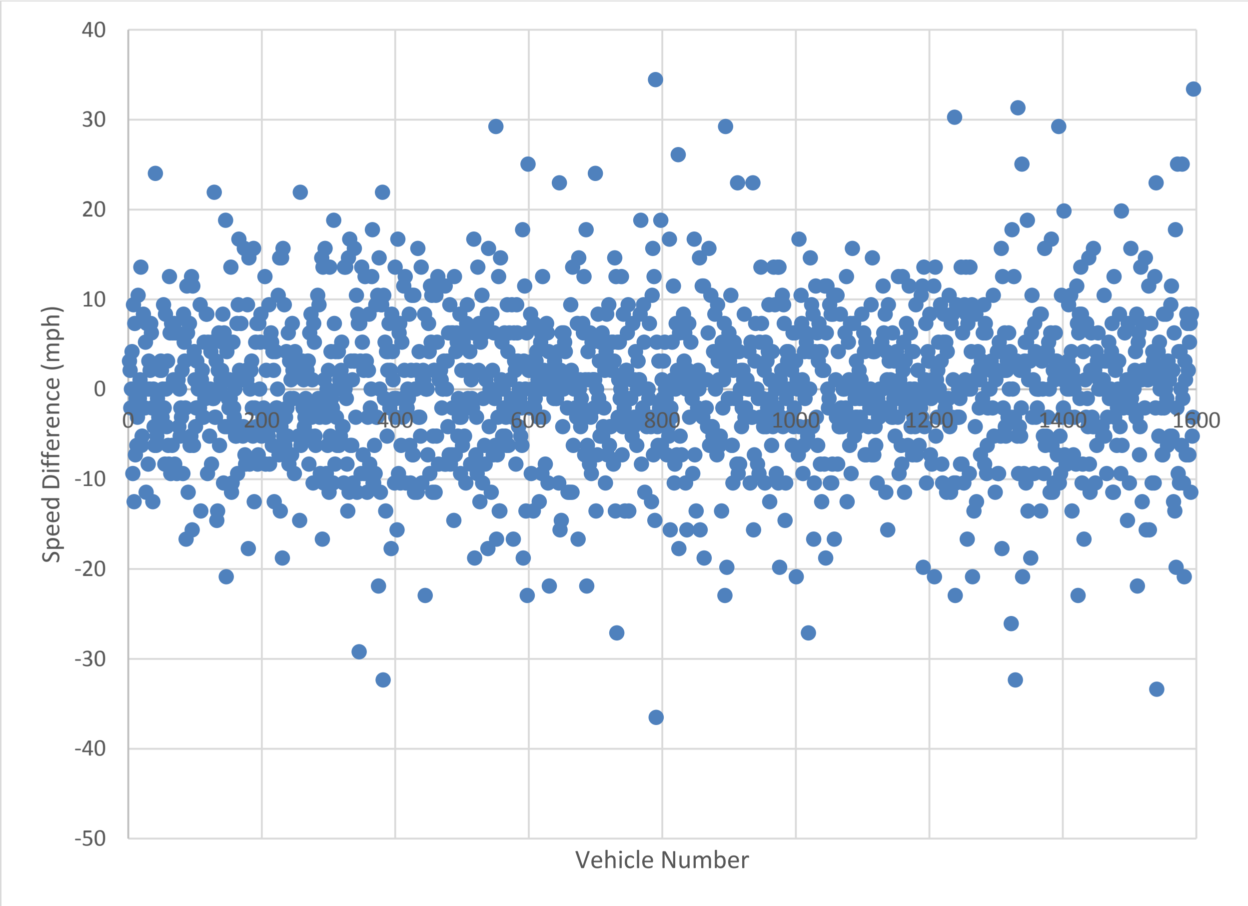


Figure 4.6: Speed Difference for Vehicles Passing Pole 5 during Operation Time, I-205, Relamping, Without RSS (Day 1)

Figure 4.7 shows the speed differences compared to the actual speed of the vehicle adjacent Pole #5 during the work operation time on Day 1 without the RSS turned on. The horizontal axis contains the speed of the trailing vehicle, and the vertical axis contains the difference in speed between the trailing vehicle and the vehicle in front of it. The figure shows an apparent positive slope. That is, as the vehicle's speed increases, the difference in speed between the vehicle under consideration and the vehicle in front of it also increases. This trend is expected because the two factors are related in nature. Speed difference is calculated from vehicle speed. If the speed for the trailing vehicle is high, there is a greater chance that the speed difference will be high also. Those vehicles represented by the data points in the upper-right portion of the figure are especially of concern; they are travelling at a high rate of speed and at a high rate of speed relative to the preceding vehicle. A reduction of the number of vehicles travelling is this manner is desired to improve safety in the work zone.

The posted regulatory speed at this location is 55 mph. During the testing on Day 1, 60% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. During the entire test period at Pole #5 within the work zone, 24% of the vehicles were going faster than the posted speed limit.

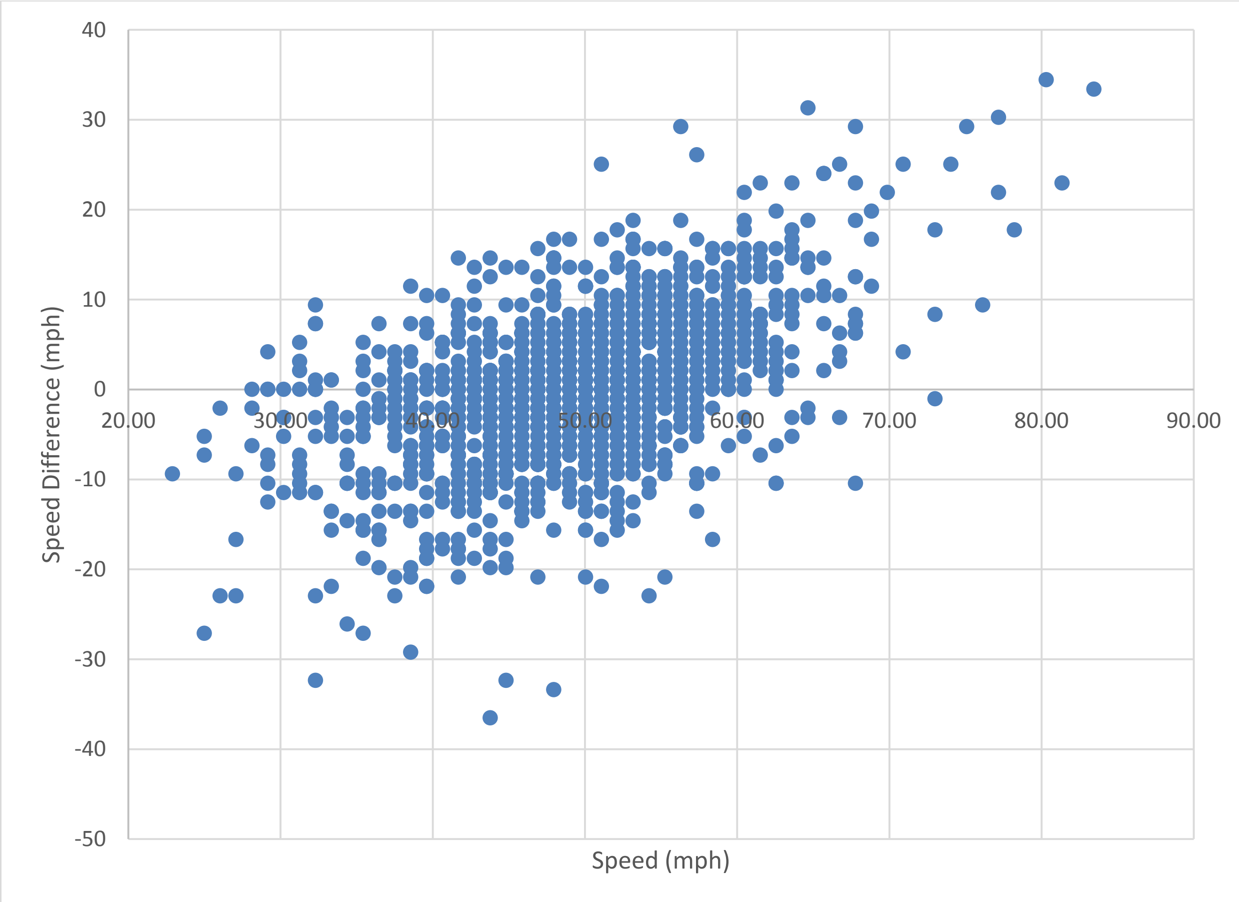


Figure 4.7: Speed Difference vs. Vehicle Speed for Vehicles Passing Pole 5 during Operation Time, I-205, Relamping, Without RSS (Day 1)

Figure 4.8 is similar to Figure 4.7, however the vertical axis in Figure 4.8 shows the distance between adjacent vehicles rather than the speed difference. Figure 4.8 shows the data for the vehicles passing Pole #5 during the work operation time on Day 1 without the RSS turned on. While the distance apart varies, the majority of vehicles are less than approximately 1,000 feet apart. The figure does not show a clear trend in distance between adjacent vehicles. Those vehicles represented by the data points in the lower-right portion of the figure are especially of concern; they are travelling at a high rate of speed and travelling close to the preceding vehicle. This type of driving behavior can be dangerous; reducing the amount of vehicles travelling in this manner will help improve safety in the work zone.

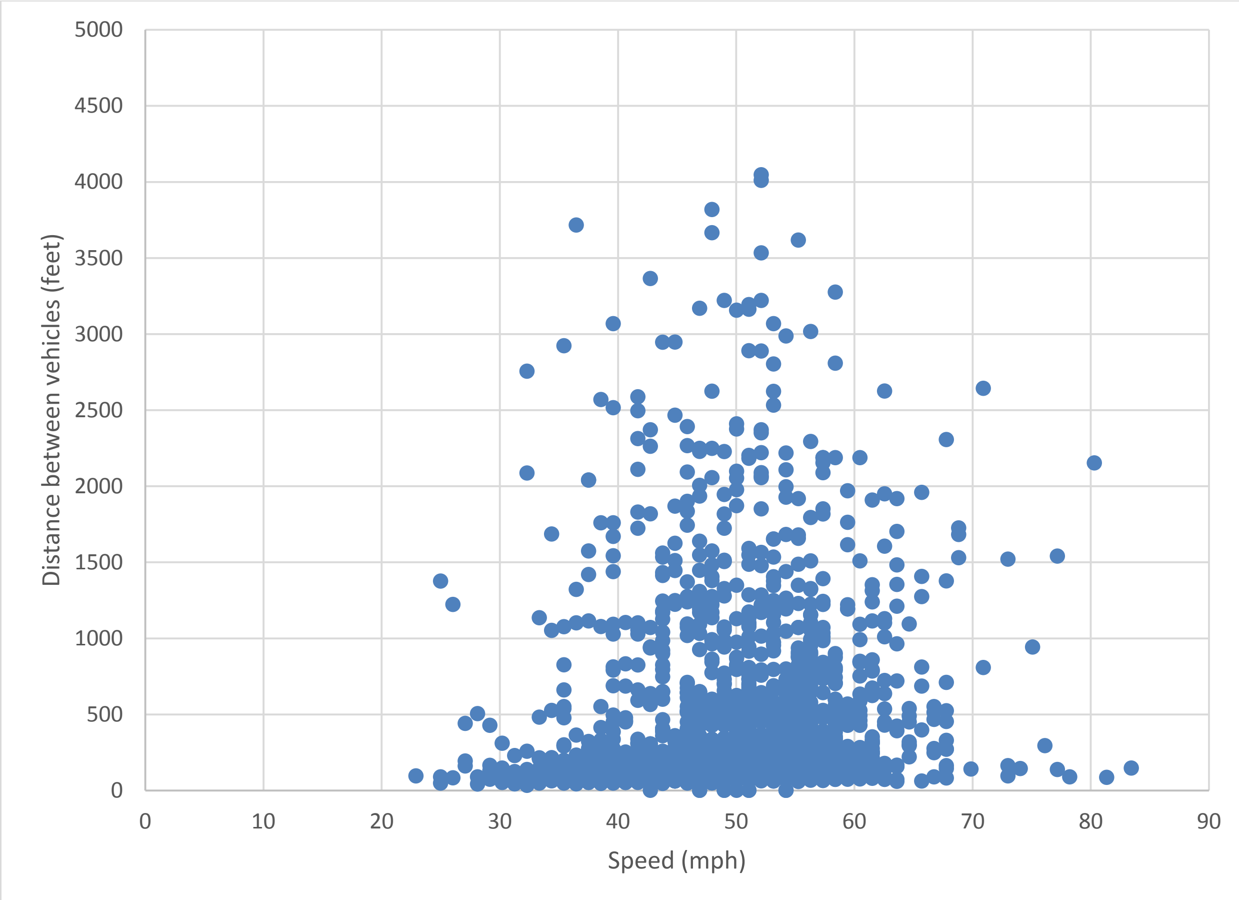


Figure 4.8: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Pole 5 during Operation Time, I-205, Relamping, Without RSS (Day 1)

The distance between adjacent vehicles compared to the speed difference between vehicles is shown in Figure 4.9. The data is shown for vehicles passing Pole #5 during the work operation time on Day 1 without the RSS turned on. Again, no particular trend is visible in the figure. The data points with negative speed difference indicate that the trailing vehicle is slower than the leading vehicle and getting farther away from the leading vehicle as the vehicles travel down the roadway. Those data points on the right side of the figure (higher positive speed difference), especially those with small distance between vehicles, are of concern. To prevent potential rear-end collisions, those vehicles with large positive speed difference (i.e., high speed relative to the vehicle in front of it) and low distance apart (i.e., close to the vehicle in front of it) is undesirable. The combination of higher speeds and shorter distances between adjacent vehicles in work zones may contribute to a high proportion of rear-end collisions among all work zone-related accidents *(Benekohal and Sun 2005)*.

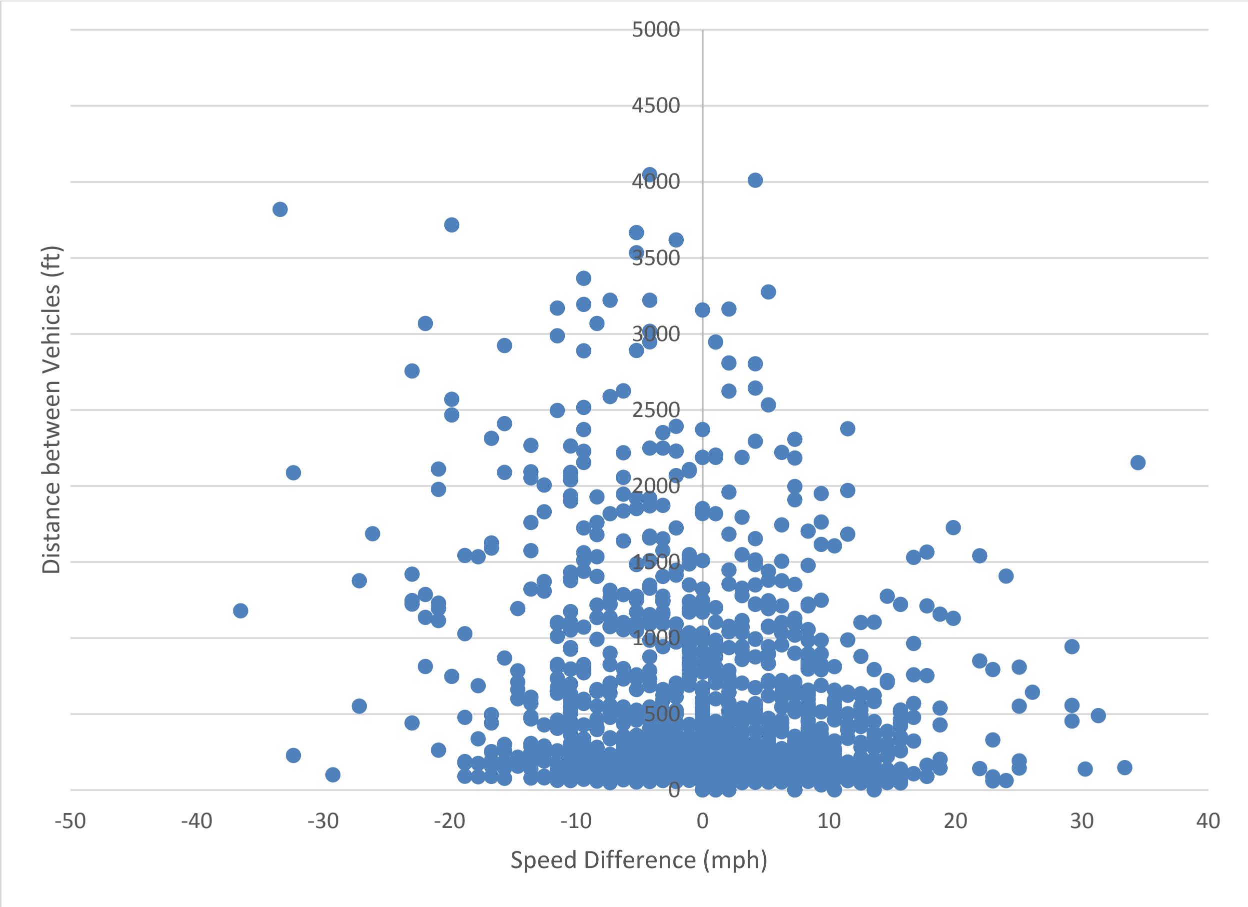


Figure 4.9: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Pole 5 during Operation Time, I-205, Relamping, Without RSS (Day 1)

For comparison, Figures 4.10, 4.11, 4.12, and 4.13 show similar speed and distance difference charts for Day 2 with the RSS turned on. In these figures, the data is based on vehicles adjacent Pole #6, near Pole #5. Similar charts at the other poles are provided in the Appendix.

During the testing on Day 2, 66% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. This percentage is slightly higher than on Day 1 without the RSS turned on. During the entire test period on Day 2, at Pole #6 within the work zone 18% of the vehicles were going faster than the posted speed limit, which is less than the 24% on Day 1. These results show that the RSS helped to decrease the percentage of vehicles travelling faster than the posted speed limit.

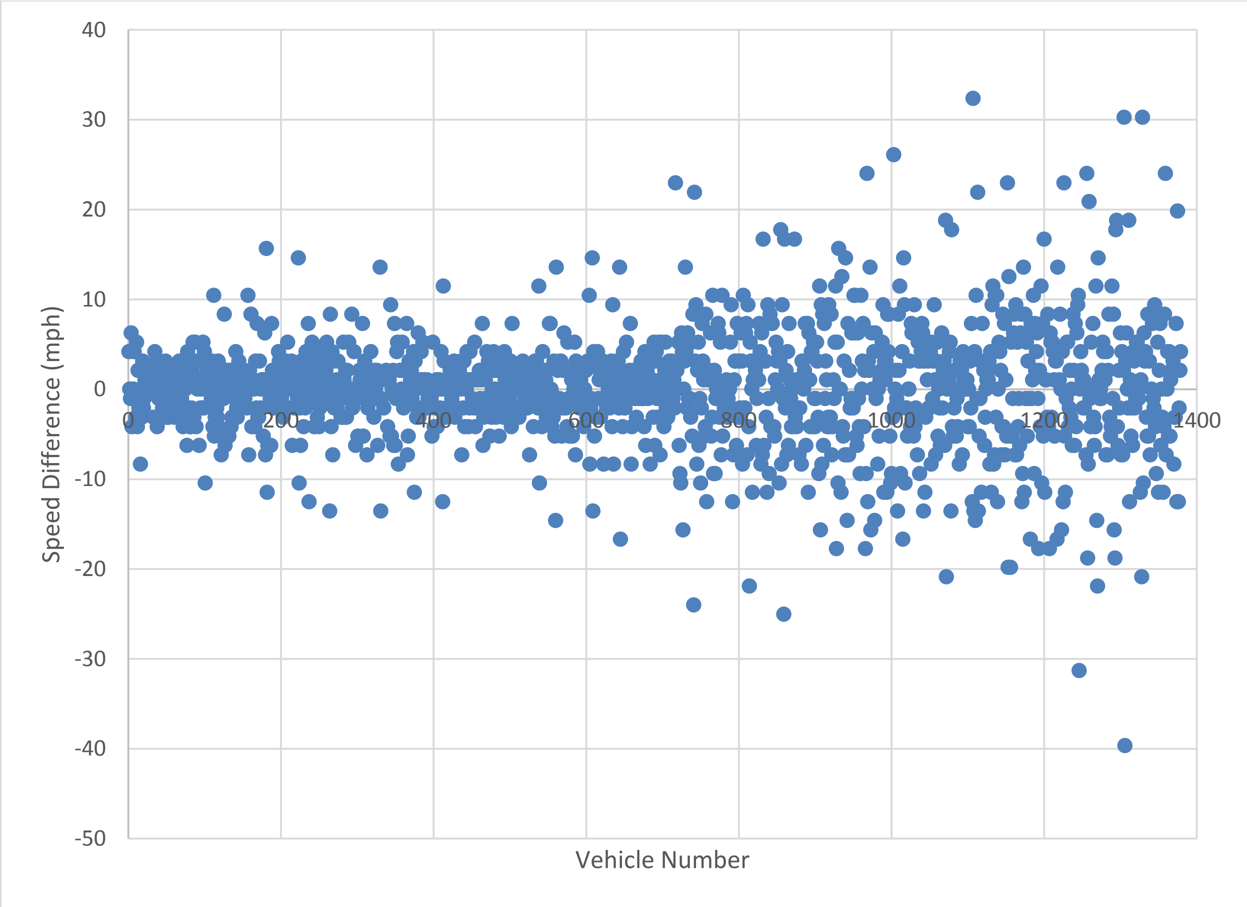


Figure 4.10: Speed Difference for Vehicles Passing Pole 6 during Operation Time, I-205, Relamping, With RSS (Day 2)

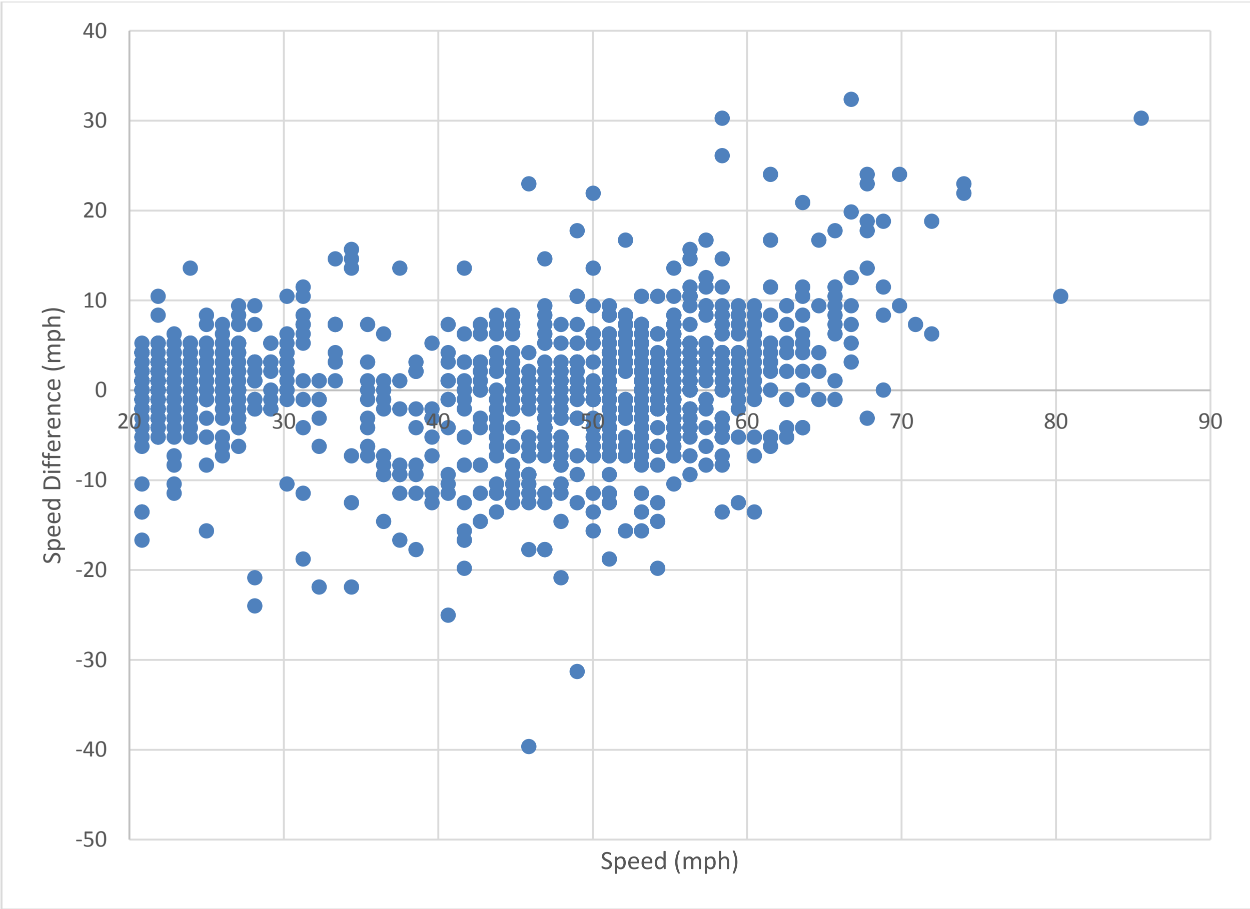


Figure 4.11: Speed Difference vs. Vehicle Speed for Vehicles Passing Pole 6 during Operation Time, I-205, Relamping, With RSS (Day 2)

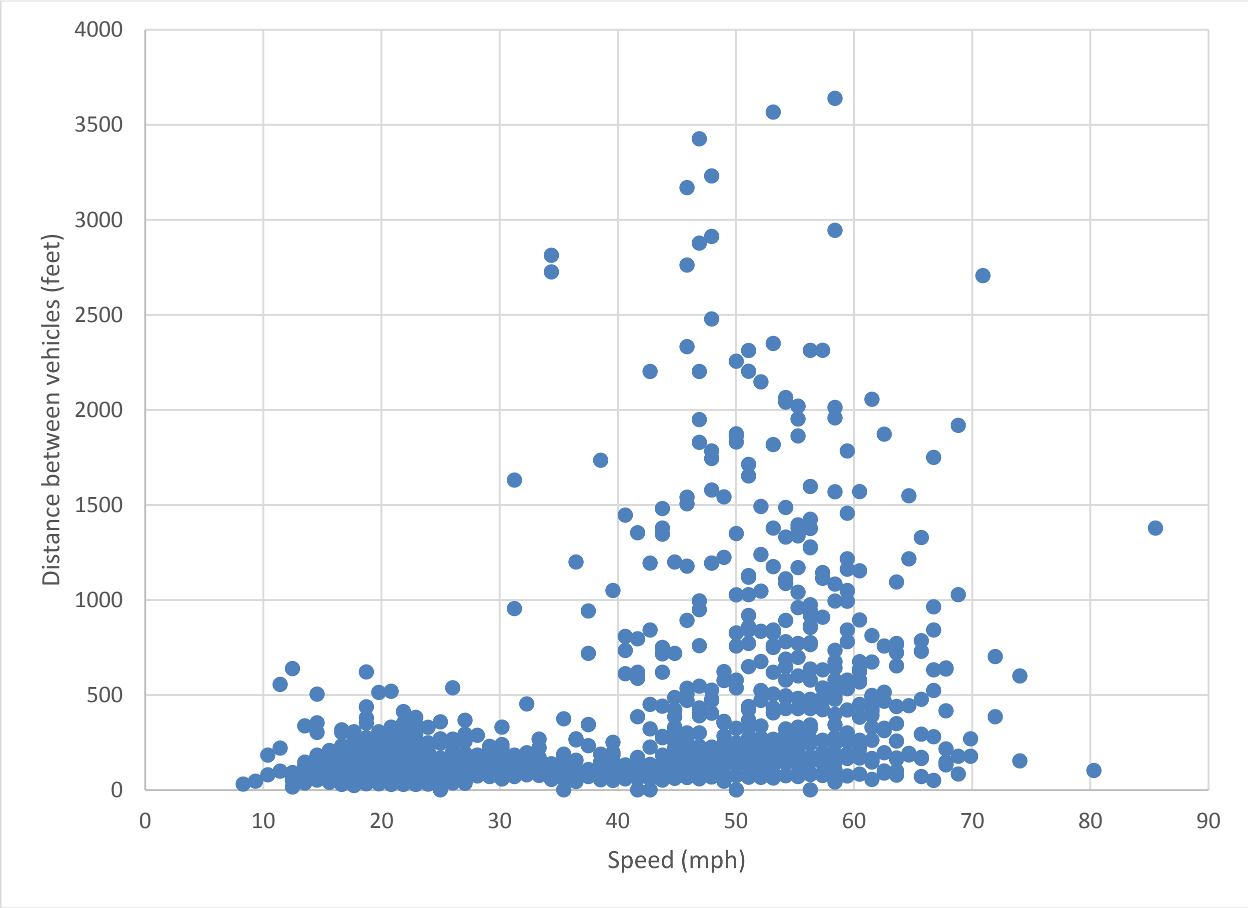


Figure 4.12: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Pole 6 during Operation Time, I-205, Relamping, With RSS (Day 2)

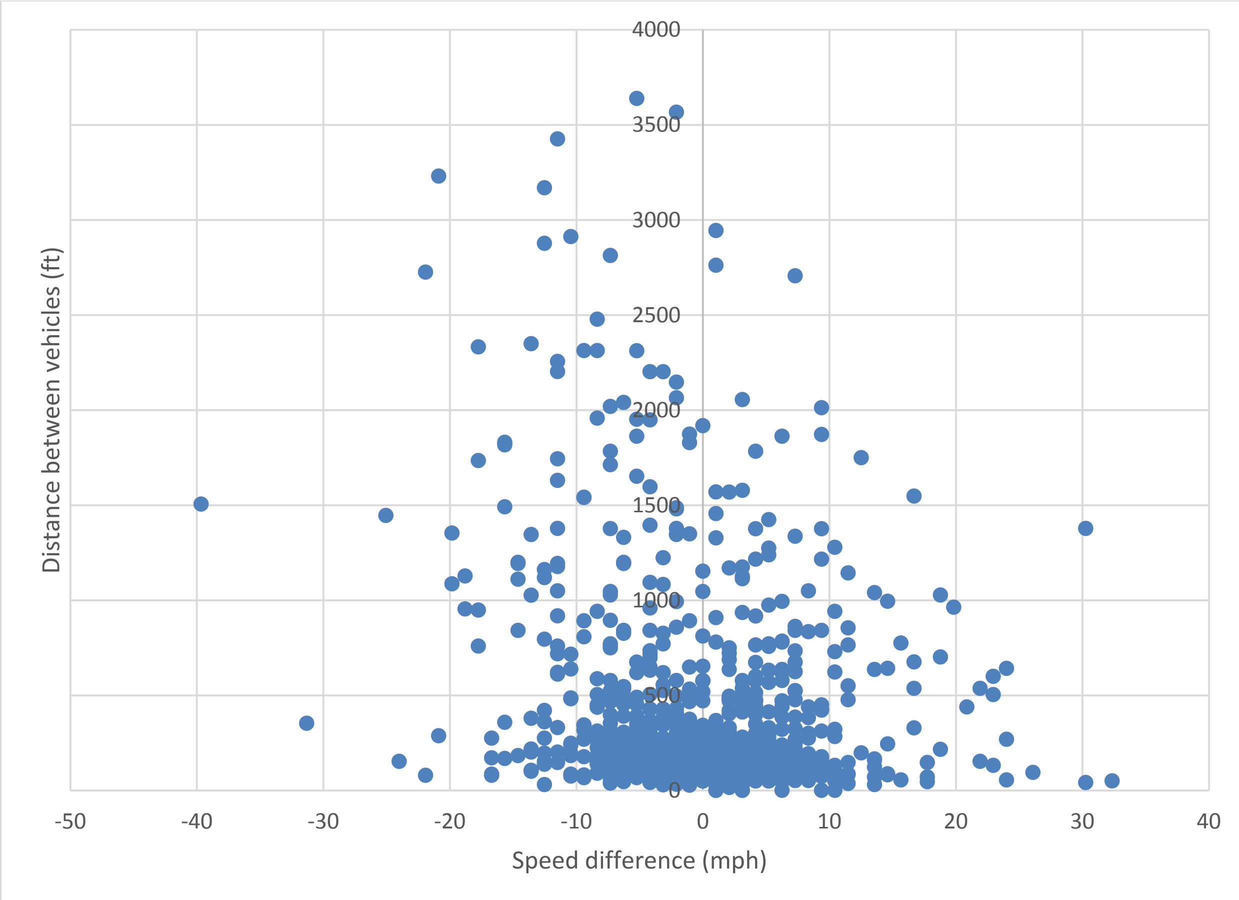


Figure 4.13: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Pole 6 during Operation Time, I-205, Relamping, With RSS (Day 2)

Statistical tools were used to analyze the treatment effect of implementing the RSS display. A two-sample t-test was conducted to determine whether turning on the RSS display has an effect on the speed difference. In the analysis, the absolute value of speed difference is used as the dependent variable. Absolute value is used due to the fact that, if the speed differences are added together, the negatives and positives will cancel each other and the mean of speed difference will be close to zero. The statistical test was conducted for all vehicles combined, for only passenger cars, and for only trucks. Table 4.9 summarizes the results. The data used to create the table consisted of all of the data recorded at Poles #5 (without RSS turned on) and #6 (with RSS turned on). Similar tables comparing the speed differences at other poles are provided in the Appendix.

Table 4.9: Effect of Radar Speed Sign on Absolute Value of Speed Differences between Adjacent Vehicles, I-205, Relamping, Pole 5 and Pole 6

Type of vehicle	Mean of absolute value of Speed difference (mph) without RSS (Day1)	Mean of absolute value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	6.27	4.36	1.91	0.0000
Passenger Cars	6.12	4.25	1.87	0.0000
Trucks	7.74	6.04	1.70	0.0464

For all vehicles, the RSS display turned on resulted in a 1.91 mph lower speed difference (p-value = 0.00). Therefore, there is statistically significant evidence that the mean of 6.27 mph without the RSS turned on and the mean of 4.36 mph with the RSS turned on are different. For passenger cars only, the p-value is 0.00 also, which indicates a difference in mean speeds when the RSS display is turned on compared to when the RSS is not used. For trucks, the p-value is 0.046, which indicates a difference as well. Overall, this test revealed that the RSS display has an impact on speed difference.

A second statistical analysis was performed using just the positive speed difference values, and omitting those with negative speed difference. Positive speed difference represents a vehicle that is driving faster than the vehicle in front of it. This situation is possibly hazardous as it can lead to rear-end crashes. The results of the analysis, shown in Table 4.10, are similar to the analysis using absolute value of speed differences. There is statistical evidence that the RSS display has an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it. This result is statistically significant (p = 0.00) for all vehicles combined and for just passenger cars (vehicles < 25 feet), and suggestive (p = 0.078) for trucks (vehicles > 25 feet).

Table 4.10: Effect of Radar Speed Sign on Vehicles with Positive Speed Differences between Adjacent Vehicles, I-205, Relamping, Pole 5 and Pole 6

Type of vehicle	Mean of positive value of Speed difference (mph) without RSS (Day1)	Mean of positive value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	6.68	4.73	1.95	0.0000
Passenger Cars	6.67	4.73	1.94	0.0000
Trucks	6.83	4.57	2.27	0.0777

Similar analyses were conducted using the distance between adjacent vehicles as the dependent variable to assess the impact of the treatment (use of RSS display). Table 4.11 shows the results of the analysis. For all vehicles and for just passenger cars, there is statistically significant evidence that the RSS display has an impact on the distance between adjacent vehicles (p = 0.00). However, the separate analyses based on different types of vehicles (passenger cars and trucks) show there is no treatment effect on trucks (p = 0.11). There is enough difference in mean distance for cars and compared to that for trucks to lead to a statistically significant result when all vehicles are combined; yet when cars and truck are analyzed separately, there is less evidence that the treatment was the sole factor impacting the difference in mean distances for trucks.

Table 4.11: Effect of Radar Speed Sign on Distance between Adjacent Vehicles, I-205, Relamping, Pole 5 and Pole 6

Type of vehicle	Mean of distance apart without RSS (feet)	Mean of distance apart with RSS (feet)	Difference in mean values (feet)	p-value
All Vehicles	516.55	313.08	203.48	0.0000
Passenger Cars	484.22	291.32	192.90	0.0000
Trucks	832.72	661.71	171.01	0.1143

Additional statistical tests were conducted to explore the effect of vehicle type on mean speed with and without the RSS display turned on. Table 4.12 shows the results of these tests. Similar to the tables above, the values shown in the table are calculated from all of the data recorded by the sensors at Pole #5 (Day 1 without the RSS turned on). The results suggest that vehicle type has an impact on the absolute value of speed difference and the distance between adjacent vehicles. Passenger cars have a lower speed difference and shorter distance to the vehicle in front of them. The p-values for both are very small, so the differences are statistically significant.

Table 4.12: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-205, Relamping, Without RSS (Day 1), Pole 5

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean absolute value of speed difference (mph)	6.12	7.74	1.62	0.0007
Mean positive speed difference (mph)	6.67	6.83	0.16	0.8330
Mean distance between adjacent vehicles (feet)	484.22	832.72	348.50	0.0000

Similarly, Table 4.13 shows the results for cars and trucks at Pole #6 with the RSS turned on (Day 2). The calculated p-values indicate a statistically significant difference between cars and trucks with respect to absolute value of speed difference and the distance between adjacent vehicles.

Table 4.13: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-205, Relamping, With RSS (Day 2), Pole 6

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean absolute value of speed difference (mph)	4.25	6.04	1.79	0.0008
Mean positive speed difference (mph)	4.73	4.57	0.17	0.8634
Mean distance between adjacent vehicles (feet)	291.32	661.71	370.39	0.0000

When the data at both Pole #5 and Pole #6 are combined, the differences between cars and trucks are shown in Table 4.14. The results are similar to that found in the tables above. In all cases, trucks have a higher mean speed difference and higher mean distance between adjacent vehicles. When designing traffic control measures for work zones, passenger cars and trucks should be considered separately. Passenger car speed relative to the speed of the vehicle in front of the car is not as great as that for trucks, yet the distance apart is shorter for cars. When designing traffic control plans, special consideration should be given to increasing the distance apart for passenger cars (e.g., minimize tailgating). Whereas for safety related to trucks, an emphasis should be placed on keeping the speeds of adjacent vehicles the same through the work zone.

Table 4.14: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-205, Relamping, With and Without RSS (Day 1 and 2), Pole 5 and Pole 6

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean absolute value of speed difference (mph)	5.24	7.14	1.90	0.0000
Mean positive speed difference (mph)	5.76	6.13	0.37	0.5481
Mean distance between adjacent vehicles (feet)	393.00	772.23	379.23	0.0000

Speeds of vehicles approaching the work operation are recorded by the radar unit attached to the RSS display. Tables 4.15 and 4.16 show the recorded speeds for vehicles approaching the equipment on Day 1 without the RSS display turned on (Table 4.15) and on Day 2 with the RSS display turned on (Table 4.16). Figure 4.14 shows these speeds in graphical format over the course of the test period. Note that the values will be different than those captured by the traffic analyzers since the RSS unit just records speeds upstream of the work equipment.

Table 4.15: Approaching Vehicle Speeds Recorded by Radar Speed Sign, I-205, Relamping, Without RSS (Day 1)

Speed / Time	11_15	16_20	21_25	26_30	31_35	36_40	40_45	46_50	51_55	56_60	61_65	66_70	71_75	76_80	81_85	86_90	91_95	96_100	Total	Median	Max	85th %ile
3/25/2015 22:05	0	0	0	4	24	15	24	34	13	0	0	0	0	0	0	0	0	0	114	33	59	52
3/25/2015 22:10	0	0	0	0	2	24	44	34	14	6	0	0	0	0	0	0	0	0	124	38	61	53
3/25/2015 22:15	0	0	1	0	0	24	31	19	37	8	7	0	0	0	0	0	0	0	127	41	68	57
3/25/2015 22:20	0	0	0	0	0	14	40	61	9	1	3	0	0	0	0	0	0	0	128	41	69	53
3/25/2015 22:25	0	0	0	0	2	7	35	47	37	3	0	0	0	0	0	0	0	0	131	40	63	56
3/25/2015 22:30	0	0	0	0	3	7	11	42	37	16	2	0	0	0	0	0	0	0	118	39	66	58
3/25/2015 22:35	0	0	0	0	1	5	23	53	35	2	0	0	0	0	0	0	0	0	119	35	62	56
3/25/2015 22:40	0	0	1	6	8	13	27	27	29	14	0	0	0	0	0	0	0	0	125	30	64	56
3/25/2015 22:45	0	0	0	0	3	5	48	42	15	1	0	0	0	0	0	0	0	0	114	39	64	53
3/25/2015 22:50	0	0	0	0	2	15	28	58	25	1	0	0	0	0	0	0	0	0	129	40	61	54
3/25/2015 22:55	0	0	0	0	1	13	26	54	26	6	0	0	0	0	0	0	0	0	126	40	62	55
3/25/2015 23:00	0	0	0	2	2	18	28	36	26	6	0	0	0	0	0	0	0	0	118	35	62	55
Total	0	0	2	12	48	160	365	507	303	64	12	0	0	0	0	0	0	0	1473	36	69	55
3/25/2015 23:05	0	0	0	5	7	14	23	25	9	7	0	0	0	0	0	0	0	0	90	31	63	53
3/25/2015 23:10	0	0	3	7	4	36	19	19	12	3	0	0	0	0	0	0	0	0	103	27	65	51
3/25/2015 23:15	0	0	0	5	22	31	31	18	8	2	0	0	0	0	0	0	0	0	117	31	64	49
3/25/2015 23:20	0	0	0	6	4	14	49	29	12	3	0	0	0	0	0	0	0	0	117	31	62	52
3/25/2015 23:25	0	0	0	11	15	19	22	18	13	1	0	0	0	0	0	0	0	0	99	31	61	51
3/25/2015 23:30	0	0	0	3	13	16	34	24	9	2	7	0	0	0	0	0	0	0	108	34	70	53
3/25/2015 23:35	0	0	4	18	7	11	15	19	6	5	0	0	0	0	0	0	0	0	85	25	61	52
3/25/2015 23:40	0	0	0	1	2	12	27	30	25	1	0	0	0	0	0	0	0	0	98	38	62	55
3/25/2015 23:45	0	0	0	4	3	12	33	28	18	1	1	0	0	0	0	0	0	0	100	32	66	54
3/25/2015 23:50	0	0	0	0	2	7	19	29	26	4	1	0	0	0	0	0	0	0	88	40	67	56
3/25/2015 23:55	0	0	2	5	7	15	16	32	9	7	0	0	0	0	0	0	0	0	93	25	63	54
3/26/2015 0:00	0	0	0	3	5	11	31	38	21	3	0	0	0	0	0	0	0	0	112	34	65	54
Total	0	0	9	68	91	198	319	309	168	39	9	0	0	0	0	0	0	0	1210	31	70	53
3/26/2015 0:05	0	0	0	0	2	3	5	16	35	17	6	0	0	0	0	0	0	0	84	35	63	55
3/26/2015 0:10	0	0	0	0	3	5	6	14	26	15	10	0	0	0	0	0	0	0	79	30	64	56
3/26/2015 0:15	0	0	0	8	30	44	3	0	1	3	0	0	2	2	3	6	13	2	117	25	97	40
3/26/2015 0:20	0	0	1	0	2	3	3	7	18	23	9	1	0	0	0	0	0	0	67	30	67	58
3/26/2015 0:25	0	0	0	0	1	2	10	17	18	18	8	11	10	0	0	0	0	1	96	38	112	62
3/26/2015 0:30	0	0	0	1	0	1	4	7	12	24	31	25	11	0	0	0	0	0	116	40	75	66
3/26/2015 0:35	0	0	0	0	1	2	1	3	16	11	29	13	2	0	0	0	0	0	78	38	73	64
3/26/2015 0:40	0	0	0	4	4	6	3	10	27	15	23	19	3	0	0	0	0	0	114	29	71	63
3/26/2015 0:45	0	0	0	1	1	3	9	21	16	2	0	0	2	1	0	0	2	1	59	25	128	54
3/26/2015 0:50	0	0	0	0	0	1	6	7	11	16	24	8	6	2	0	0	0	1	82	42	96	64
3/26/2015 0:55	0	0	3	2	2	5	12	11	9	23	4	4	3	6	4	3	3	2	96	22	98	60
3/26/2015 1:00	0	1	0	0	1	11	29	21	21	11	3	0	0	0	0	0	0	0	98	35	65	52
Total	0	1	4	16	47	86	91	134	210	178	147	81	39	11	7	9	18	7	1086	30	128	61

Table 4.16: Approaching Vehicle Speeds Recorded by Radar Speed Sign, I-205, Relamping, With RSS (Day 2)

Speed / Time	11_15	16_20	21_25	26_30	31_35	36_40	40_45	46_50	51_55	56_60	61_65	66_70	71_75	76_80	81_85	86_90	91_95	96_100	Total	Median	Max	85th %ile
3/26/2015 22:05	0	0	0	0	1	5	17	33	31	37	1	0	0	0	0	0	0	0	125	35	63	55
3/26/2015 22:10	0	0	0	0	6	6	23	44	40	8	0	0	0	0	0	0	0	0	127	33	59	52
3/26/2015 22:15	0	1	1	0	2	10	17	33	40	15	1	0	0	0	0	0	0	0	120	33	61	53
3/26/2015 22:20	0	0	0	1	4	3	20	44	34	11	0	0	0	0	0	0	0	0	117	30	60	52
3/26/2015 22:25	0	0	0	1	3	4	3	38	26	23	9	6	0	0	0	0	0	0	113	30	70	56
3/26/2015 22:30	0	0	0	3	7	13	33	22	20	16	3	0	0	0	0	0	0	0	117	30	65	51
3/26/2015 22:35	0	0	0	0	5	6	9	16	34	17	11	1	0	0	0	0	0	0	99	30	66	55
3/26/2015 22:40	0	1	0	0	2	2	5	22	31	20	8	0	0	0	0	0	0	0	91	30	64	56
3/26/2015 22:45	0	1	0	1	6	14	38	33	24	2	2	0	0	0	0	0	0	0	121	30	64	49
3/26/2015 22:50	0	1	1	4	5	10	15	14	30	22	6	2	0	0	0	0	0	0	110	20	67	55
3/26/2015 22:55	0	0	0	4	4	12	21	29	14	8	4	0	0	0	0	0	0	0	96	28	65	50
3/26/2015 23:00	0	0	0	0	0	3	5	20	40	35	7	1	0	0	0	0	0	0	111	40	67	57
Total	0	4	2	14	45	88	206	348	364	214	52	10	0	0	0	0	0	0	1347	31	70	54
3/26/2015 23:05	0	0	0	2	5	6	20	12	27	22	3	0	0	0	3	0	0	0	100	30	84	55
3/26/2015 23:10	0	0	0	2	10	3	7	16	31	25	7	0	0	0	0	0	0	0	101	28	61	56
3/26/2015 23:15	0	0	1	4	4	11	15	35	36	18	2	0	0	0	0	0	0	0	126	27	63	53
3/26/2015 23:20	0	0	0	0	1	8	8	30	39	16	6	0	0	0	0	0	0	0	108	36	65	54
3/26/2015 23:25	0	0	0	4	4	7	6	8	10	22	28	15	6	6	2	1	0	0	119	30	87	65
3/26/2015 23:30	0	0	0	0	1	2	22	9	13	19	22	15	5	0	0	0	0	0	108	38	73	63
3/26/2015 23:35	0	0	0	0	0	2	2	3	12	15	17	22	17	4	0	0	0	0	94	43	76	69
3/26/2015 23:40	0	0	0	0	0	0	0	2	14	34	29	11	0	0	0	0	0	0	90	51	69	63
3/26/2015 23:45	0	0	0	0	3	2	1	13	33	43	25	5	4	1	0	0	0	0	130	35	77	60
3/26/2015 23:50	0	0	0	2	1	6	11	6	27	7	3	1	0	1	0	0	0	0	65	25	119	54
3/26/2015 23:55	0	2	0	0	0	0	5	20	50	23	5	1	0	0	0	0	0	0	106	15	68	55
3/27/2015 0:00	0	0	1	0	1	1	3	1	5	16	12	3	1	4	6	1	4	9	68	35	115	85
Total	0	2	2	14	30	48	100	155	297	260	159	73	33	16	11	2	4	9	1215	32	119	60

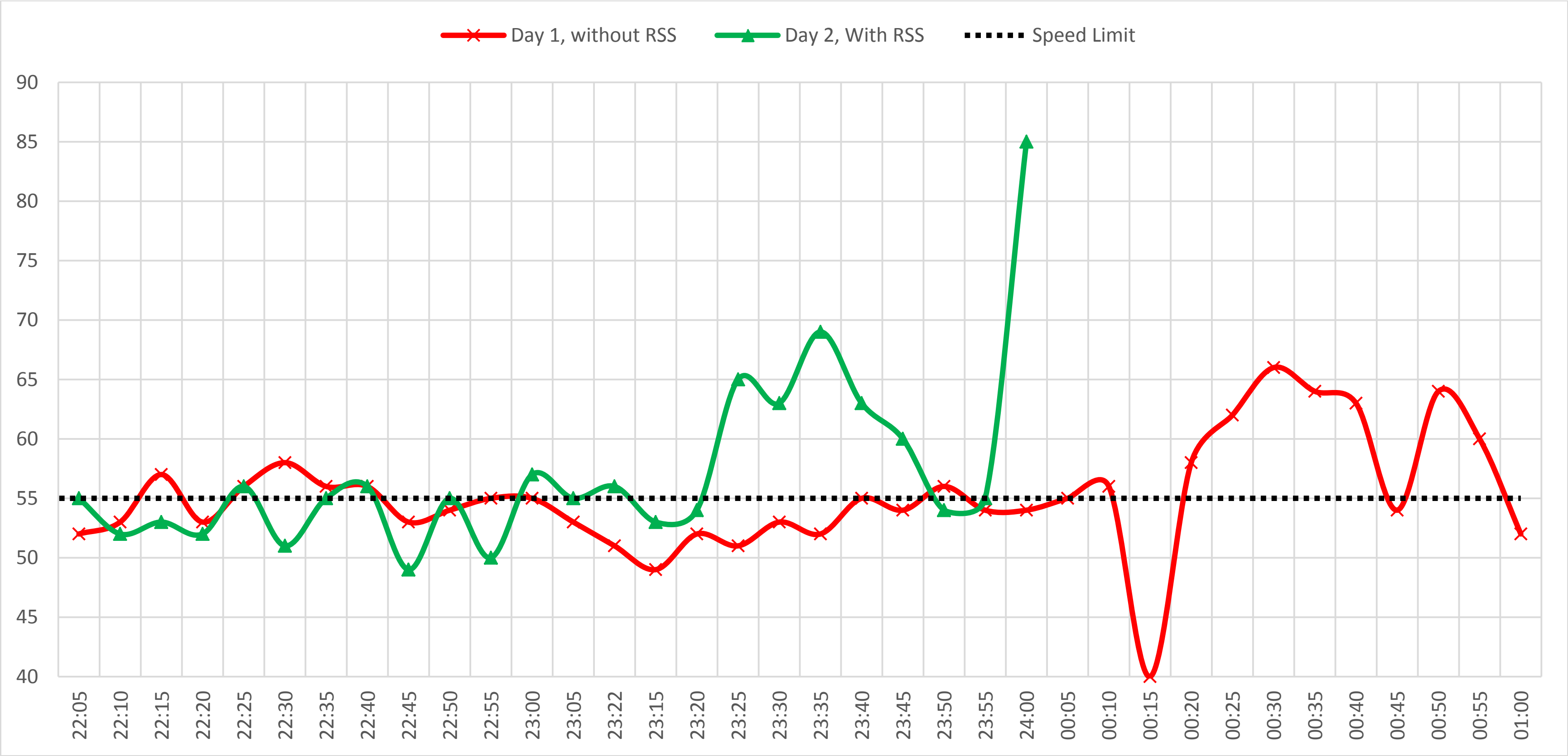


Figure 4.14: Approaching Vehicle Speed Recorded by Radar Speed Sign, I-205, Relamping

Lastly, the researchers performed multiple probe vehicle passes through the work zones on both Day 1 and Day 2 to monitor the nature of the traffic throughout the entire length of the work zone. Figure 4.15 shows an example of the speeds recorded by the probe vehicle on Day 1 without the RSS turned on when the work operation was located at Pole #1. The figure shows that the probe vehicle speeds in the work zone were near the 55 mph speed limit. Figure 4.16 shows a similar chart on Day 2 with the RSS turned on when the work operation was located at Pole #6. The queuing that occurred on Day 2 is noticeable in the figure.

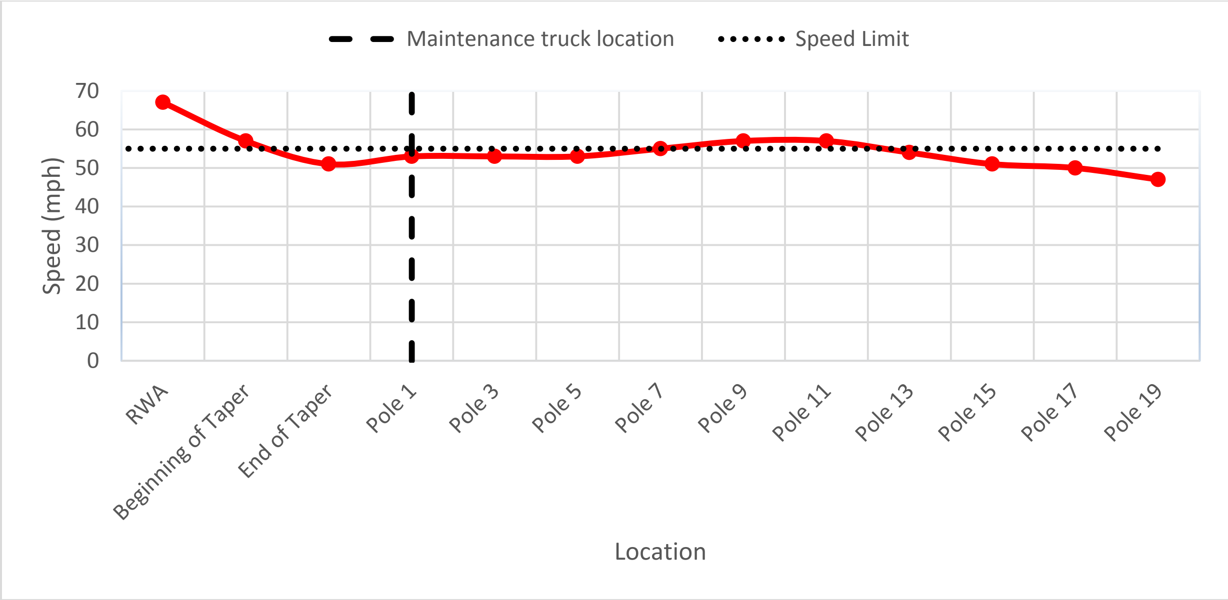


Figure 4.15: Probe Vehicle, I-205, Relamping, Without RSS (Day 1)

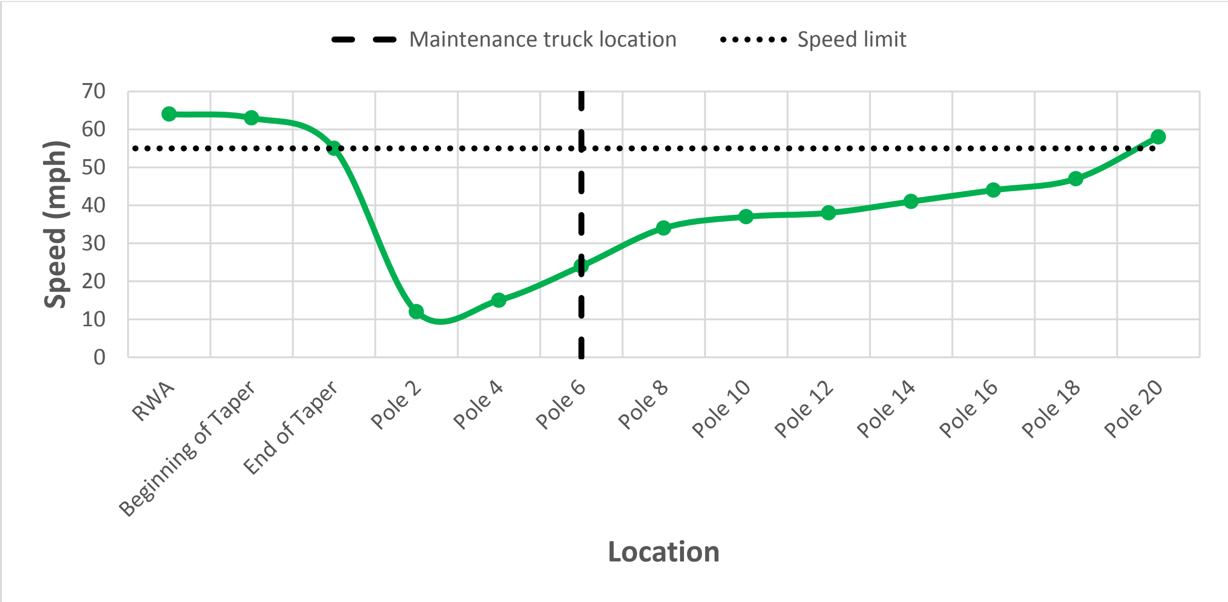


Figure 4.16: Probe Vehicle, I-205, Relamping, With RSS (Day 2)

4.2 CASE STUDY#2: I-205 SWEEPING

This section of the report presents the results and analysis of the data collected during the sweeping operation on I-205 (Case Study #2). The tables and figures provided in this section are similar to that provided for Case Study #1 above. Discussion of the results shown in each table and figure are also similar to that for Case Study #1 above, and repeated here for clarity. Modifications to the discussion are made to reflect the Case Study #2 data. Only summary tables and figures are provided and discussed below; additional tables and figures related to Case Study #2 are provided in the Appendix.

Figure 4.17 presents the recorded traffic volumes during the testing periods on the day of testing. The duration of each period is different. The duration of the first period without the RSS turned on and the first free flow were significantly greater than the later periods. Therefore, the traffic volumes are expected to be different. Total traffic volumes decreased during the course of the testing. In addition, the percentage of cars (vehicles < 25 feet in length) and percentage of trucks (vehicles > 25 feet in length) are approximately the same during each test period. Based on the traffic volumes recorded during each time period, and considering the difference in duration of each time period, no meaningful impact due to a difference in traffic volumes between the control (without RSS turned on) and treatment (with RSS turned on) periods is expected.

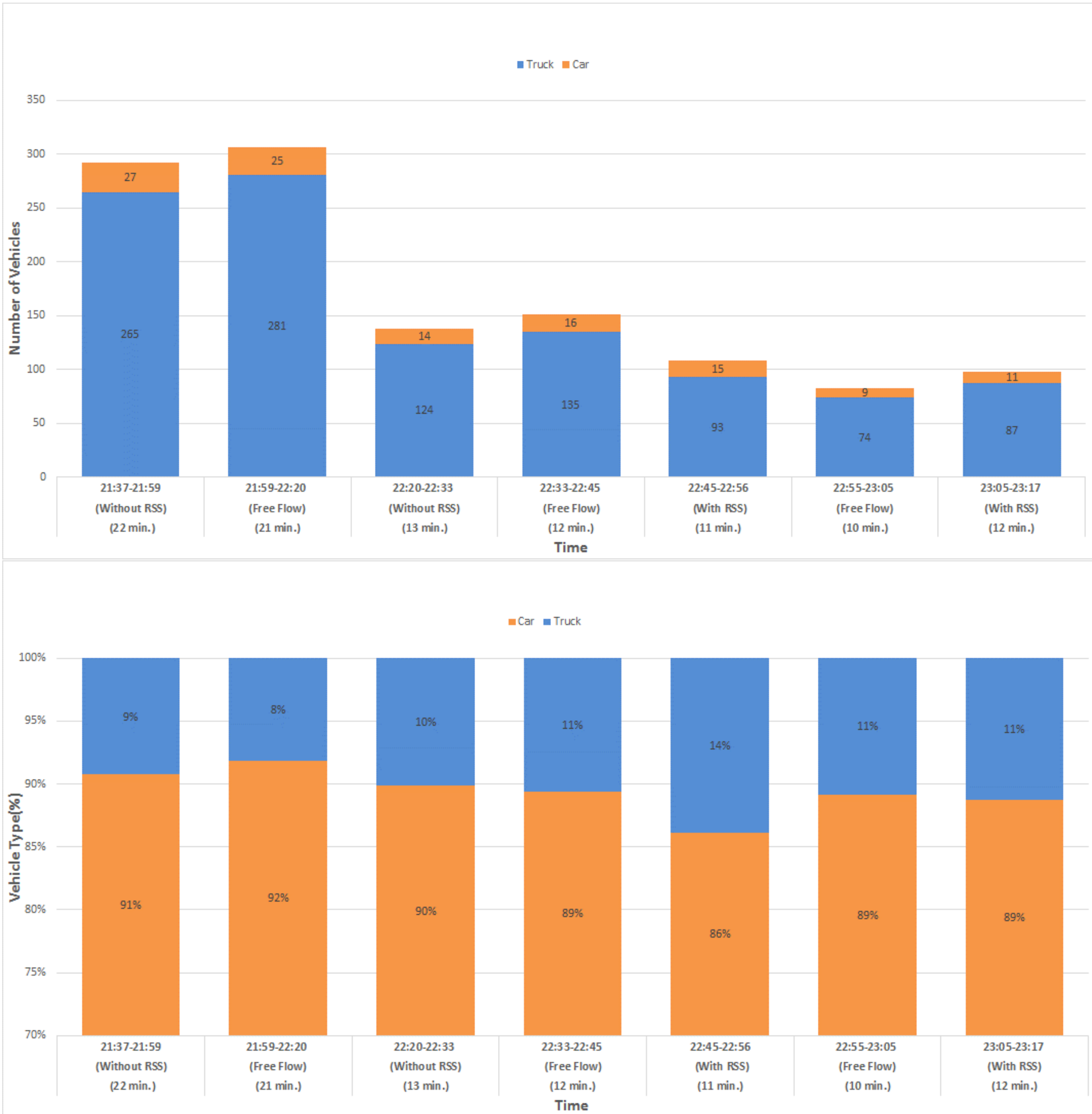


Figure 4.17: Traffic Volume, Number of Vehicles, and Vehicle Type Percentage, I-205, Sweeping, Pole 10

Table 4.17 presents a summary of the vehicle speeds recorded for all vehicles at the RWA sign location during the testing period. For this table, the values represent the data downloaded from the sensors in both the A and B lanes. The 85th percentile speed for all three timeframes (without RSS turned on, free flow, and with RSS turned on) was the same at 66.7 mph. Similarly, Table 4.18 shows a summary of the vehicle speeds over the same period recorded in the work area, specifically at Pole #10. The 85th percentile speed decreased to 62.9 mph without the RSS turned on and 60.7 mph with the RSS turned on at this location.

Table 4.17: Hourly Summary of Vehicle Speed, I-205, Sweeping, RWA

	Time									
Vehicle Speed (all vehicles)	Total (without RSS)	Total (Free Flow)	Total (with RSS)	21:37-21:59 (without RSS)	21:59-22:20 (Free Flow)	22:20-22:33 (without RSS)	22:33-22:45 (Free Flow)	22:45-22:56 (with RSS)	22:55-23:05 (Free Flow)	23:05-23:17 (with RSS)
MPH										
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	0.0%	0.2%	0.6%	0.0%	0.4%	0.0%	0.0%	1.0%	0.0%	0.0%
35-39	0.0%	0.8%	0.0%	0.0%	0.4%	0.0%	0.7%	0.0%	2.5%	0.0%
40-44	0.5%	1.5%	1.7%	0.4%	1.1%	0.8%	2.2%	1.0%	1.2%	2.4%
45-49	6.4%	4.2%	3.4%	6.4%	1.9%	6.3%	5.9%	5.2%	8.6%	1.2%
50-54	12.8%	14.2%	11.2%	12.8%	14.9%	12.7%	14.0%	12.5%	12.3%	9.8%
55-59	30.9%	28.7%	27.5%	28.9%	30.7%	34.9%	25.7%	31.3%	27.2%	23.2%
60-64	30.4%	29.9%	33.1%	30.1%	31.0%	31.0%	29.4%	27.1%	27.2%	40.2%
65-69	11.5%	13.6%	12.4%	11.7%	11.5%	11.1%	16.9%	11.5%	14.8%	13.4%
70-74	4.1%	4.0%	4.5%	4.9%	4.6%	2.4%	3.7%	4.2%	2.5%	4.9%
>=75	3.6%	2.9%	5.6%	4.9%	3.4%	0.8%	1.5%	6.3%	3.7%	4.9%
Total # of vehicles	392	478	178	266	261	126	136	96	81	82
Average speed	60.3	59.9	61.2	60.6	60.1	59.5	59.7	60.7	59.4	61.6
St. Dev.	7.1	7.1	7.7	7.5	6.8	6.2	7.2	8.4	7.9	6.8
85th percentile	66.7	66.7	66.7	67.6	65.8	64.9	66.7	67.4	66.7	66.7
Min	43.6	31.6	33.4	43.6	31.6	43.8	35.3	33.4	39.0	40.7
Max	88.0	81.5	86.1	88.0	81.5	82.4	77.2	86.1	77.2	80.6
Range	44.4	50.0	52.7	44.4	50.0	38.7	41.9	52.7	38.2	39.9

Table 4.18: Hourly Summary of Vehicle Speed, I-205, Sweeping, Pole 10

	Time									
Vehicle Speed (all vehicles)	Total (without RSS)	Total (Free Flow)	Total (with RSS)	21:37-21:59 (without RSS)	21:59-22:20 (Free Flow)	22:20-22:33 (without RSS)	22:33-22:45 (Free Flow)	22:45-22:56 (with RSS)	22:55-23:05 (Free Flow)	23:05-23:17 (with RSS)
MPH										
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.7%	0.2%	1.0%	0.7%	0.3%	0.7%	0.0%	0.0%	0.0%	2.0%
30-34	0.9%	0.0%	1.5%	1.4%	0.0%	0.0%	0.0%	0.9%	0.0%	2.0%
35-39	2.8%	0.6%	5.8%	3.1%	0.0%	2.2%	1.3%	2.8%	1.2%	9.2%
40-44	7.9%	0.9%	13.6%	7.9%	0.7%	8.0%	1.3%	13.9%	1.2%	13.3%
45-49	15.6%	4.1%	14.1%	13.0%	3.3%	21.0%	4.0%	15.7%	7.2%	12.2%
50-54	19.5%	10.9%	18.0%	17.8%	11.1%	23.2%	9.3%	25.0%	13.3%	10.2%
55-59	26.3%	35.0%	27.7%	29.1%	31.7%	20.3%	39.7%	24.1%	38.6%	31.6%
60-64	15.6%	30.2%	12.1%	16.4%	35.6%	13.8%	23.8%	10.2%	21.7%	14.3%
65-69	8.6%	13.9%	5.3%	9.6%	13.4%	6.5%	15.2%	5.6%	13.3%	5.1%
70-74	2.1%	3.0%	0.5%	1.0%	2.6%	4.3%	4.0%	0.9%	2.4%	0.0%
>=75	0.0%	1.3%	0.5%	0.0%	1.3%	0.0%	1.3%	0.9%	1.2%	0.0%
Total # of vehicles	430	540	206	292	306	138	151	108	83	98
Average speed	54.6	59.7	52.6	54.8	60.1	54.3	59.6	53.1	58.4	52.0
St. Dev.	8.4	6.3	8.8	8.4	5.9	8.3	6.6	8.0	6.8	9.5
85th percentile	62.9	65.4	60.7	62.6	65.2	62.9	66.2	60.4	65.3	60.7
Min	25.1	25.8	25.9	25.1	25.8	29.3	38.5	32.6	38.5	25.9
Max	71.5	79.5	76.3	70.6	79.5	71.5	76.3	76.3	78.9	68.8
Range	46.4	53.7	50.4	45.5	53.7	42.2	37.8	43.7	40.4	42.9

Similar to Case Study #1, the traffic analyzers also provided the opportunity to view the vehicle speeds at various locations through the work zone. Figure 4.18 shows how the 85th percentile speed changed from the RWA signs to the end of the work zone at Pole #20 for all cases (with and without RSS turned on, and free flow). As seen in the figure, for much of the work zone, the speeds with the RSS turned on were lower than without the RSS turned on. This difference ranged from approximately 1 to 3 mph.

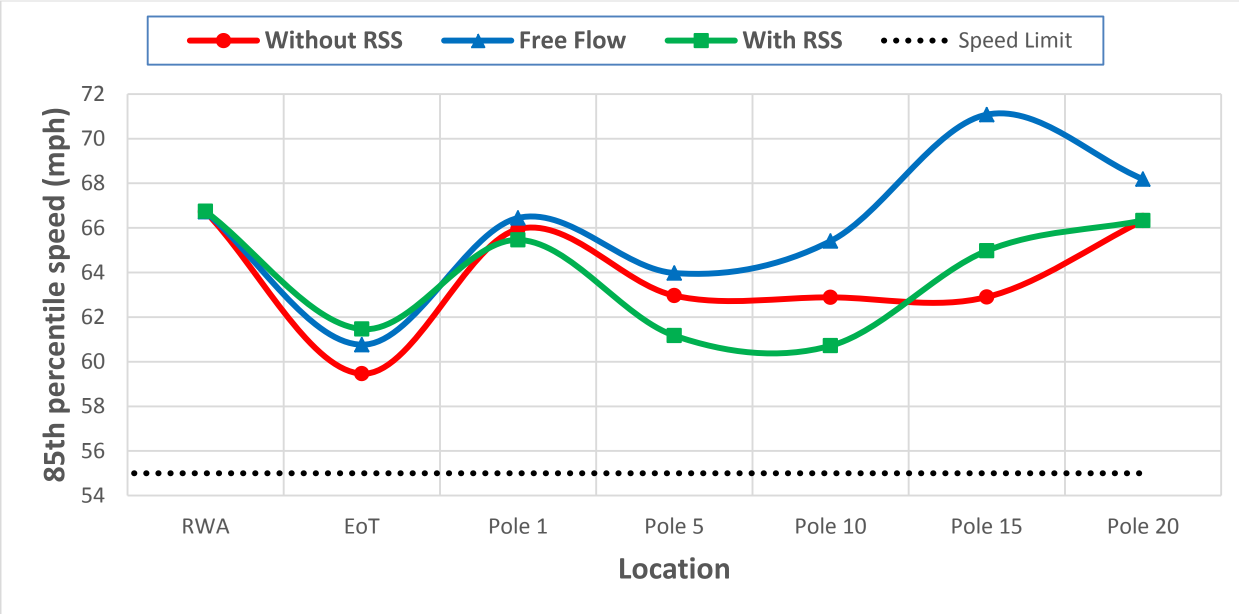


Figure 4.18: Vehicle Speed (85th percentile) at Different Locations during Operation Time, I-205, Sweeping

It is likely that the speed in the work zone, at least in the initial portion of the work zone, depends on the speed of the vehicles prior to the work zone. Figure 4.19 shows the 85th percentile speeds at the RWA signs throughout the testing period. Similarly, Figure 4.20 shows the 85th percentile speeds at Pole #10 during the testing period. Compared to speeds at the RWA signs, in the work zone the speed were consistently lower during all periods of the testing (with and without RSS turned on, and free flow). Additionally, Figure 4.20 shows that with the RSS turned on, the 85th percentile speed was consistently lower (by about 2 – 2.5 mph) than without the RSS turned on over the course of the testing time period. Free flow speeds while the sweeping equipment was returning to the start of the work area to make another pass were always higher than the periods when the sweeping operation was taking place.

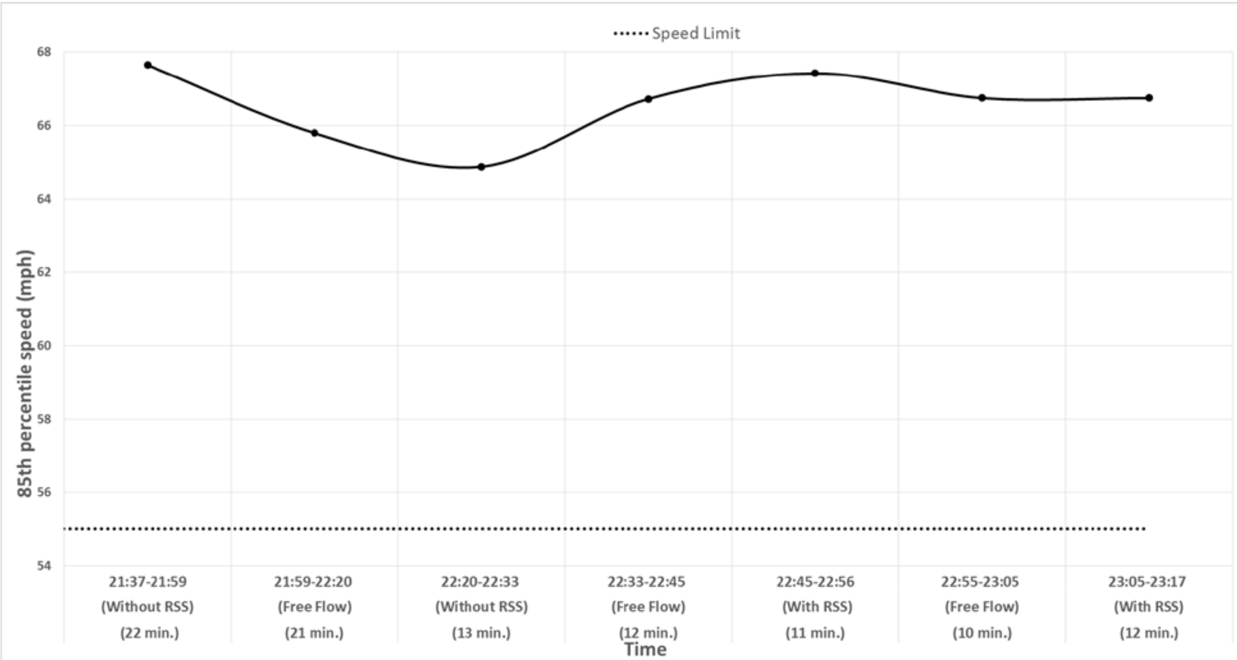


Figure 4.19: Vehicle Speed (85th Percentile) at RWA during Operation Time, I-205, Sweeping

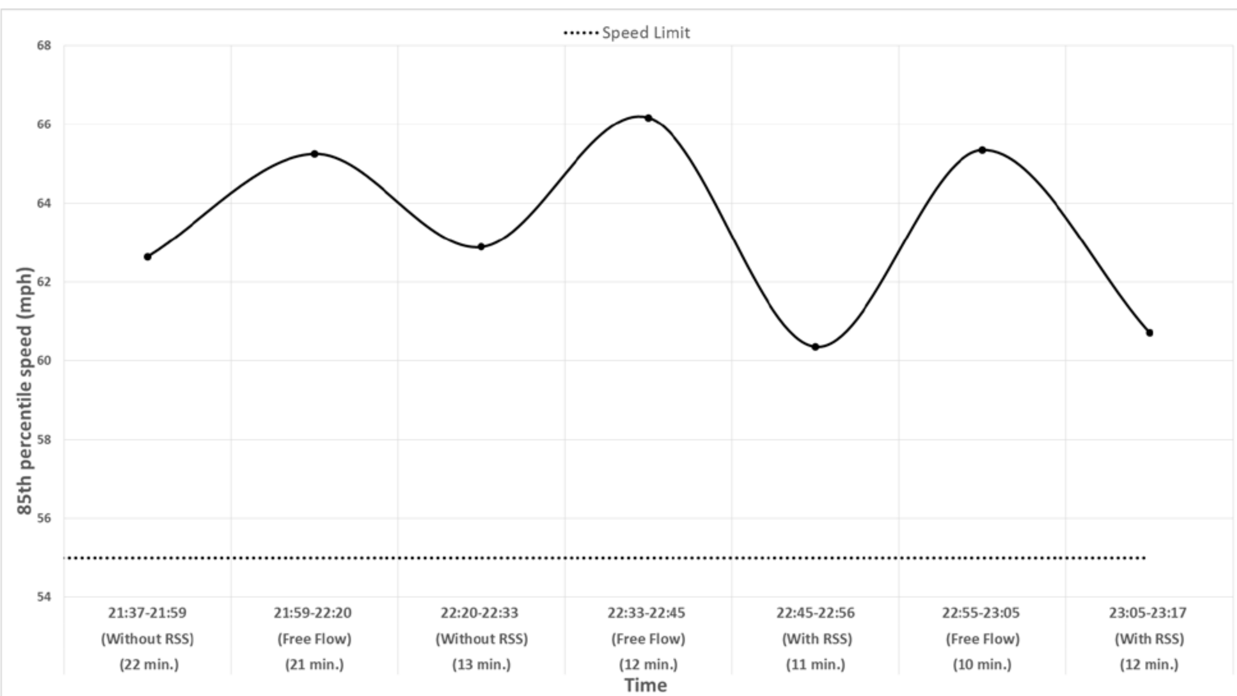


Figure 4.20: Vehicle Speed (85th Percentile) at Pole 10 during Operation Time, I-205, Sweeping

Similar to Case Study #1, as part of the data analysis, comparisons were made between the vehicle speeds during the different work periods. Figure 4.21 shows a comparison of 85th percentile speeds at Pole #10 with and without the RSS turned on. Pole #10 was selected for illustration purposes only; similar charts showing comparisons for other poles are provided in the Appendix. The figure illustrates the effect of the presence of the work equipment at Pole #10.

The vehicles slow down as they approach the work operation and then speed up afterwards. Over the same distance, the amount of decrease was greater with the RSS display turned on. For example, from Pole #1 to Pole #10, the speeds decreased from approximately 67 to 55 mph (12 mph decrease) with the RSS turned on, and from approximately 64 to 55 mph (9 mph decrease) without the RSS turned on.

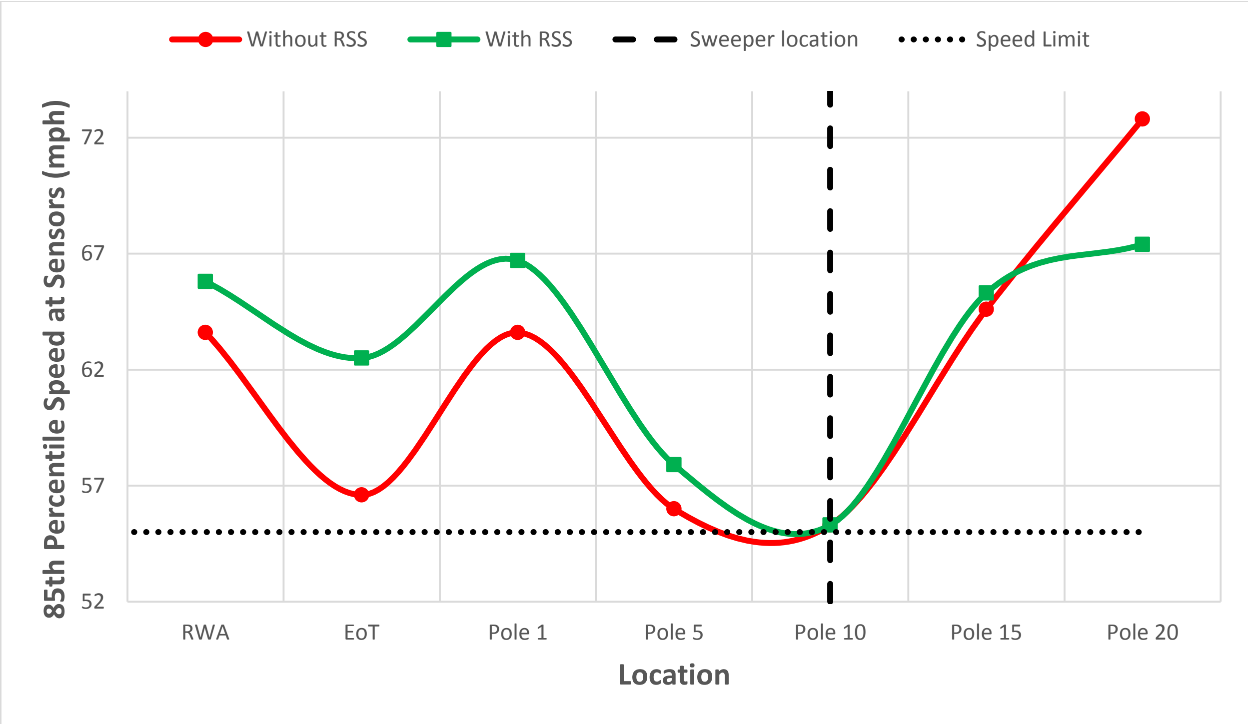


Figure 4.21: 85th Percentile Speed at Different Distances from the Operation, I-205, Sweeping, Pole 10

The vehicle speed data collected enables calculating the amount of decrease in speed from the RWA signs to the work zone for both periods of testing. For this analysis, the speeds in the work zone (WZ) were those recorded by all of the traffic sensors adjacent all of the light poles. Table 4.19 shows this comparison. For all vehicles, mean speed decreased from 60.3 mph at the RWA signs to 55.7 mph in the work zone, a 7.6% decrease, without the RSS turned on. During the work periods with the RSS turned on, the amount of decrease for all vehicles was greater at 12%. In addition, the magnitude of the mean speed in the work zone was less. When analyzing cars and truck separately, similar results were found: the percentage decrease in mean speed was greater with the RSS turned on.

Table 4.19: Percentage of Vehicle Speed Decrease in the Work Zone Area, I-205, Sweeping

Type of vehicle	Mean Speed (mph) without RSS at RWA	Mean Speed (mph) without RSS at WZ	Decrease in mean speed (%) without RSS	Mean Speed (mph) with RSS at RWA	Mean Speed (mph) with RSS at WZ	Decrease in mean speed (%) with RSS
All Vehicles	60.3	55.7	7.63%	61.6	54.2	12%
Passenger Cars	60.6	56.1	7.43%	61.4	54.4	11%
Trucks	56.8	54.5	4.05%	59.4	52.4	12%

Table 4.20 shows an additional comparison of mean speeds, this time just comparing the speeds within the work zone adjacent the poles. For all vehicles, the mean speed in the WZ during the periods without the RSS turned on was 55.6 mph and the mean speed in the WZ with the RSS turned on was 54.8 mph, a difference of 0.79 mph. This difference was found to be statistically significant (p = 0.029). Suggestive evidence of a difference in mean speeds was found for cars (p = 0.058), while no difference was found for trucks (p = 0.360). For this case study, the amount of difference in the mean speeds was less for cars (0.71 mph) than for trucks (1.15 mph).

Table 4.20: Effect of Radar Speed Sign on Vehicle Speed, I-205, Sweeping

Type of vehicle	Mean Speed (mph) without RSS	Mean Speed (mph) with RSS	Difference in mean speed (mph)	p-value
All Vehicles	55.57	54.78	0.79	0.0290
Passenger Cars	55.79	55.08	0.71	0.0579
Trucks	53.57	52.42	1.15	0.3604

Expanded comparisons of the vehicle speeds are shown in Tables 4.21 and 4.22. The tables show the speed data at the RWA signs and at Pole #10, respectively. Similar tables for other poles are provided in the Appendix. As seen in Table 4.22, the mean and 85th percentile speeds at Pole #10 are approximately 1 to 2 mph less with the RSS turned on for all vehicles combined and for just passenger cars. For just trucks, the difference is greater.

For this case study, as noted previously, the testing with the RSS turned on occurred slightly later in the evening than the testing without the RSS turned on. As a result, the volume of traffic was less with the RSS turned on as shown in the tables. The decreased volume may have an impact on vehicle speeds as well. It should be noted also that the standard deviation for all vehicles combined and for just passenger cars was found to be greater with the RSS turned on. However, for trucks, the standard deviation was less with the RSS turned on. For this case study, the variation in truck speeds was less with the RSS turned on than without the RSS turned on.

Table 4.21: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, I-205, Sweeping, RWA

Test	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Without RSS	359	66.73	60.6	7.1	33	64.87	56.8	7.0	392	60.26	66.7	7.1
With RSS	160	66.88	61.4	7.8	18	62.42	59.4	6.9	178	61.15	66.7	7.7

Table 4.22: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, I-205, Sweeping, Pole 10

Test	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Without RSS	389	62.89	54.8	8.2	41	63.73	52.7	9.3	430	62.89	54.6	8.4
With RSS	180	61.20	53.5	8.6	26	53.85	46.2	7.1	206	60.72	52.6	8.8

As with Case Study #1, analyses were also conducted that focused on the difference in speed between adjacent vehicles and the travel distance between adjacent vehicles as they passed through the work zone. Figure 4.22 shows the speed difference for vehicles passing Pole #10 during the work operation time without the RSS turned on. Each dot in the figure represents one vehicle. As seen in the figure, the speed differences vary significantly, with a range of approximately -20 mph to +20 mph, and no particular trend in the data is visible.

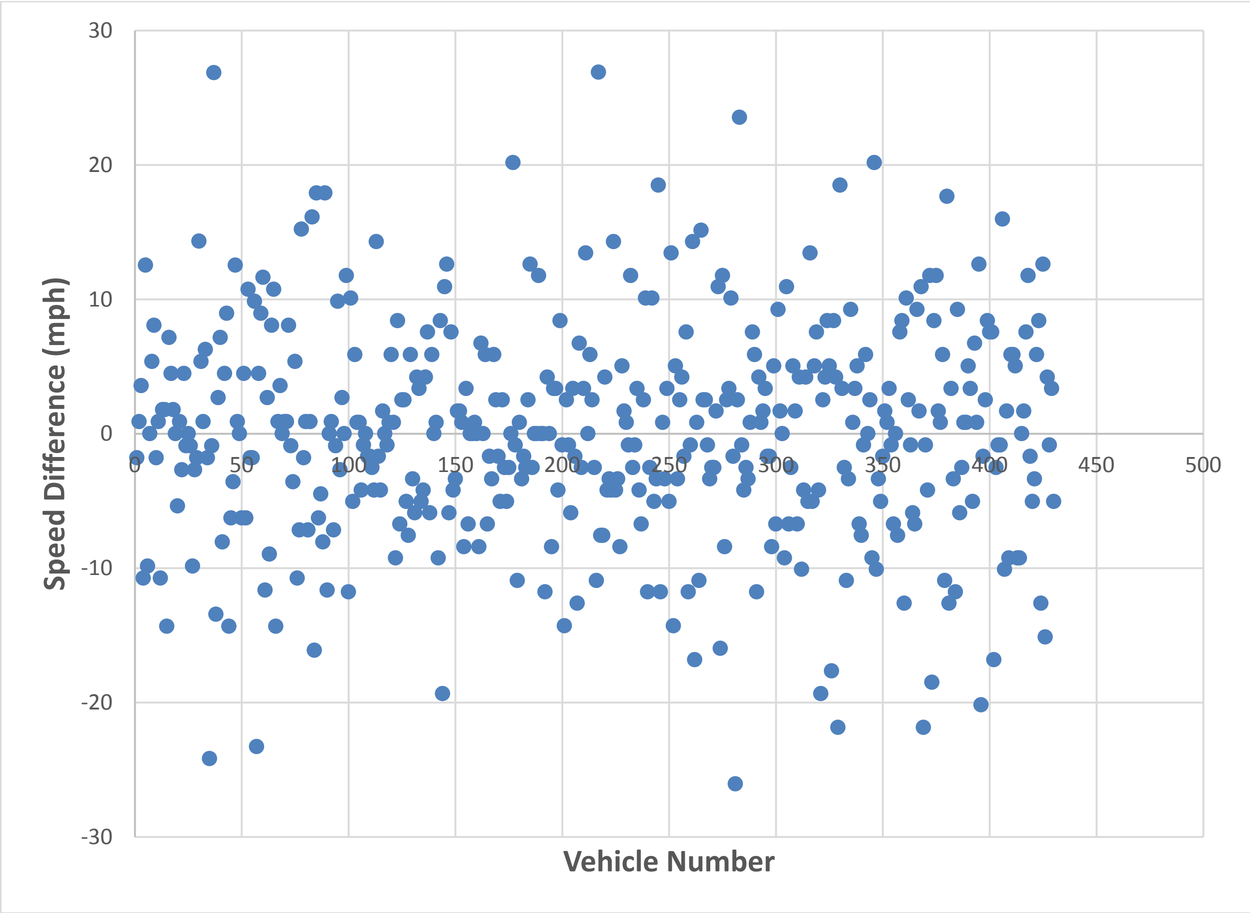


Figure 4.22: Speed Difference for Vehicles Passing Pole 10, I-205, Sweeping, Without RSS

Figure 4.23 shows the speed differences compared to the actual speed of the vehicle adjacent Pole #10 during the work operation time without the RSS turned on. The horizontal access contains the speed of the trailing vehicle, and the vertical axis contains the difference in speed between the trailing vehicle and the vehicle in front of it. The figure shows an apparent positive slope. As the vehicle’s speed increases, the difference in speed between the vehicle under consideration and the vehicle in front of it also increases. This trend is expected because the two factors are related in nature. Speed difference is calculated from vehicle speed. If the speed for the trailing vehicle is high, there is a greater chance that the speed difference will be high also. Those vehicles represented by the data points in the upper-right portion of the figure are especially of concern; they are travelling at a high rate of speed and at a high rate of speed relative to the preceding vehicle.

The posted regulatory speed at this location is 55 mph. During the testing without the RSS turned on, 80% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. During the entire test period at Pole #10 within the work zone, 53% of the vehicles were going faster than the posted speed limit. When the maintenance equipment was located at Pole #10, 18% of the vehicles were going faster than the speed limit.

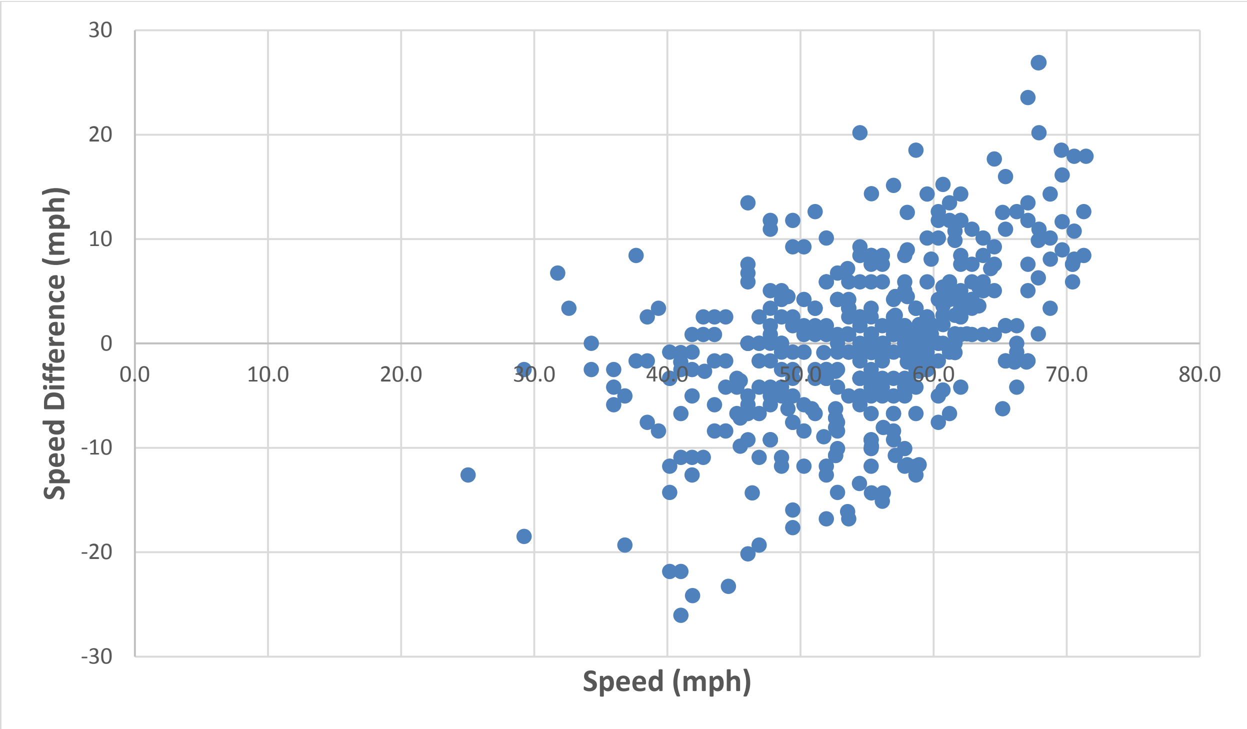


Figure 4.23: Speed Difference vs. Vehicle Speed for Vehicles Passing Pole 10, I-205, Sweeping, Without RSS

Figure 4.24 is similar to Figure 4.23, however the vertical axis in Figure 4.24 shows the distance between adjacent vehicles (measured in feet) rather than the speed difference. Figure 4.24 shows the data for the vehicles passing Pole #10 during the work operation time without the RSS turned on. While the distance apart varies, the majority of vehicles are less than approximately 1,000 feet apart. The figure does not show a clear trend in distance between adjacent vehicles with respect to the vehicle's speed. Those vehicles represented by the data points in the lower-right portion of the figure are especially of concern; they are travelling at a high rate of speed and travelling close to the preceding vehicle.

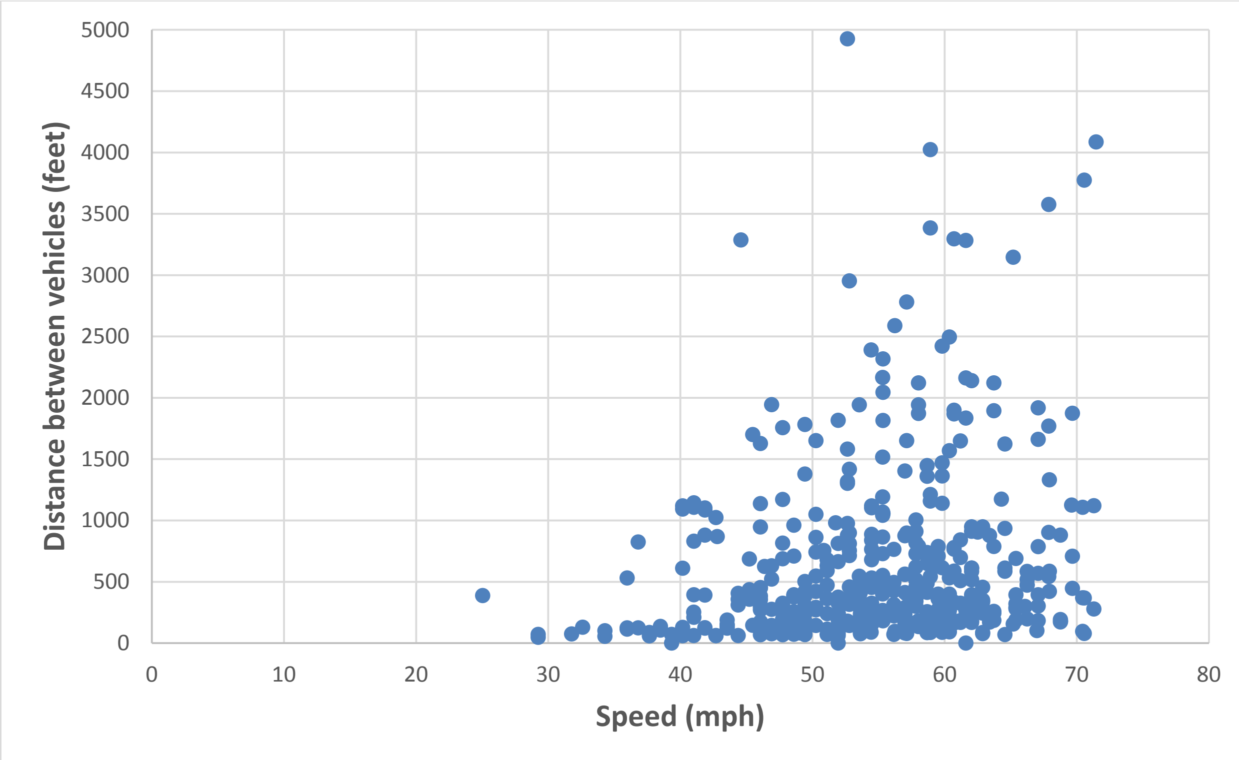


Figure 4.24: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Pole 10, I-205, Sweeping, Without RSS

The distance between adjacent vehicles compared to the speed difference between vehicles is shown in Figure 4.25. The data is shown for vehicles passing Pole #10 during the work operation time without the RSS turned on. Again, no particular trend is visible in the figure. The data points with negative speed difference indicate that the trailing vehicle is slower than the leading vehicle and getting farther away from the leading vehicle as the vehicles travel down the roadway. Those data points on the right side of the figure (higher positive speed difference), especially those with small distance between vehicles, are of concern. To prevent potential rear-end collisions, those vehicles with large positive speed difference (i.e., high speed relative to the vehicle in front of it) and low distance apart (i.e., close to the vehicle in front of it) is undesirable.

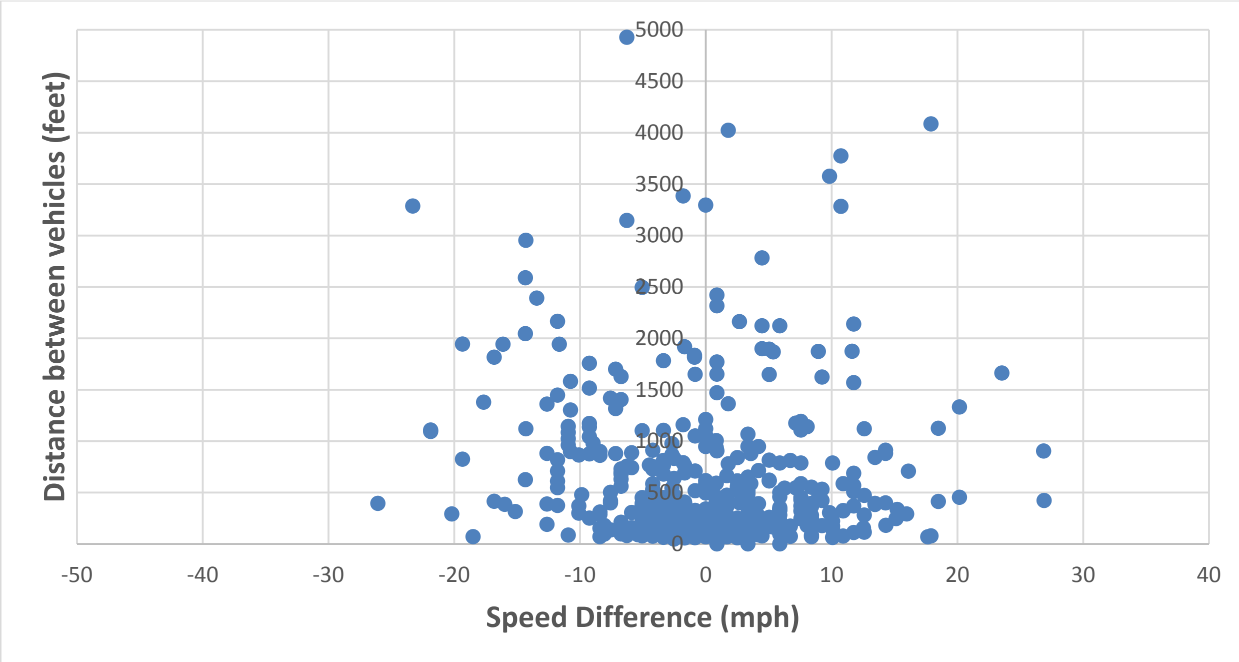


Figure 4.25: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Pole 10, I-205, Sweeping, Without RSS

For comparison, Figures 4.26, 4.27, 4.28, and 4.29 show similar speed and distance difference charts during the work operation with the RSS turned on. In these figures, the data is based on vehicles passing Pole #10. Similar charts at the other poles are provided in the Appendix. As with the analysis of the data without the RSS display turned on, no particular trend is observed in the data with the RSS display turned on.

During the testing with the RSS turned on, 83% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. This percentage is approximately the same as that during the time period without the RSS turned on. During the entire test period with the RSS turned on, at Pole #10 within the work zone 46% of the vehicles were going faster than the posted speed limit, which is less than the 53% without the RSS turned on. During the period of time when the maintenance equipment was located at Pole #10, 18% of the vehicles were travelling faster than the speed limit. These results show that the RSS helped to decrease the percentage of vehicles travelling faster than the posted speed limit.

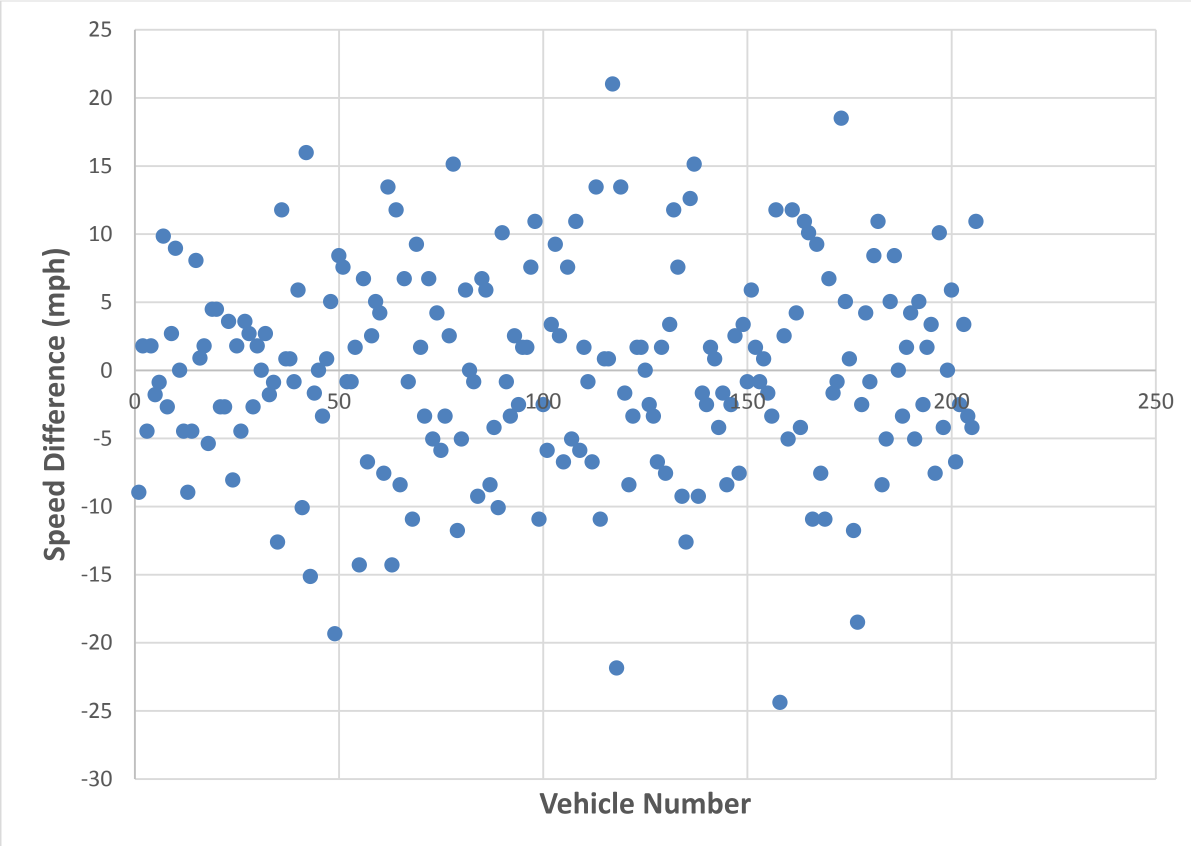


Figure 4.26: Speed Difference for Vehicles Passing Pole 10, I-205, Sweeping, With RSS

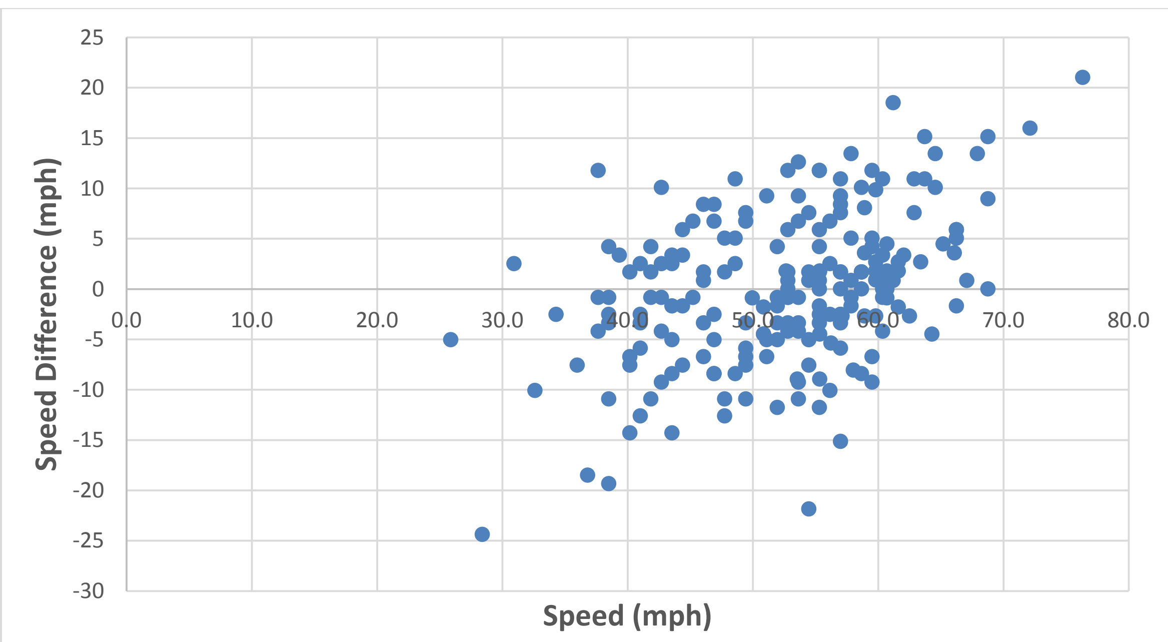


Figure 4.27: Speed Difference vs. Vehicle Speed for Vehicles Passing Pole 10, I-205, Sweeping, With RSS

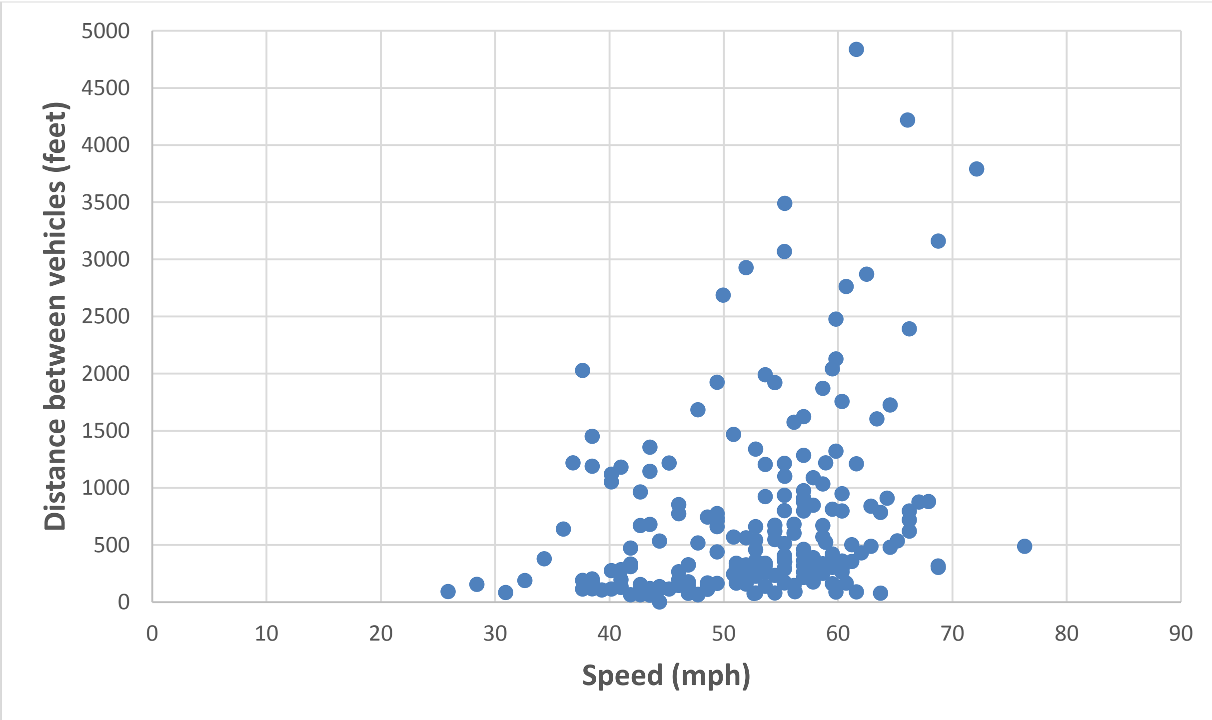


Figure 4.28: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Pole 10, I-205, Sweeping, With RSS

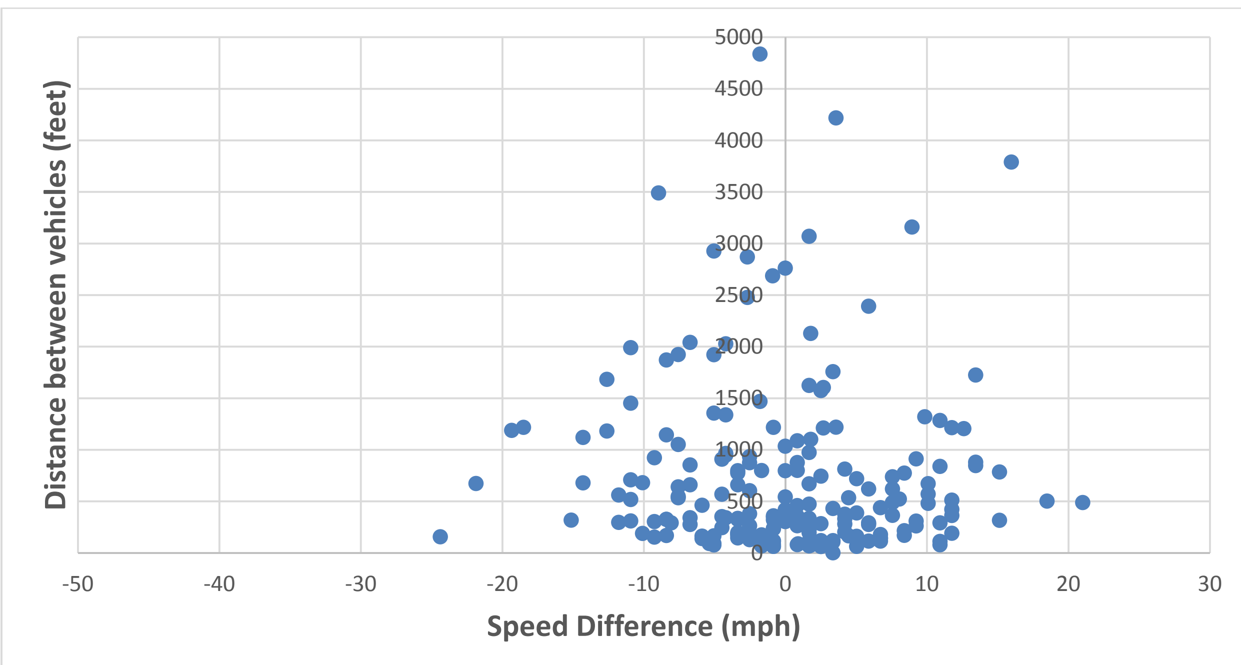


Figure 4.29: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Pole 10, I-205, Sweeping, With RSS

Statistical tools were used to analyze the treatment effect of implementing the RSS display in a manner similar to Case Study #1. A two-sample t-test was conducted to see whether turning on the RSS display has an effect on the speed difference. In the analysis, the absolute value of speed difference is used as the dependent variable. Absolute value is used due to the fact that, if the speed differences are added together, the negatives and positives will cancel each other and the mean of speed difference will be close to zero. The statistical test was conducted for all vehicles combined, for only passenger cars, and for only trucks. Table 4.23 summarizes the results. The data used to create the table consisted of all of the data recorded at Poles #10. Similar tables comparing the speed differences at other poles are provided in the Appendix.

Table 4.23: Effect of Radar Speed Sign on Absolute Value of Speed Differences between Adjacent Vehicles, I-205, Sweeping, Pole 10

Type of vehicle	Mean of absolute value of Speed difference (mph) without RSS	Mean of absolute value of Speed difference (mph) with RSS	Difference in mean values (mph)	p-value
All Vehicles	6.06	5.78	0.28	0.5172
Passenger Cars	5.86	5.54	0.32	0.4726
Trucks	7.95	7.41	0.54	0.7395

As seen in Table 4.23, for all vehicles, the RSS display turned on resulted in a 0.28 mph lower mean speed difference. However, the p-value was high (0.517). Therefore, there is no statistically significant evidence that the means are different. For passenger cars and trucks, the mean differences were greater (0.32 and 0.54 mph respectively), however the differences were also found to not be significant.

A second statistical analysis was performed using just the positive speed difference values, and omitting those with negative speed difference. Positive speed difference represents a vehicle that is driving faster than the vehicle in front of it. This situation is possibly hazardous as it can lead to rear-end crashes. The results of the analysis, shown in Table 4.24, are similar to the analysis using absolute value of speed differences. There is no statistical evidence that the RSS display has an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it.

Table 4.24: Effect of Radar Speed Sign on Vehicles with Positive Speed Differences between Adjacent Vehicles, I-205, Sweeping, Pole 10

Type of vehicle	Mean of positive value of Speed difference (mph) without RSS (Day1)	Mean of positive value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	6.35	6.04	0.32	0.6049
Passenger Cars	6.28	6.07	0.21	0.7384
Trucks	7.48	5.68	1.81	0.5306

Similar analyses were conducted using the distance between adjacent vehicles as the dependent variable to assess the impact of the treatment (use of RSS display). Table 4.25 shows the results of the analysis. For all vehicles, just passenger cars, and just trucks, there is no statistically significant evidence that the RSS display has an impact on the distance between adjacent vehicles.

Table 4.25: Effect of Radar Speed Sign on Distance between Adjacent Vehicles, I-205, Sweeping, Pole 10

Type of vehicle	Mean of distance apart without RSS (feet)	Mean of distance apart with RSS (feet)	Difference in mean values (feet)	p-value
All Vehicles	788.82	1059.90	271.09	0.1055
Passenger Cars	777.77	1109.10	331.33	0.0748
Trucks	893.30	721.18	172.11	0.4855

Additional statistical tests were conducted to explore the effect of vehicle type on mean speed with and without the RSS display turned on. Table 4.26 shows the results of these tests without the RSS display turned on. Similar to the tables above, the values shown in the table are calculated from all of the data recorded by the sensors at Pole #10. The results suggest that vehicle type has an impact on the absolute value of speed difference (p = 0.016). Also, passenger cars have a lower speed difference and shorter distance to the vehicle in front of them than trucks.

Table 4.26: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-205, Sweeping, Without RSS, Pole 10

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference (mph)	5.86	7.95	2.09	0.0163
Mean positive speed difference (mph)	6.28	7.48	1.21	0.4195
Mean distance between adjacent vehicles (feet)	777.77	893.30	115.52	0.6064

Table 4.27 shows the results for cars and trucks at Pole #10 with the RSS turned on. The calculated p-values indicate a suggestive difference between cars and trucks with respect to absolute value of speed difference (p = 0.059).

Table 4.27: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-205, Sweeping, With RSS, Pole 10

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference(mph)	5.54	7.41	1.86	0.0593
Mean positive speed difference (mph)	6.07	5.68	0.39	0.8160
Mean distance between adjacent vehicles (feet)	1109.10	721.18	387.92	0.5179

Analyzing the data at Pole #10, the differences between cars and trucks are shown in Table 4.28. The results are similar to that found in the tables above. In all cases, trucks have a higher mean speed difference and higher positive speed difference between adjacent vehicles. When designing traffic control measures for work zones, passenger cars and trucks should be considered together and separately. Passenger car speed relative to the speed of the vehicle in front of the car is not as great as that for trucks, yet the distance apart is shorter for trucks. When designing traffic control plans, special consideration should be given to increasing the distance apart for trucks (e.g., minimize tailgating). Whereas for safety related to cars, an emphasis should be placed on keeping the speeds of adjacent vehicles the same through the work zone.

Table 4.28: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-205, Sweeping, With and Without RSS, Pole 10

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference(mph)	5.76	7.74	1.98	0.0027
Mean positive speed difference (mph)	6.21	6.79	0.58	0.6048
Mean distance between adjacent vehicles (feet)	882.37	826.50	55.87	0.8266

Speeds of vehicles approaching the work operation are recorded by the radar unit attached to the RSS display. Table 4.29 shows the recorded speeds for vehicles approaching the equipment during the entire work operation with and without the RSS turned on. It should be noted that while the sweeping equipment returned to the starting point to make another pass through the work zone, the RSS board was lowered and no speeds were recorded by the RSS unit. Also, the values will be different than those captured by the traffic analyzers since the RSS unit records speeds upstream of the work equipment while the sweeping operation moves up the roadway, not at a specific location.

Table 4.29: Approaching Vehicle Speeds Recorded by Radar Speed Sign, I-205, Sweeping, Without RSS

Time	Total	0_5	6_10	11_15	16_20	21_25	26_30	31_35	36_40	40_45	46_50	51_55	56_60	61_65	66_70	71_75	76_80	81_85	86_90	91_95	96_100	>100	Median	Max	85th %ile
3/30/2015 21:30	0	122	0	0	0	0	0	2	8	32	33	42	8	0	0	0	0	0	0	0	0	0	33	59	52
3/30/2015 21:35	0	104	0	0	0	2	3	9	13	24	22	19	5	2	1	1	0	2	0	1	0	4	25	113	51
3/30/2015 21:40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3/30/2015 21:45	0	41	0	0	1	0	1	3	2	0	0	1	7	7	0	0	2	3	7	3	3	7	32	146	90
3/30/2015 21:50	0	105	0	0	0	3	13	5	17	21	20	22	6	1	2	0	0	0	0	0	0	0	24	68	50
3/30/2015 21:55	0	115	0	0	0	0	0	4	13	25	37	24	14	3	0	0	0	0	0	0	0	0	33	64	52
3/30/2015 22:00	0	26	0	0	0	0	0	5	3	5	2	8	3	0	0	0	0	0	0	0	0	0	30	58	52
3/30/2015 22:05	0	50	0	0	0	0	0	0	3	2	11	5	7	2	2	3	0	2	2	0	6	10	39	120	95
3/30/2015 22:10	0	124	0	0	0	0	0	2	25	25	27	28	14	9	3	0	0	0	0	0	0	0	36	67	53
3/30/2015 22:15	0	113	0	0	0	0	0	1	6	14	27	25	26	15	0	0	0	0	0	0	0	0	30	64	57
3/30/2015 22:20	0	60	0	0	0	1	5	1	4	4	18	15	12	2	0	0	0	0	0	0	0	0	25	63	54

The researchers also performed multiple probe vehicle passes through the work zones to monitor the nature of the traffic throughout the entire length of the work zone both with and without the RSS turned on. Figure 4.30 shows an example of the speeds recorded by the probe vehicle without the RSS turned on when the work operation was located at Pole #10. Figure 4.31 shows a similar chart with the RSS turned on when the work operation was located at Pole #5. The decrease in speeds as the vehicles approach the equipment is evident in these figures. The amount of decrease is greater (approximately 9 mph greater) with the RSS turned on.

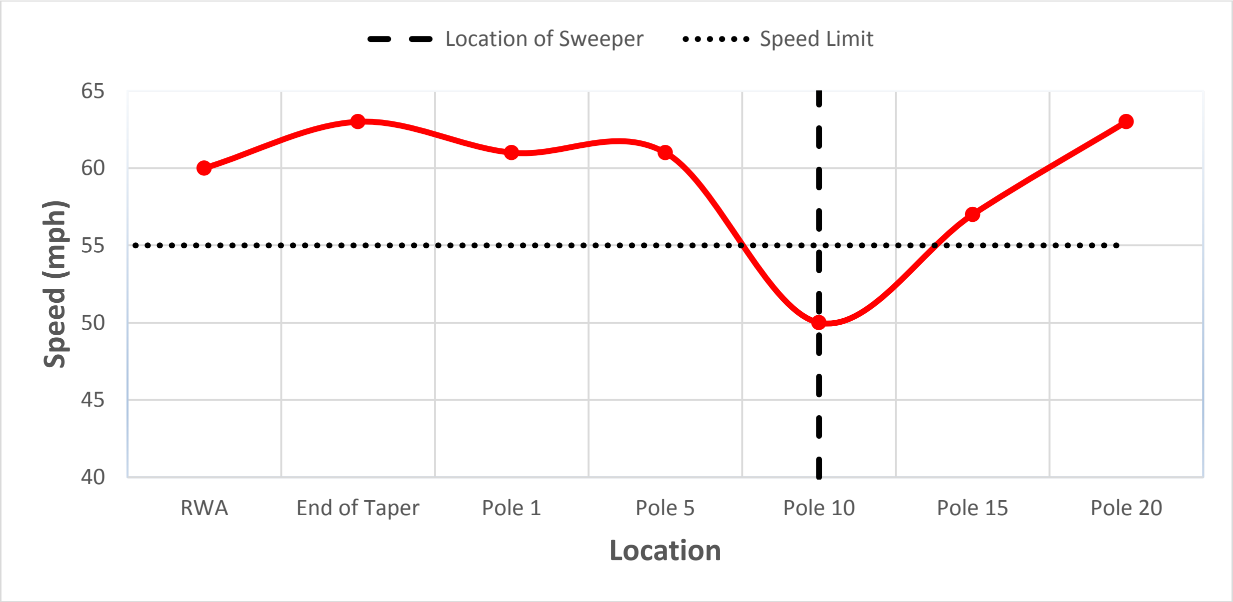


Figure 4.30: Probe Vehicle, I-205, Sweeping, Without RSS

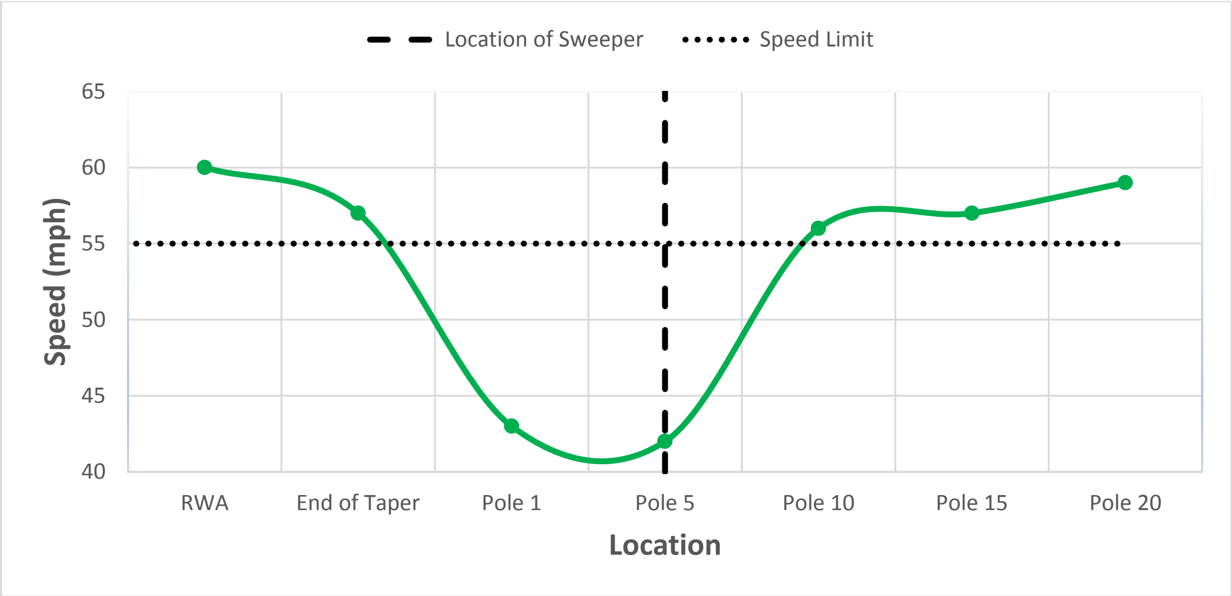


Figure 4.31: Probe Vehicle, I-205, Sweeping, With RSS

4.3 CASE STUDY #3: I-84 (BANFIELD EXPRESSWAY) VACTORING

The traffic volumes recorded during the testing on Day 1 without the RSS display turned on and on Day 2 with the RSS display turned on are shown in Figure 4.32. Given the short duration of testing each night, the volumes are shown at 15 minute intervals from 21:45 to 23:15. Total traffic volume was highest early in the testing period from 21:45 to 22:00. Afterwards the volume decreased, fluctuating slightly over the remainder of the testing period. Comparing one day to the next, the total traffic volume was similar during some 15 minute intervals, but differed in other intervals. For example, on Day 2 the total traffic volume from 21:45 to 22:00 was approximately 25% less than on Day 1. Later in the evening the volume on Day 2 was appreciably greater than on Day 1. With regards to the type of vehicle, the percentage of cars (vehicles < 25 feet in length) and percentage of trucks (vehicles > 25 feet in length) were approximately the same for each day.

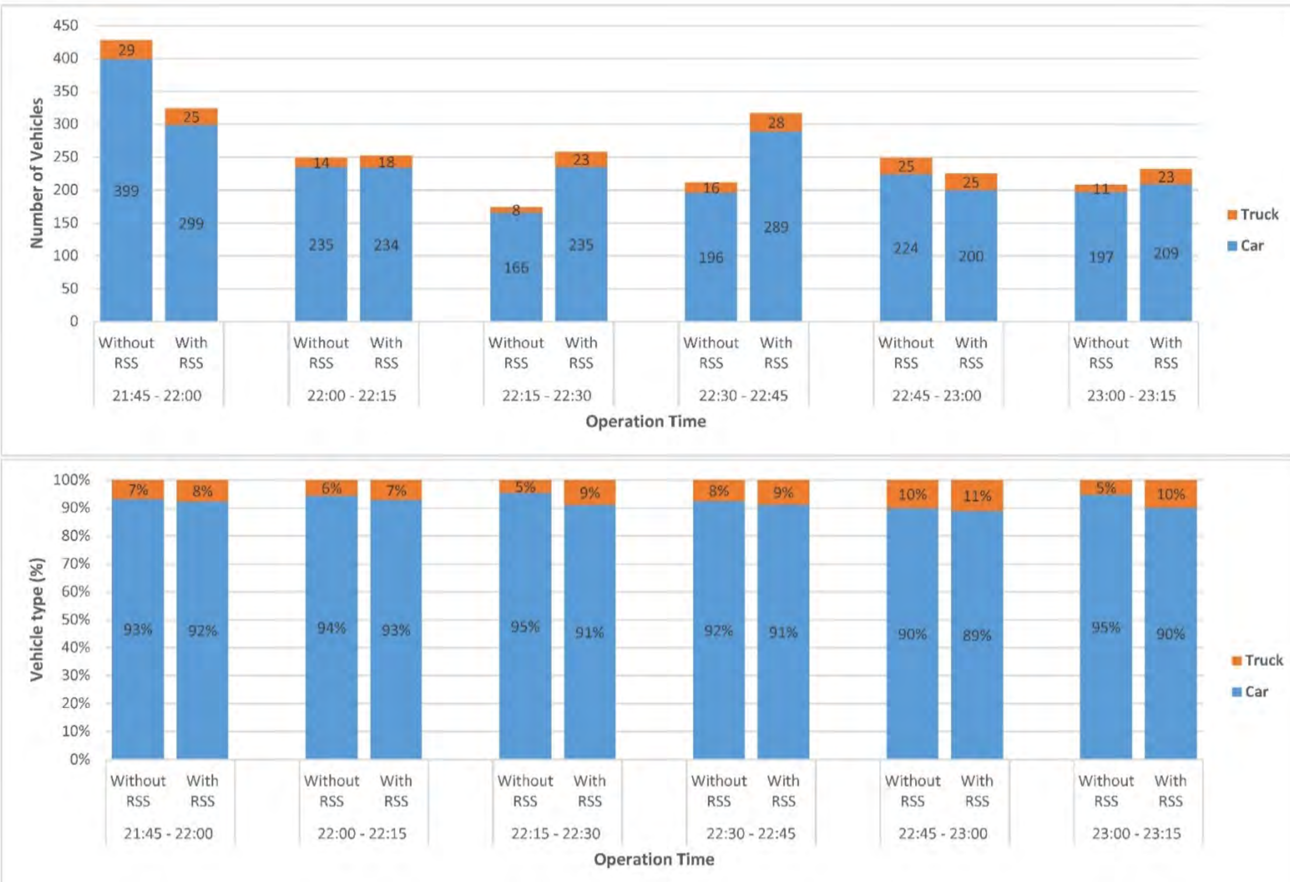


Figure 4.32: Traffic Volume, Number of Vehicles and Vehicle Type Percentage, I-84, Vactoring, Drain 3 (Day 1, Without RSS) and Drain 4 (Day 2, With RSS)

Table 4.30 presents a summary of the vehicle speeds recorded for all vehicles at the RWA sign location on Day 1 without the RSS turned on. For this table, the values represent the data downloaded from the sensors in both the B and C lanes. 85th percentile speed for the entire work period was 62.6 mph. This value ranged from 63.6 down to 61.5 mph throughout the test period.

Table 4.30: Hourly Summary of Vehicle Speed, I-84, Vactoring, Without RSS (Day 1), RWA

	Time						
Vehicle Speed (all vehicles)	Total	21:45-22:00	22:00-22:15	22:15-22:30	22:30-22:45	22:45-23:00	23:00-23:15
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.1%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%
20-24	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%
25-29	0.2%	0.0%	0.3%	0.0%	0.7%	0.0%	0.0%
30-34	0.4%	0.0%	0.3%	0.0%	1.5%	0.0%	1.4%
35-39	0.7%	0.5%	1.2%	0.9%	0.0%	0.8%	0.7%
40-44	4.1%	2.5%	5.3%	3.3%	3.7%	2.5%	11.6%
45-49	8.9%	9.9%	10.2%	7.8%	8.5%	6.2%	10.9%
50-54	29.3%	31.0%	29.7%	23.6%	26.3%	36.0%	31.2%
55-59	29.5%	29.5%	27.9%	32.5%	28.9%	31.8%	23.2%
60-64	18.0%	19.1%	15.8%	20.0%	21.9%	14.9%	13.0%
65-69	5.9%	5.7%	5.0%	8.1%	6.3%	4.1%	5.8%
70-74	2.0%	1.0%	2.8%	2.4%	1.9%	2.5%	1.4%
>=75	0.9%	0.7%	1.5%	1.5%	0.4%	0.8%	0.0%
Total # of vehicles	1711	403	323	335	270	242	138
Average speed	56.1	56.2	55.6	57.3	56.3	56.0	53.8
St. Dev.	7.1	6.4	7.7	7.1	7.4	6.7	8.0
85th percentile	62.6	62.6	62.4	63.6	62.6	61.5	61.5
Min	19.8	36.5	26.2	37.0	27.1	19.8	20.9
Max	86.2	82.4	86.2	84.4	84.4	78.1	73.6
Range	66.4	45.9	59.9	47.4	57.3	58.3	52.8

Similarly, Table 4.31 shows a summary of the vehicle speeds over the same period recorded in the work area, specifically at Drain #3. The 85th percentile speed over the entire work period was calculated to be 65.0 mph at this location. The 85th percentile speed varied from a low of 55.4 mph to a high of 66.9 mph. It is interesting to note that the lowest 85th percentile speed value of the 15-minute periods (55.4 mph from 22:15 to 22:30) occurred with the lowest traffic volume.

Table 4.31: Hourly Summary of Vehicle Speed, I-84, Vactoring, Without RSS (Day 1), Drain 3

	Time						
Vehicle Speed (all vehicles)	Total	21:45-22:00	22:00-22:15	22:15-22:30	22:30-22:45	22:45-23:00	23:00-23:15
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.1%	0.0%	0.0%	0.0%	0.9%	0.0%	0.0%
30-34	0.6%	0.0%	0.0%	1.1%	3.3%	0.0%	0.0%
35-39	2.2%	0.2%	0.4%	10.3%	6.1%	0.4%	0.0%
40-44	4.3%	0.7%	2.4%	23.6%	5.7%	1.2%	0.0%
45-49	9.5%	4.0%	12.9%	25.3%	7.5%	10.0%	4.8%
50-54	21.4%	19.4%	28.5%	22.4%	20.3%	24.5%	13.9%
55-59	26.5%	29.4%	25.3%	10.9%	28.8%	29.7%	28.8%
60-64	23.0%	30.8%	20.5%	5.7%	19.3%	21.3%	29.8%
65-69	7.8%	9.8%	6.8%	0.0%	5.7%	8.0%	13.0%
70-74	3.6%	3.7%	2.8%	0.6%	1.4%	4.0%	8.2%
>=75	1.1%	1.9%	0.4%	0.0%	0.9%	0.8%	1.4%
Total # of vehicles	1520	428	249	174	212	249	208
Average speed	57.0	59.7	56.7	48.3	54.5	57.8	60.7
St. Dev.	8.0	6.4	6.7	7.1	9.4	6.6	6.4
85th percentile	65.0	65.9	63.1	55.4	63.1	64.8	66.9
Min	28.5	39.1	36.6	31.4	28.5	37.6	45.7
Max	91.3	91.3	75.5	74.6	85.2	76.5	76.5
Range	62.8	52.2	38.9	43.2	56.7	38.8	30.7

Table 4.32 and Table 4.33 provide similar vehicle speed data during the testing on Day 2 with the RSS turned on. Table 4.32 shows the speeds collected at the RWA signs, and Table 4.33 shows the data in the work area at Drain #4. The 85th percentile speeds at each location were 64.7 mph and 64.0 mph, respectively. The 85th percentile speeds were fairly consistent throughout the testing period except from 22:00-22:30 at Drain #4. The 85th percentile speed during this period decreased to approximately 54 mph. Based on the 85th percentile speeds calculated for each 15 minute period on each day of testing, the difference in traffic volume between Day 1 (without RSS turned on) and Day 2 (with RSS turned on) does not appear to

show a specific relationship with the difference in vehicle speeds on those days. Further analysis comparing vehicle speeds on each day is provided below.

Table 4.32: Hourly Summary of Vehicle Speed, I-84, Vactoring, With RSS (Day 2), RWA

	Time						
Vehicle Speed (all vehicles)	**Total**	21:45-22:00	22:00-22:15	22:15-22:30	22:30-22:45	22:45-23:00	23:00-23:15
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.1%	0.0%	0.0%	0.3%	0.0%	0.0%	0.0%
25-29	0.4%	0.3%	0.0%	0.6%	0.6%	0.4%	0.5%
30-34	0.4%	0.5%	0.8%	0.3%	0.3%	0.0%	0.0%
35-39	0.8%	1.8%	0.5%	0.3%	0.3%	1.6%	0.0%
40-44	3.0%	5.7%	2.9%	1.7%	2.3%	3.2%	1.4%
45-49	8.6%	10.2%	10.8%	7.7%	7.4%	4.0%	10.9%
50-54	23.7%	24.0%	24.5%	26.1%	25.4%	20.4%	19.0%
55-59	32.0%	31.3%	31.8%	37.5%	32.9%	25.6%	30.3%
60-64	17.6%	14.9%	16.3%	15.6%	16.0%	22.0%	25.6%
65-69	8.2%	7.8%	8.2%	6.5%	7.4%	12.4%	7.6%
70-74	2.9%	1.6%	2.6%	1.7%	3.4%	6.0%	3.3%
>=75	2.4%	1.8%	1.6%	1.7%	4.0%	4.4%	1.4%
Total # of vehicles	1926	383	380	352	350	250	211
Average speed	57.3	56.0	56.9	56.9	57.7	59.6	58.0
St. Dev.	8.0	8.1	7.5	7.4	8.3	9.1	7.1
85th percentile	64.7	63.2	64.2	63.6	64.7	67.8	63.9
Min	23.0	27.2	31.4	23.0	26.1	27.2	26.1
Max	93.8	93.8	88.5	89.6	91.7	93.8	80.1
Range	70.9	66.6	57.1	66.6	65.6	66.6	53.9

Table 4.33: Hourly Summary of Vehicle Speed, I-84, Vactoring, With RSS (Day 2), Drain 4

Vehicle Speed (all vehicles)	Total	Time					
		21:45-22:00	22:00-22:15	22:15-22:30	22:30-22:45	22:45-23:00	23:00-23:15
MPH							
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.1%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%
20-24	0.2%	0.0%	0.4%	1.2%	0.0%	0.0%	0.0%
25-29	1.1%	0.0%	2.4%	3.9%	0.6%	0.0%	0.0%
30-34	2.8%	0.0%	9.5%	6.6%	0.9%	0.0%	0.4%
35-39	4.2%	1.2%	12.3%	10.9%	1.6%	0.0%	0.0%
40-44	9.9%	2.8%	29.0%	20.2%	6.6%	0.0%	1.7%
45-49	13.1%	12.7%	19.0%	24.4%	11.7%	4.0%	5.2%
50-54	19.9%	29.0%	15.9%	20.5%	18.9%	16.9%	15.1%
55-59	18.9%	22.8%	7.1%	6.6%	26.5%	26.7%	22.0%
60-64	17.6%	21.0%	2.0%	3.9%	21.5%	27.6%	30.2%
65-69	7.2%	8.0%	1.2%	1.2%	7.3%	13.3%	12.9%
70-74	3.0%	1.5%	0.8%	0.0%	2.5%	6.2%	8.6%
>=75	2.0%	0.9%	0.4%	0.4%	1.9%	5.3%	3.9%
Total # of vehicles	1608	324	252	258	317	225	232
Average speed	54.4	56.7	45.3	46.0	56.3	61.4	61.0
St. Dev.	10.4	7.3	8.7	9.1	8.7	8.2	8.2
85th percentile	64.0	64.0	53.5	54.4	64.0	68.8	68.8
Min	19.4	36.2	24.7	19.4	25.5	46.8	32.4
Max	93.8	89.3	83.2	80.3	84.2	93.8	91.3
Range	74.3	53.1	58.5	60.9	58.7	47.0	59.0

The traffic analyzers also provide the opportunity to view the vehicle speeds over the length of the work zone. Figure 4.33 shows how the 85th percentile speed changed from the RWA signs to the end of the work zone at Drain #8 for both cases (with and without RSS turned on). The 85th percentile speeds on both days were above the 55 mph regulatory speed limit on this section of roadway. The speeds shown are only those recorded during the time in which the work operation took place. As seen in the figure, for much of the work zone, the speeds with the RSS turned on were lower than without the RSS turned on. The amount of difference varied from approximately 1 to 2 mph depending on the drain location.

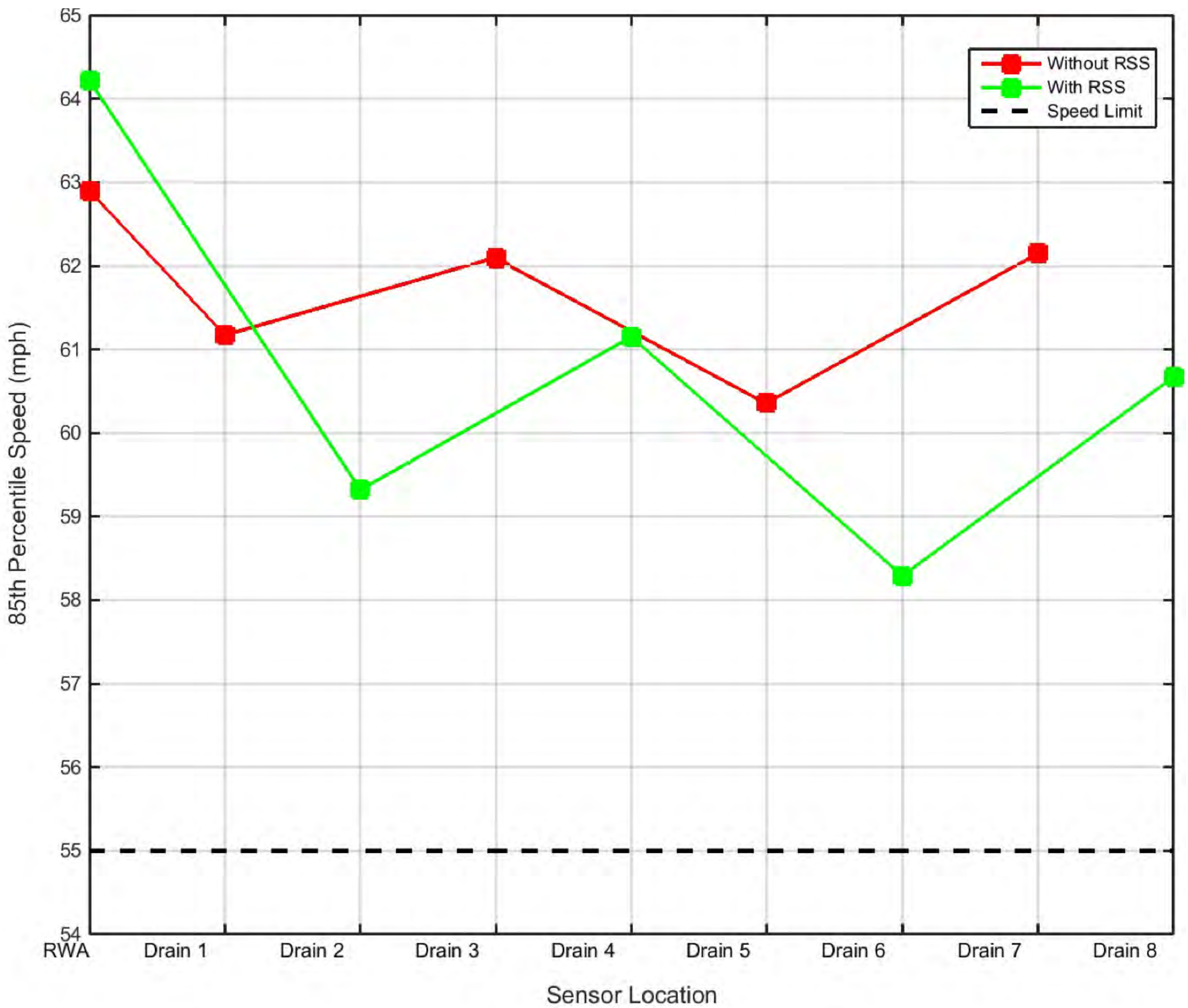


Figure 4.33: Vehicle Speed (85th percentile) at Different Locations during Operation Time, I-84, Vactoring

It is likely that the speed in the work zone, at least in the initial portion of the work zone, depends on the speed of the vehicles prior to the work zone, i.e., those vehicles entering the work area with a higher speed will also have a higher speed in the work area. Figure 4.34 shows the 85th percentile speeds at the RWA signs throughout the work period on each day of testing. The 85th percentile speeds on both days were above the 55 mph regulatory speed limit on this section of roadway. The figure shows that on Day 2 of the testing with the RSS turned on, the 85th percentile speed was consistently higher than on Day 1 without the RSS turned on over the course of the testing time period except from 22:15-22:30. This difference should be taken into consideration when comparing the speeds between each day in the work zone. However, at the RWA signs there would be no impact from to the presence of the RSS because at the RWA sign location the RSS is downstream and not yet visible to the drivers.

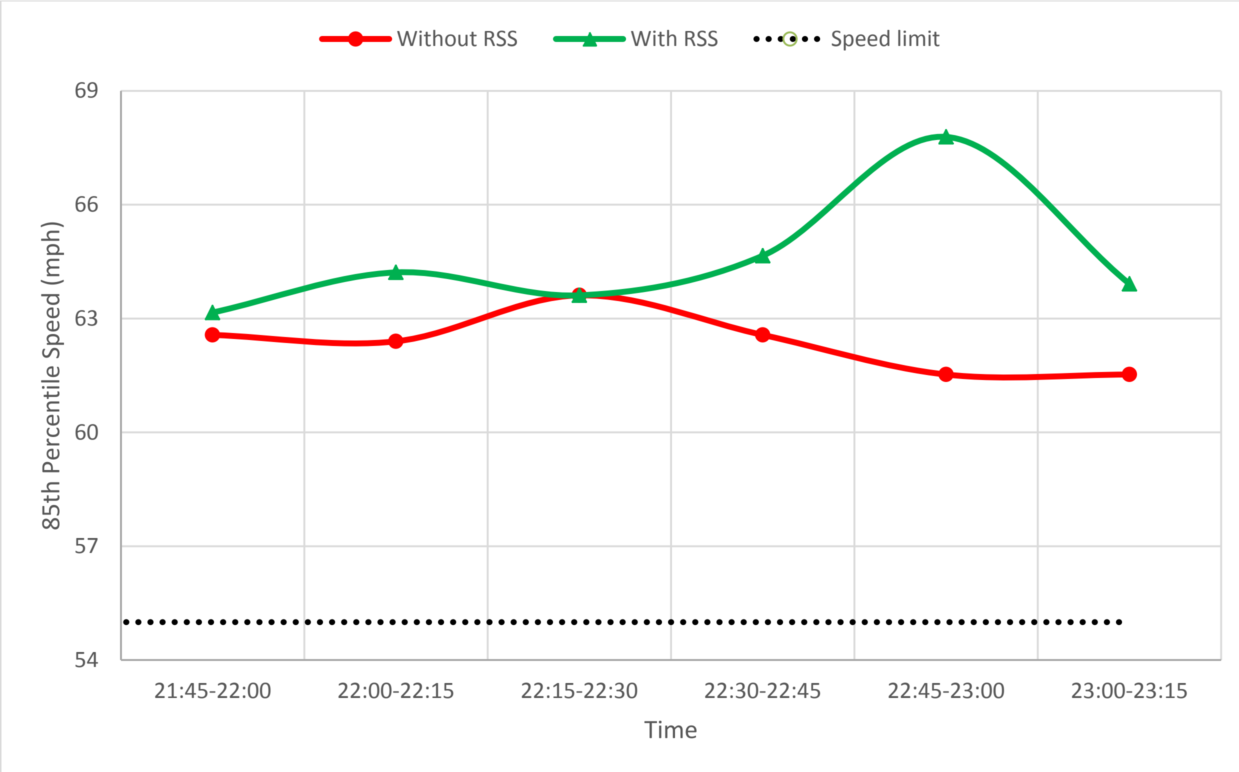


Figure 4.34: Vehicle Speed (85^{th} Percentile) at RWA during Operation Time, I-84, Vactoring

As part of the data analysis, comparisons were made between the vehicle speeds on each day at specific locations. Figure 4.35 shows a comparison of 85^{th} percentile speeds at Drain #3 (without RSS turned on) to that at Drain #4 (with RSS turned on). Work was performed at odd-numbered drains on Day 1 without the RSS turned on and at even-numbered drains with the RSS turned on. Drains #3 and #4 were selected for illustration purposes only; similar charts showing comparisons between adjacent drains are provided in the Appendix.

Figure 4.35 also shows that the vehicle speeds are lower when adjacent the work equipment. For example, between 22:15 and 22:30 on Day 1 without the RSS turned on, the work took place at Drain #3. At this time, the 85^{th} percentile speed was approximately 55.4 mph. On the second day of testing (with the RSS turned on), the work on Drain #4 took place earlier in the evening. From 22:15-22:30 on Day 2 there was no work going at Drain #4 and the 85^{th} percentile speed was approximately 54.4 mph, slightly lower than the prior day at the adjacent Drain #3. On Day 2 with the RSS turned on, the 85^{th} percentile speed at the location of the work equipment was less at 53.5 mph.

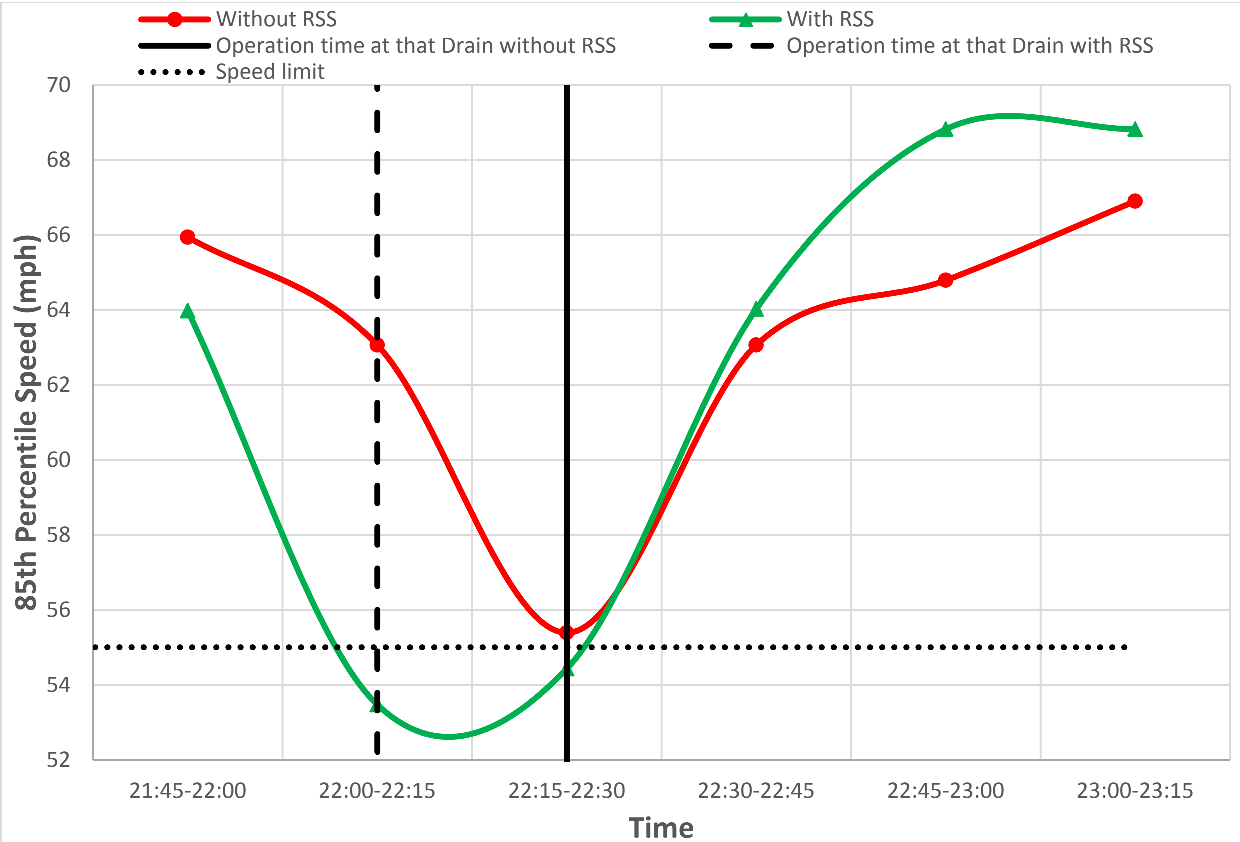


Figure 4.35: Vehicle Speed (85th Percentile) at Drain 3 (Without RSS) and Drain 4 (With RSS) during Operation Time, I-84, Vactoring

The effect of the presence of the work equipment on vehicle speeds is illustrated in Figure 4.36. This figure shows the speeds recorded at different locations throughout the work zone while the workers were located at Drain #3 on Day 1 (without RSS turned on). Similarly, Figure 4.37 shows the 85th percentile speed through the work zone at Drain #4 on Day 2 (with RSS turned on). Additional graphs are provided in the Appendix for other drains. Regardless whether the RSS display was turned on, the vehicles slow down as they approach the equipment and then speed up downstream of the work equipment. However, comparison of the figures shows that the 85th percentile speed was lower by approximately 7-8 mph with the RSS turned on as the vehicles approached the work equipment.

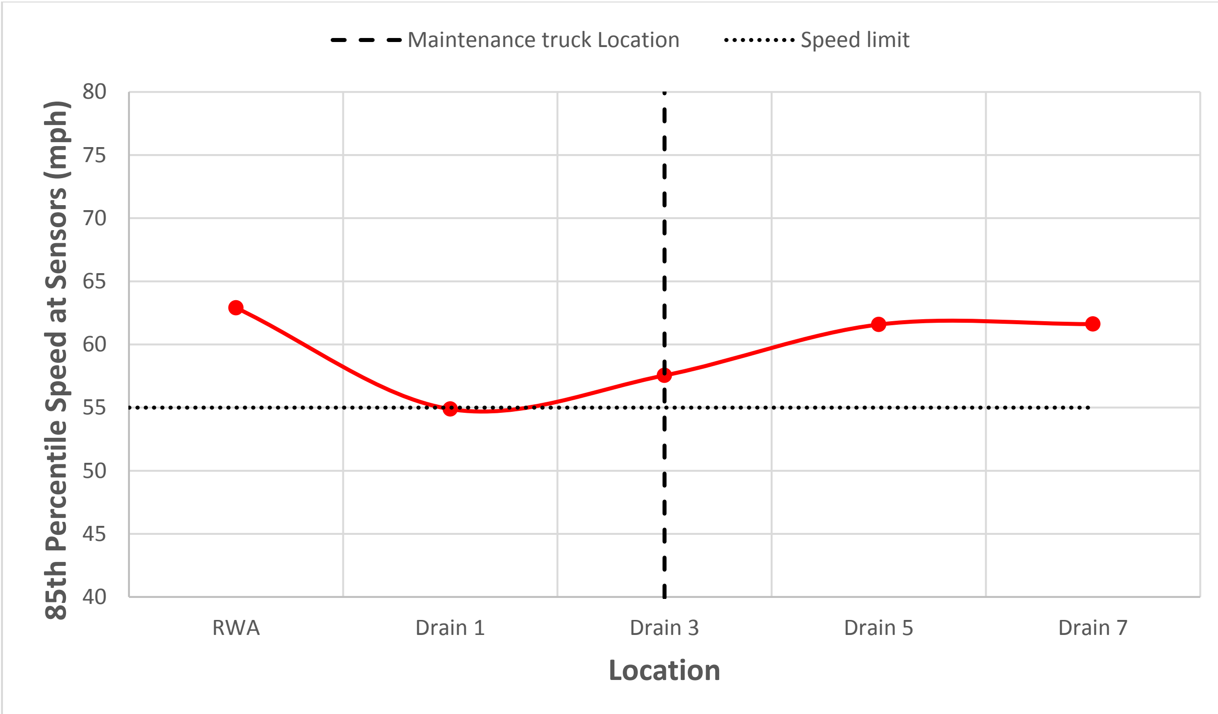


Figure 4.36: 85th Percentile Speed in different Distance from the Operation, I-84, Vactoring, Without RSS (Day 1), Drain 3

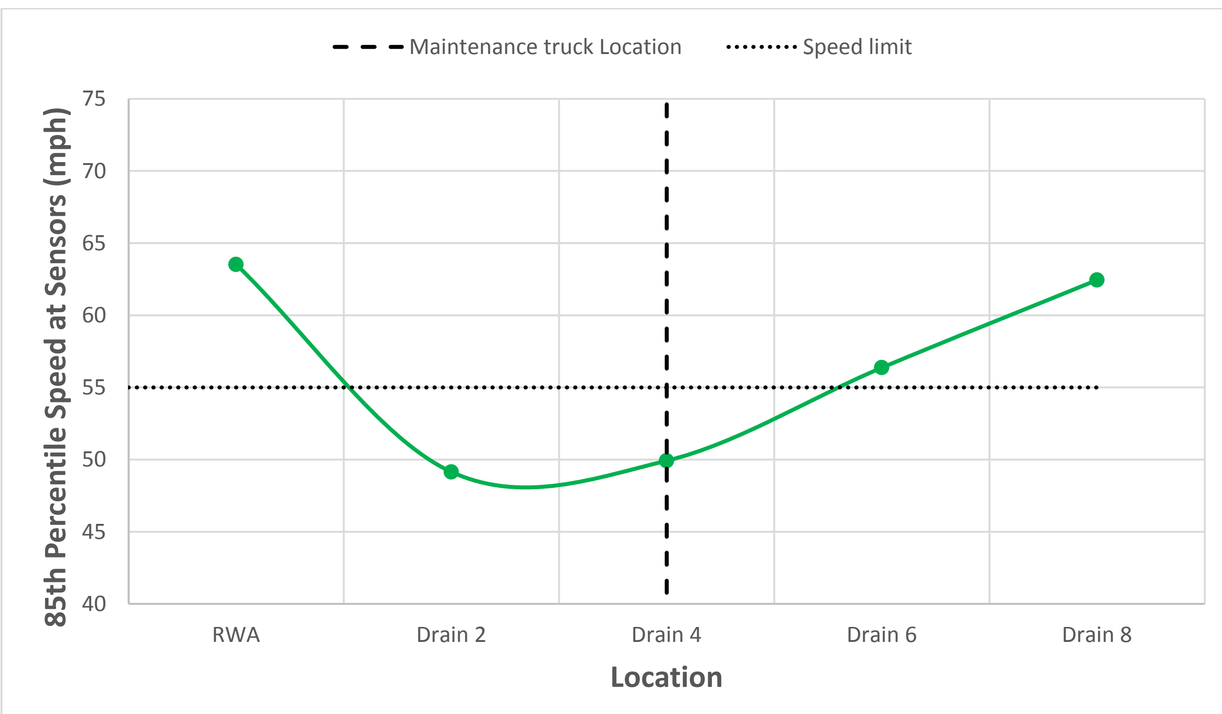


Figure 4.37: 85th Percentile Speed in different Distance from the Operation, I-84, Vactoring, With RSS (Day 2), Drain 4

The vehicle speed data collected provided an opportunity to calculate the amount of decrease in speed from the RWA signs to the work zone for both days of testing. The speeds in the work zone (WZ) were those recorded by all of the traffic sensors adjacent all of the drains. Table 4.34 shows this comparison. For all vehicles, mean speed decreased from 56.6 mph at the RWA signs to 53.0 mph in the work zone, a 6% decrease, on Day 1 without the RSS turned on. On Day 2 with the RSS turned on, the amount of decrease for all vehicles was greater at 12% (57.2 mph to 50.5 mph). When analyzing cars and truck separately, similar results were found: the percentage decrease in mean speed was greater with the RSS turned on. For all cases, the mean speed in the WS with the RSS turned on was less than without the RSS turned on.

Table 4.34: Percentage of Vehicle Speed Decrease in the Work Zone Area, I-84, Vactoring

Type of vehicle	Mean Speed (mph) without RSS (Day1) at RWA	Mean Speed (mph) without RSS (Day1) at WZ	Decrease in mean speed (%) without RSS (Day1)	Mean Speed (mph) with RSS (Day2) at RWA	Mean Speed (mph) with RSS (Day2) at WZ	Decrease in mean speed (%) with RSS (Day2)
All Vehicles	56.59	52.96	6%	57.2	50.5	12%
Passenger Cars	56.68	52.97	7%	57.2	50.6	12%
Trucks	54.52	52.82	3%	56.0	50.2	10%

Table 4.35 shows an additional comparison of mean speeds, this time just comparing the speeds within the work zone. For all vehicles, the mean speed in the WZ on Day 1 without the RSS turned on was 45.5 mph and the mean speed in the WZ on Day 2 with the RSS turned on was 39.9 mph, a difference of 5.6 mph. This difference was found to be statistically significant ($p < 0.0001$). A similar statistically significant result was found for cars: mean speeds throughout the work zone were less with the RSS turned on. For trucks, while the difference in mean speed was greatest, the difference was not found to be statistically significant ($p = 0.269$), likely due in part to the low volume of trucks recorded.

Table 4.35: Effect of Radar Speed Sign on Vehicle Speed, I-84, Vactoring

Type of vehicle	Mean Speed (mph) without RSS (Day1)	Mean Speed (mph) with RSS (Day2)	Difference in mean speed (mph)	p-value
All Vehicles	45.49	39.91	5.58	< 0.0001
Passenger Cars	45.27	39.70	5.57	< 0.0001
Trucks	48.62	42.60	6.02	0.2692

Expanded comparisons of the vehicle speeds are shown in Tables 4.36, 4.37, 4.38, and 4.39. These tables show the speed data at the RWA signs and at Drains #3 and #4 both with and without the RSS display turned on. Similar tables for other adjacent drains are provided in the Appendix. Table 4.36 summarizes the data during the entire period from 21:45-23:15. On Day 1, the operation time was from 22:03-22:51, while on Day 2 it was from 21:50-22:51. Therefore, Table 4.36 includes some free flow vehicle speeds (without the work operation in place) for a short period of time on Day 2. The free flow speeds are typically higher, therefore increasing recorded speeds for Day 2. Table 4.37 summarizes the data for only the time periods when the work operation took place on both days, and presents a more accurate representation of the impact of the operation on vehicle speeds. As seen in Table 4.37, the mean and 85th percentile speeds were greater on Day 2 with the RSS turned on at the RWA signs. The standard deviation was also found to be greater with the RSS turned on. There was greater variation in speeds amongst all vehicles over the duration of the work period on Day 2.

Within the work zone, Tables 4.38 and 4.39 show similar comparisons at Drain #3 (without RSS turned on) and Drain #4 (with RSS turned on). As seen in the tables, the mean and 85th percentile speeds were less on Day 2 with the RSS display turned on. This difference was present for all vehicles combined and for just cars and just trucks. The speed differences ranged from 6.44 to 7.89 mph, and were found to be statistically significant for all vehicles ($p < 0.0001$) and for cars ($p < 0.0001$), but not for trucks ($p = 0.160$). The volume of trucks was very small, in part limiting the ability to obtain meaningful comparisons between the means on each day.

Table 4.36: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, I-84, Vactoring, RWA, 21:45-23:15

Test Day	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Day 1 (without RSS)	1624	62.57	56.23	7.09	87	60.22	53.64	7.86	1711	62.57	56.10	7.15
Day 2 (with RSS)	1825	64.66	57.43	7.82	101	61.04	55.63	10.52	1926	64.66	57.34	7.99

Table 4.37: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, I-84, Vactoring, RWA, Operation Time*

Test Day	Passenger Cars				Trucks				Total Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Day 1 (without RSS)	1112	62.90	56.68	7.17	58	60.35	54.52	6.99	1170	62.90	56.59	7.17
Day 2 (with RSS)	1514	64.22	57.24	7.69	80	59.67	55.98	8.46	1594	64.22	57.18	7.73

*: For Day 1 the operation time has considered from 22:03-22:51 and for Day 2 it has considered from 21:50-22:51.

Table 4.38: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, I-84, Vactoring, Drain 3 or 4

Test Day	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Day 1 (without RSS) (22:16-22:22)	63	57.98	48.86	7.94	3	52.89	47.71	7.62	66	57.55	48.80	7.88
Day 2 (with RSS) (22:03-22:10)	130	50.26	42.54	7.03	9	45.60	39.83	7.84	139	49.92	42.36	7.08

Table 4.39: Effect of Radar Speed Sign on Vehicle Speed, I-84, Vactoring, Drain 3 and Drain 4

Type of vehicle	Mean Speed (mph) without RSS (Day1)	Mean Speed (mph) with RSS (Day2)	Difference in mean speed (mph)	p-value
All Vehicles	48.80	42.36	6.44	< 0.0001
Passenger Cars	48.86	42.54	6.32	< 0.0001
Trucks	47.71	39.83	7.89	0.1598

Similar to Case Studies #1 and #2, analyses were also conducted that focused on the difference in speed between adjacent vehicles and the distance between adjacent vehicles as they passed through the work zone. Figure 4.38 shows the speed difference for vehicles passing Drain #3 during the work operation time on Day 1 without the RSS turned on. Each dot in the figure represents one vehicle. As seen in the figure, the speed differences vary significantly, with the majority in a range from approximately -10 mph to +10 mph. No particular trend in the data is visible from the figure.

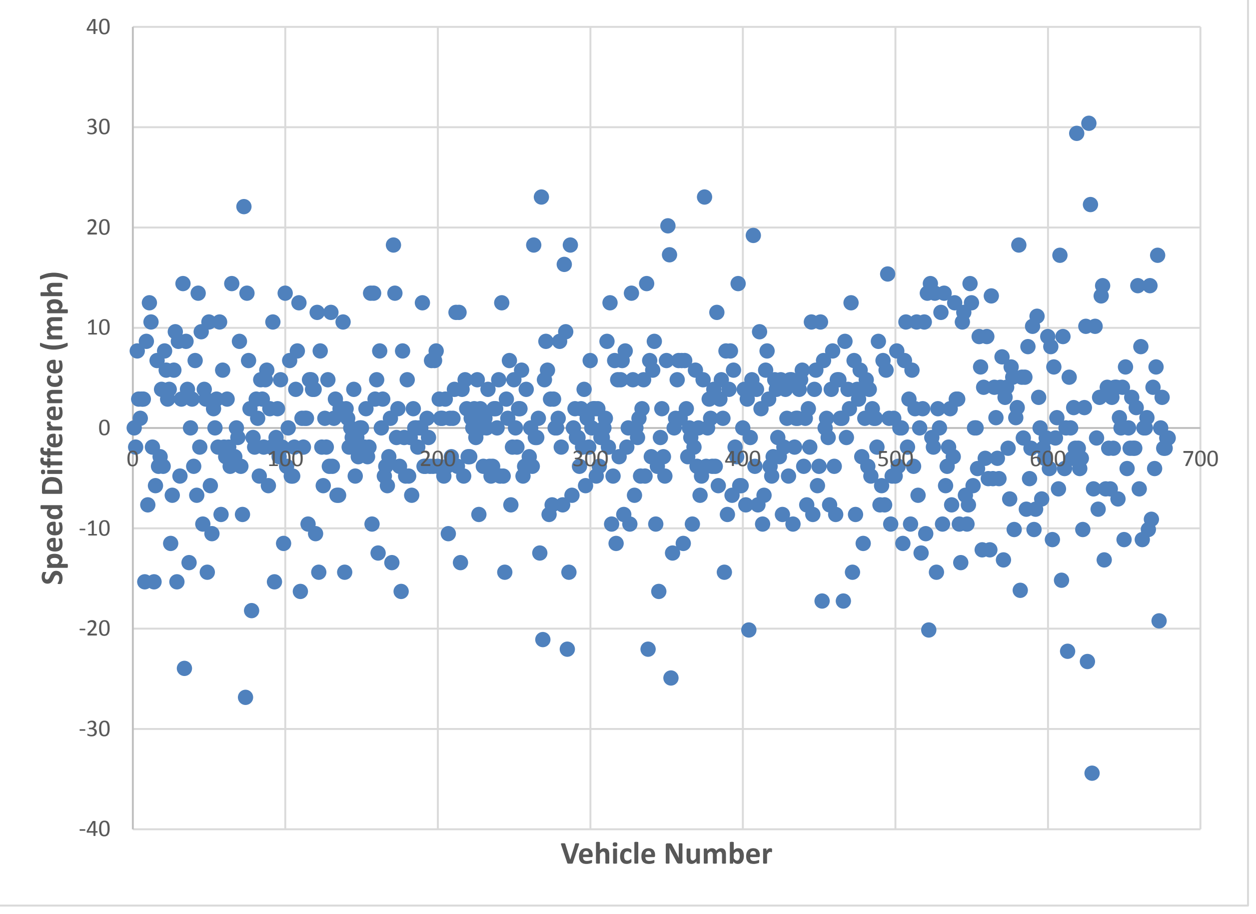


Figure 4.38: Speed Difference for Vehicles Passing Drain 3 during Operation Time, I-84, Vactoring, Without RSS (Day 1)

Figure 4.39 shows the speed differences compared to the actual speed of the vehicle adjacent Drain #3 during the work operation time on Day 1 without the RSS turned on. The horizontal access contains the speed of the trailing vehicle, and the vertical axis contains the difference in speed between the trailing vehicle and the vehicle in front of it. The figure shows an apparent positive slope; as the vehicle's speed increases, the difference in speed between the vehicle under consideration and the vehicle in front of it also increases. This trend is expected because the two factors are related in nature. Speed difference is calculated from vehicle speed. If the speed for the trailing vehicle is high, there is a greater chance that the speed difference will be high also. The vehicles represented by the data points in the upper-right portion of the figure are especially of concern because they are travelling at a high rate of speed and at a high rate of speed relative to the preceding vehicle. A reduction of the number of vehicles travelling is this manner is desired to improve safety in the work zone.

The posted regulatory speed at this location is 55 mph. During the testing on Day 1, 60% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. During the entire test period at Drain #3 within the work zone, 46% of the vehicles were going faster than the posted speed limit. During the time when the maintenance equipment was located at Drain #3, 27% of the vehicles were travelling faster than the speed limit.

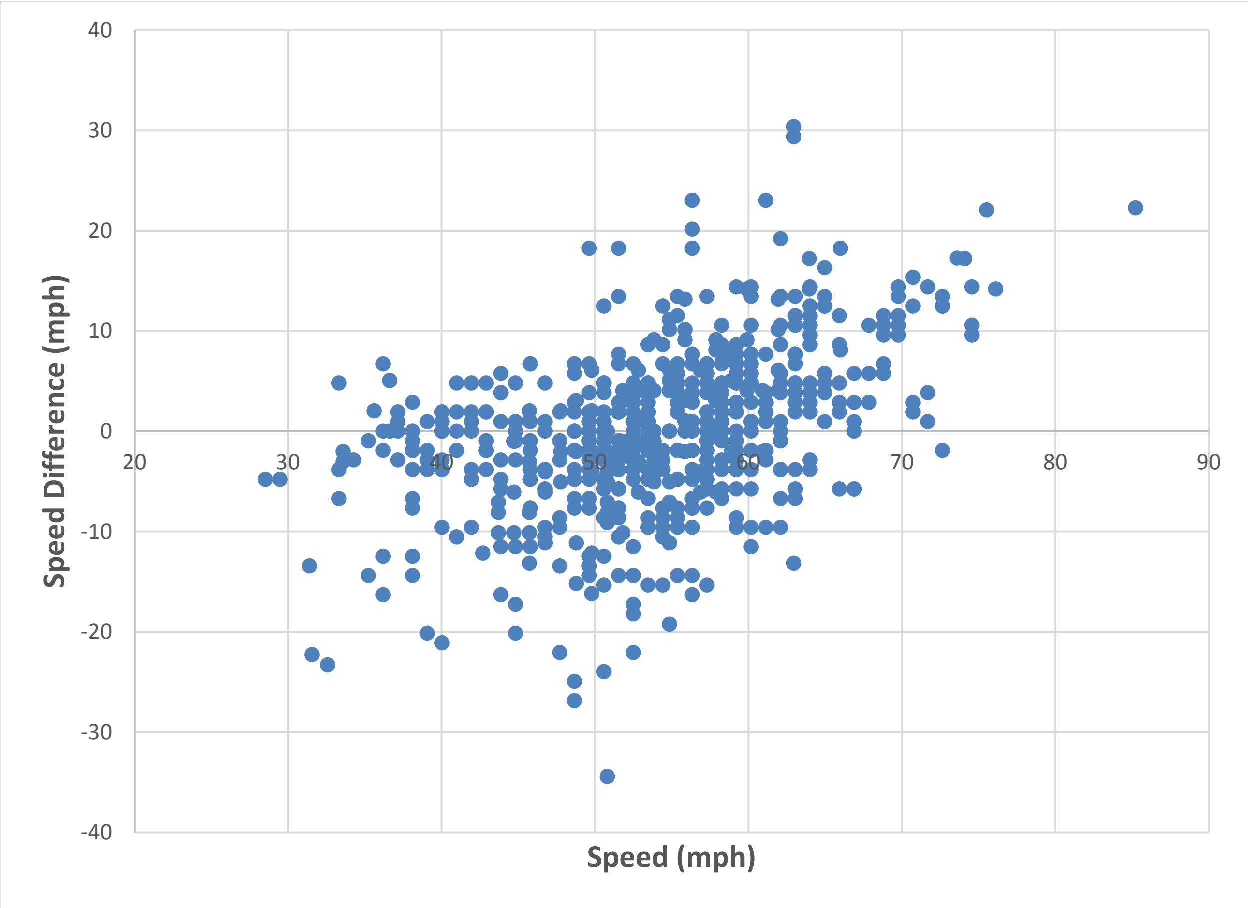


Figure 4.39: Speed Difference vs. Vehicle Speed for Vehicles Passing Drain 3 during Operation Time, I-84, Vactoring, Without RSS (Day 1)

Figure 4.40 is similar to Figure 4.39, however the vertical axis in Figure 4.40 shows the distance between adjacent vehicles rather than the speed difference. Figure 4.40 shows the data for the vehicles passing Drain #3 during the work operation time on Day 1 without the RSS turned on. While the distance apart varies, the majority of vehicles are less than approximately 750 feet apart. The figure does not show a clear trend in distance between adjacent vehicles. The vehicles represented by the data points in the lower-right portion of the figure are travelling at a high rate of speed and travelling close to the preceding vehicle. This type of driving behavior can be dangerous; reducing the amount of vehicles travelling in this manner will help improve safety in the work zone.

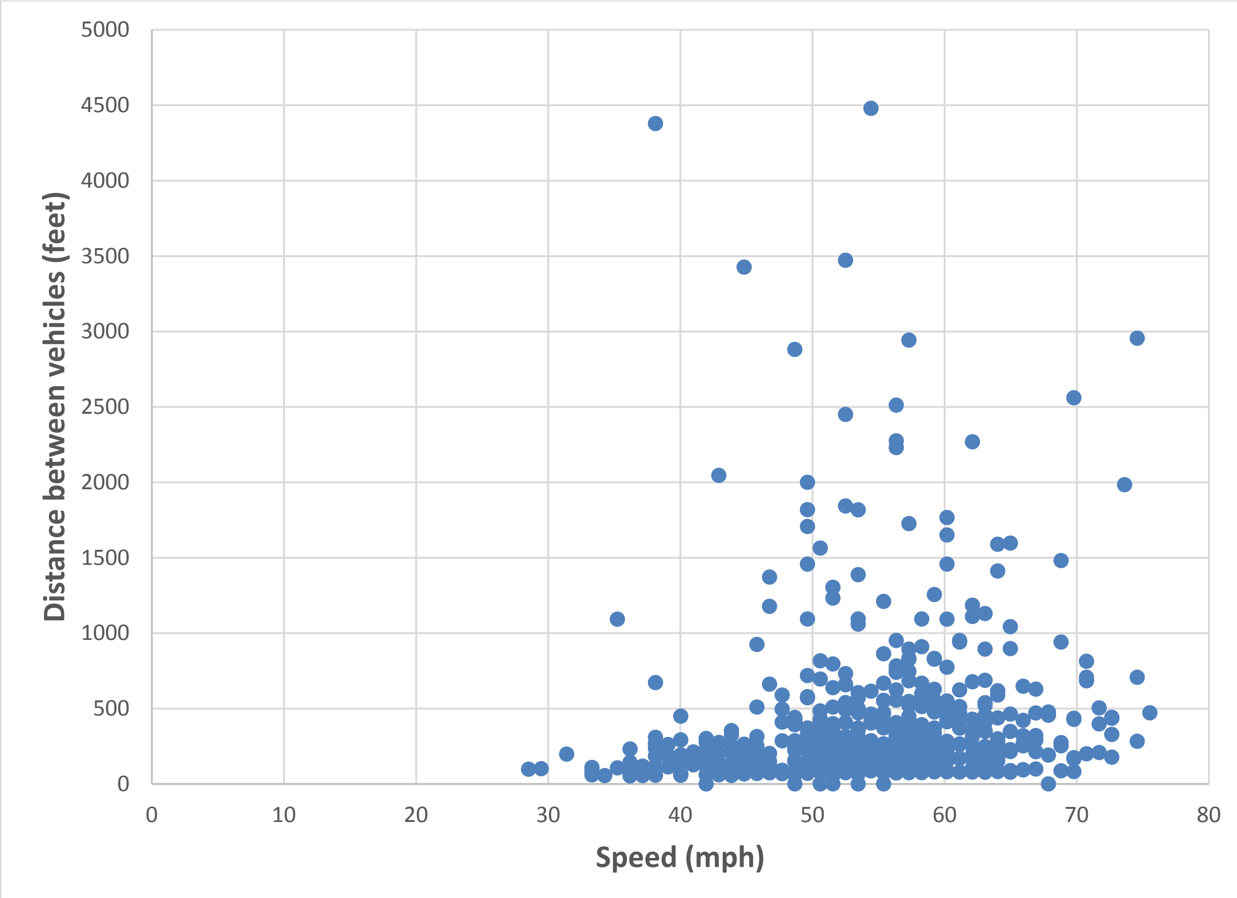


Figure 4.40: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Drain 3 during Operation Time, I-84, Vactoring, Without RSS (Day 1)

The distance between adjacent vehicles compared to the speed difference between vehicles is shown in Figure 4.41. The data is shown for vehicles passing Drain #3 during the work operation time on Day 1 without the RSS turned on. Again, no particular trend is visible in the figure. The data points with negative speed difference indicate that the trailing vehicle is slower than the leading vehicle and getting farther away from the leading vehicle as the vehicles travel down the roadway. Those data points on the right side of the figure (higher positive speed difference), especially those with small distance between vehicles, are of concern. To prevent potential rear-end collisions, those vehicles with large positive speed difference (i.e., high speed relative to the vehicle in front of it) and low distance apart (i.e., close to the vehicle in front of it) is undesirable.

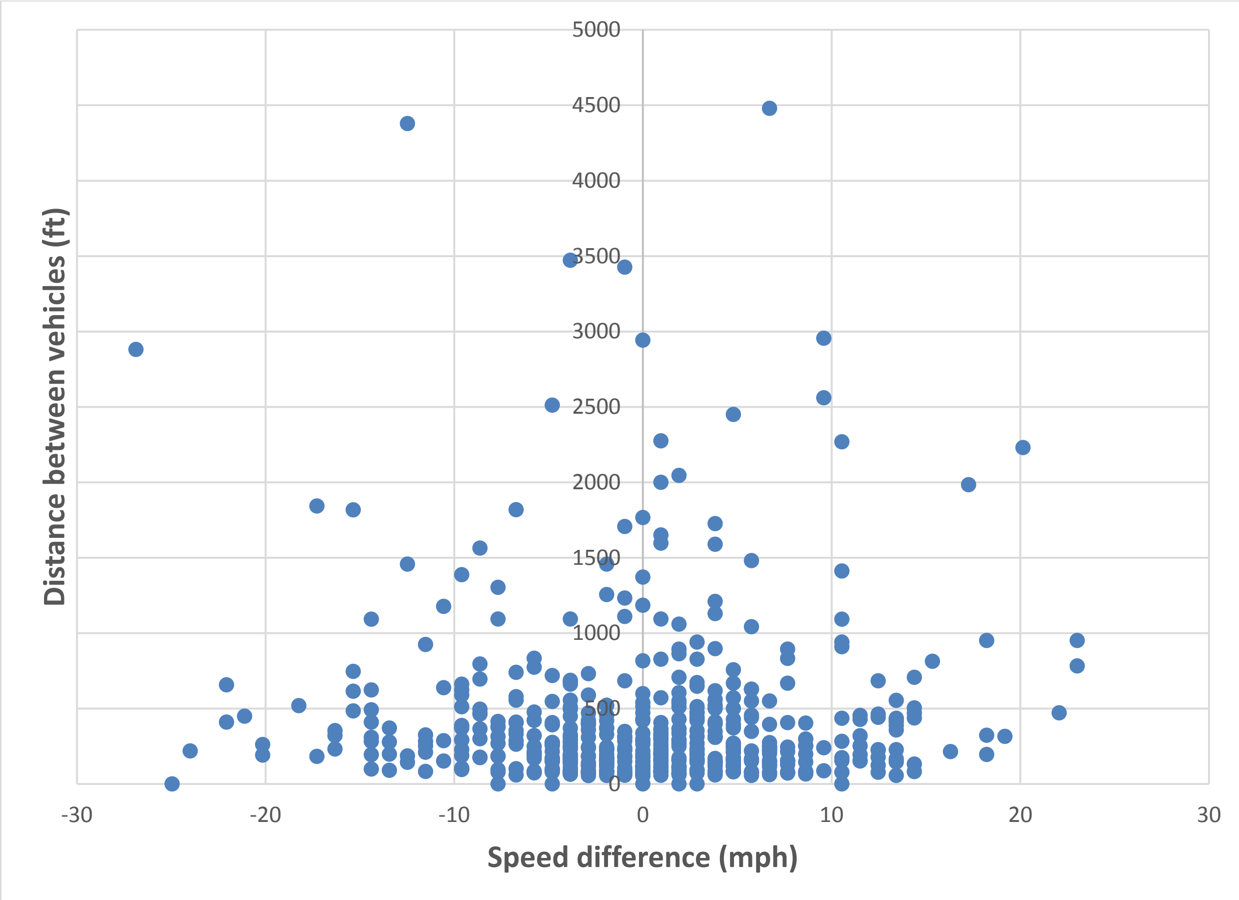


Figure 4.41: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Drain 3 during Operation Time, I-84, Vactoring, Without RSS (Day 1)

For comparison, Figures 4.42, 4.43, 4.44, and 4.45 show similar speed and distance difference charts for Day 2 with the RSS turned on. In these figures, the data is based on vehicles adjacent Drain #4, which is near Drain #3. Similar charts at the other drains are provided in the Appendix.

During the testing on Day 2, 62% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. This percentage is approximately the same as on Day 1 without the RSS turned on. During the entire test period on Day 2, at Drain #4 within the work zone 36% of the vehicles were going faster than the posted speed limit, which is less than the 46% on Day 1. During the time when the maintenance equipment was located at Drain #4, 3% of the vehicles were travelling greater than the speed limit. It should be noted that for this case study, speed sensors were only placed in the B (middle) and C (slow) lanes at this location; vehicle speeds in the A (fast) lane were not recorded and were likely higher than in the B and C lanes. These results show that the RSS helped to decrease the percentage of vehicles travelling faster than the posted speed limit.

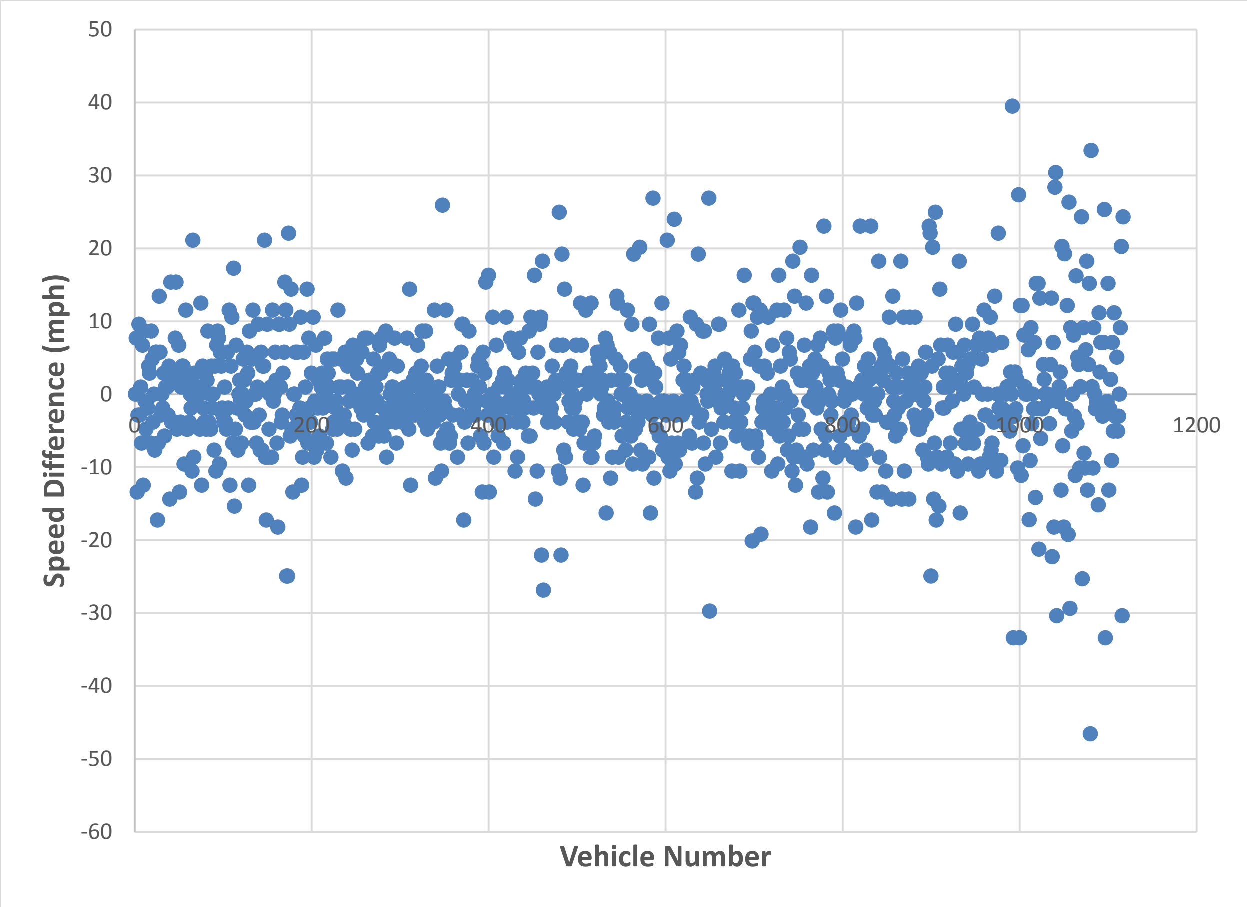


Figure 4.42: Speed Difference for Vehicles Passing Drain 4 during Operation Time, I-84, Vactoring, With RSS (Day 2)

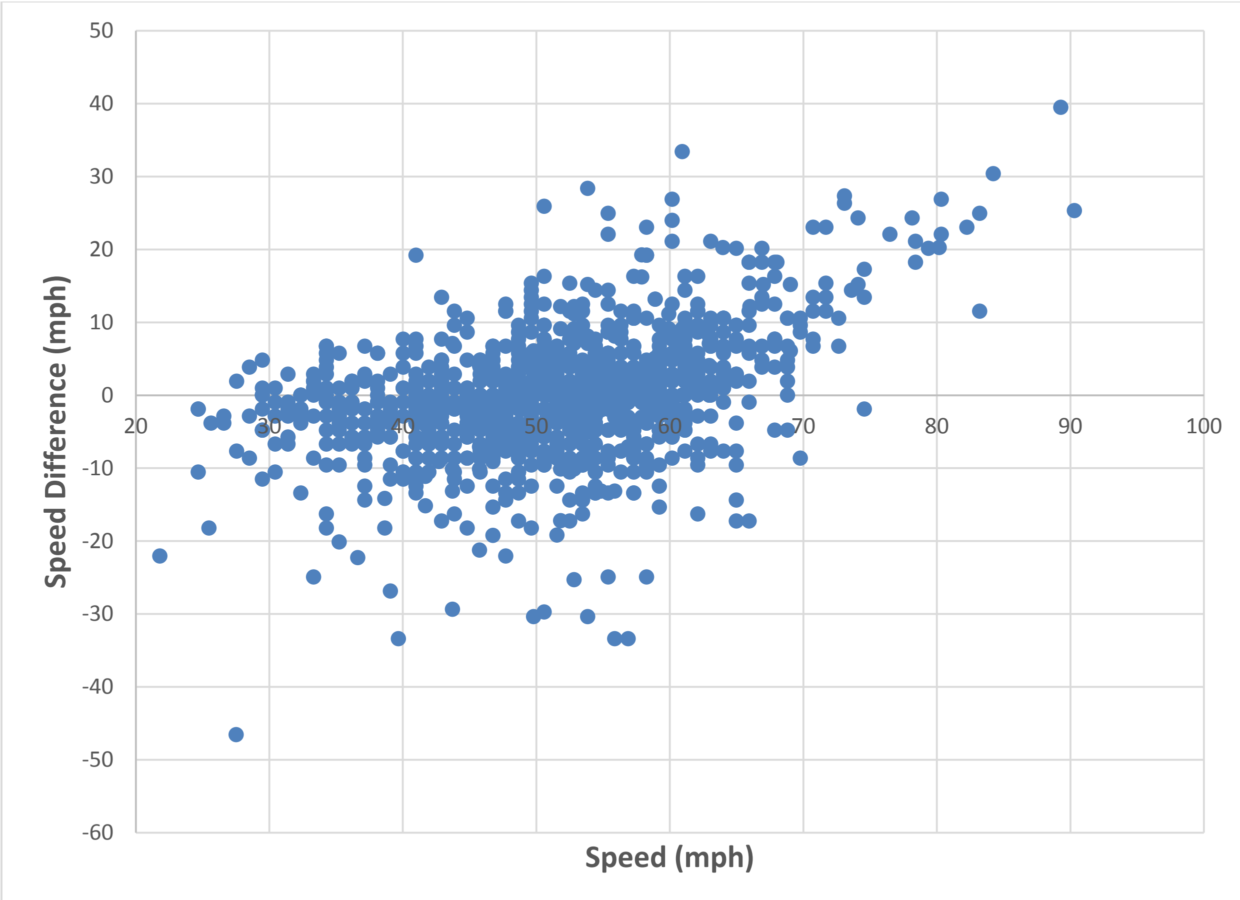


Figure 4.43: Speed Difference vs. Vehicle Speed for Vehicles Passing Drain 4 during Operation Time, I-84, Vactoring, With RSS (Day 2)

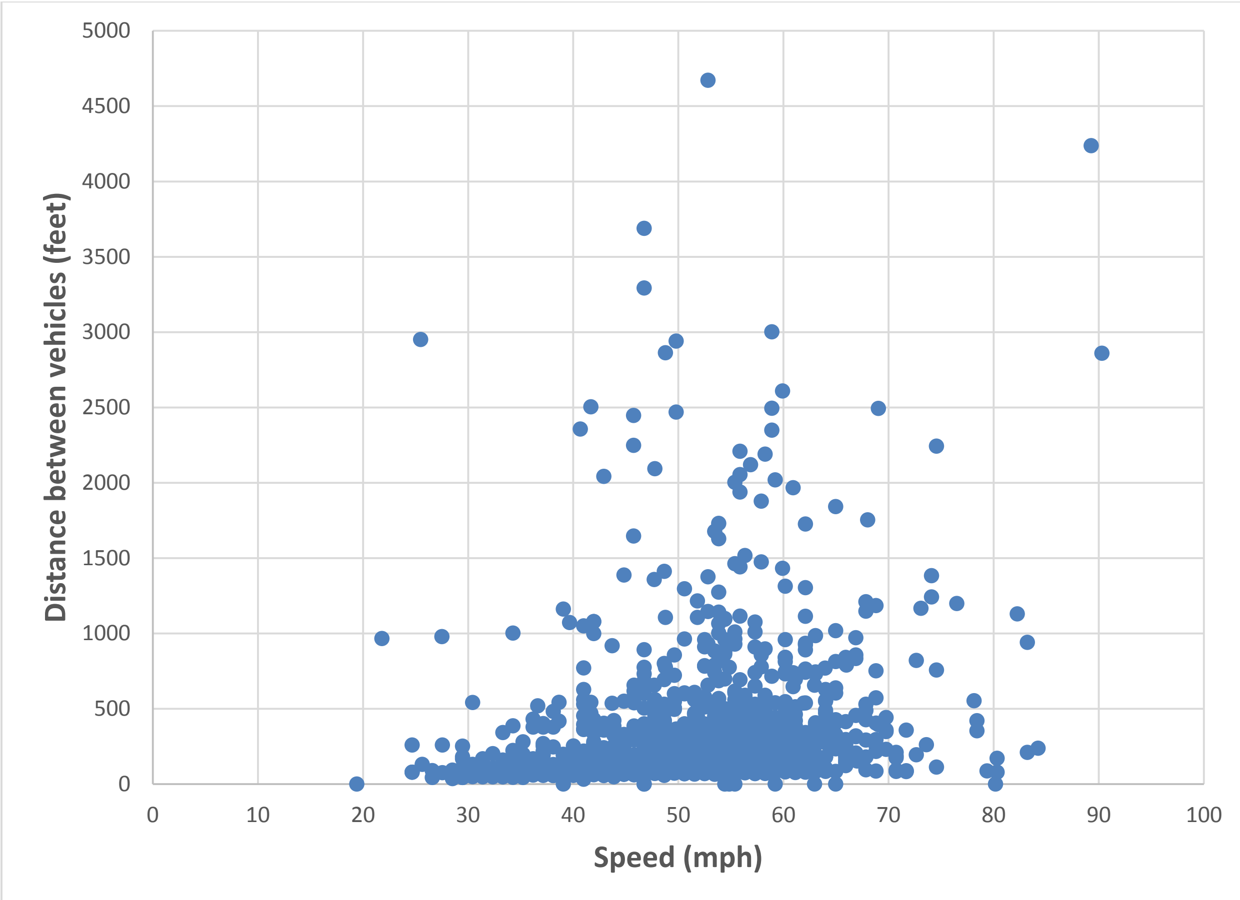


Figure 4.44: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Drain 4 during Operation Time, I-84, Vactoring, With RSS (Day 2)

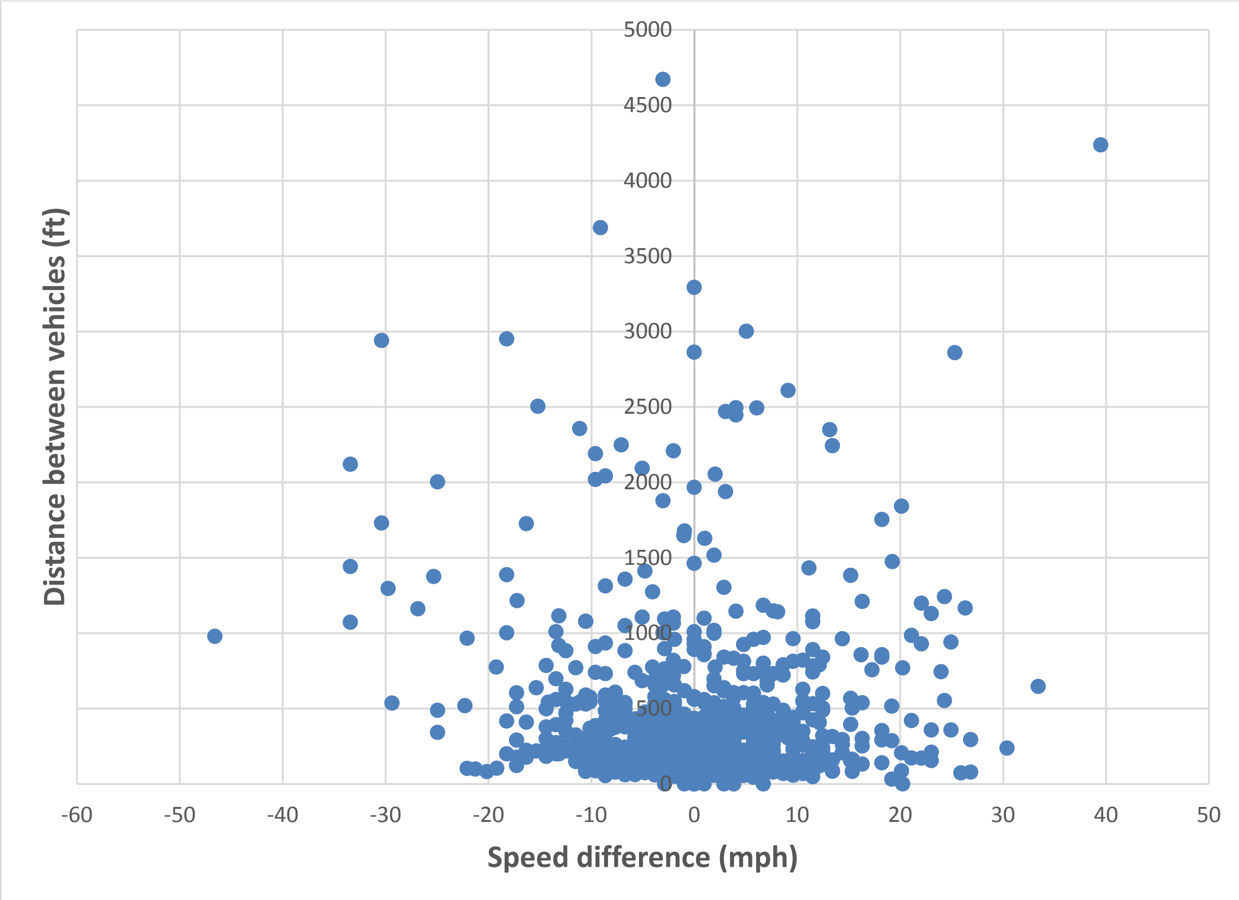


Figure 4.45: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Drain 4 during Operation Time, I-84, Vactoring, With RSS (Day 2)

Statistical tools were used to analyze the treatment effect of implementing the RSS display. A two-sample t-test was conducted to see whether turning on the RSS display has an effect on the speed difference. In the analysis, the absolute value of speed difference is used as the dependent variable. Absolute value is used due to the fact that, if the speed differences are added together, the negatives and positives will cancel each other and the mean of speed difference will be close to zero. The statistical test was conducted for all vehicles combined, for only passenger cars, and for only trucks.

Table 4.40 summarizes the results of this analysis. The data used to create the table consisted of all of the data recorded at Drains #3 (without RSS turned on) and #4 (with RSS turned on). Similar tables comparing the speed differences at other adjacent drains are provided in the Appendix.

For all vehicles at Drains #3 and #4, the RSS display turned on resulted in a 0.24 mph higher speed difference (p-value = 0.396). Therefore, there is no statistically significant evidence that the mean of 5.91 mph without the RSS turned on and the mean of 6.15 mph with the RSS turned on are different. For passenger cars only, the p-value is 0.166, which also indicates no statistically significant difference in mean speeds when the RSS display is turned on compared to when the RSS is not used. For trucks, the p-value is 0.383, which indicates no difference as well.

Overall, this test revealed that the RSS display does not have a significant impact on absolute value of speed difference.

Table 4.40: Effect of Radar Speed Sign on Absolute Value of Speed Differences between Adjacent Vehicles, I-84, Vactoring, Drain 3 and Drain 4

Type of vehicle	Mean of absolute value of Speed difference (mph) without RSS (Day1)	Mean of absolute value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	5.91	6.15	0.24	0.3960
Passenger Cars	5.91	6.33	0.41	0.1662
Trucks	5.77	6.83	1.06	0.3829

A second statistical analysis was performed using just the positive speed difference values, and omitting those with negative speed difference. Positive speed difference represents a vehicle that is driving faster than the vehicle in front of it. This situation is possibly hazardous as it can lead to rear-end crashes. The results of the analysis, shown in Table 4.41, are similar to the analysis using absolute value of speed differences. There is no statistical evidence that the RSS display has an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it for all vehicles combined ($p = 0.099$) and for just trucks ($p = 0.292$). However, for passenger cars (vehicles < 25 feet), the difference of 0.85 mph is statistically significant ($p = 0.048$).

Table 4.41: Effect of Radar Speed Sign on Vehicles with Positive Speed Differences between Adjacent Vehicles, I-84, Vactoring, Drain 3 and Drain 4

Type of vehicle	Mean of positive value of Speed difference (mph) without RSS (Day1)	Mean of positive value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	6.24	6.93	0.69	0.0994
Passenger Cars	6.25	7.10	0.85	0.0483
Trucks	6.11	8.30	2.19	0.2919

Similar analyses were conducted using the distance between adjacent vehicles as the dependent variable to assess the impact of the treatment (use of RSS display). Table 4.42 shows the results of the analysis. For all vehicles, for just passenger cars, and for just trucks, there is statistically significant evidence that the RSS display has an impact on the distance between adjacent vehicles ($p = 0.0000$, 0.0003, and 0.0147, respectively). The difference in distance between adjacent vehicles was approximately 158 feet for all vehicles combined, 141 feet for passenger cars, and 404 feet for trucks.

Table 4.42: Effect of Radar Speed Sign on Distance between Adjacent Vehicles, I-84, Vactoring, Drain 3 and Drain 4

Type of vehicle	Mean of distance apart without RSS (feet)	Mean of distance apart with RSS (feet)	Difference in mean values (feet)	p-value
All Vehicles	559.09	400.42	158.67	< 0.0001
Passenger Cars	544.01	402.09	141.92	0.0003
Trucks	786.38	381.67	404.71	0.0147

Additional statistical tests were conducted to explore the effect of vehicle type on mean speed with and without the RSS display turned on. Table 4.43 shows the results of these tests. Similar to the tables above, the values shown in the table are calculated from all of the data recorded by the sensors at Drain #3 (Day 1 without the RSS turned on). The results suggest that vehicle type does not have an impact on the speed difference and the distance between adjacent vehicles.

Table 4.43: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-84, Vactoring, Without RSS (Day 1), Drain 3

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference (mph)	5.91	5.77	0.14	0.8645
Mean positive speed difference (mph)	6.25	6.11	0.14	0.9022
Mean distance between adjacent vehicles (feet)	544.01	786.38	242.37	0.0921

Table 4.44 shows the results for cars and trucks at Drain #4 with the RSS turned on (Day 2). The calculated p-values indicate no statistically significant difference between cars and trucks with respect to absolute value of speed difference ($p = 0.466$), positive speed difference ($p = 0.260$), and distance between adjacent vehicles ($p = 0.790$).

Table 4.44: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-84, Vactoring, With RSS (Day 2), Drain 4

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference (mph)	6.33	6.83	0.51	0.4665
Mean positive speed difference (mph)	7.10	8.30	1.19	0.2596
Mean distance between adjacent vehicles (feet)	402.09	381.67	20.42	0.7895

When the data at both Drain #3 and Drain #4 are combined, the differences between cars and trucks are shown in Table 4.45. The results are similar to that found in the tables above. In all cases, trucks have a higher mean speed difference and higher mean distance between adjacent vehicles. The differences between cars and trucks, however, were not found to be statistically significant.

Table 4.45: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, I-84, Vactoring, With and Without RSS (Day 1 and 2), Drain 3 and Drain 4

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference(mph)	6.18	6.50	0.32	0.5540
Mean positive speed difference (mph)	6.78	7.58	0.80	0.3198
Mean distance between adjacent vehicles (feet)	450.77	509.47	58.70	0.4041

In Case Study #3, the RSS unit displayed the approaching vehicle speed when the RSS was turned on. As described above, the RSS unit has the capability of saving the speeds recorded to an internal file. However, this capability was not operable during the case study testing. Therefore, no speeds of approaching vehicles are available for analysis.

Lastly, for this case study, the researchers also performed multiple probe vehicle passes through the work zone on both Day 1 and Day 2. Figure 4.46 shows an example of the speeds recorded by the probe vehicle on Day 1 without the RSS turned on when the work operation was located at Drain #3. Figure 4.47 shows a similar chart on Day 2 with the RSS turned on when the work operation was located at Drain #4.

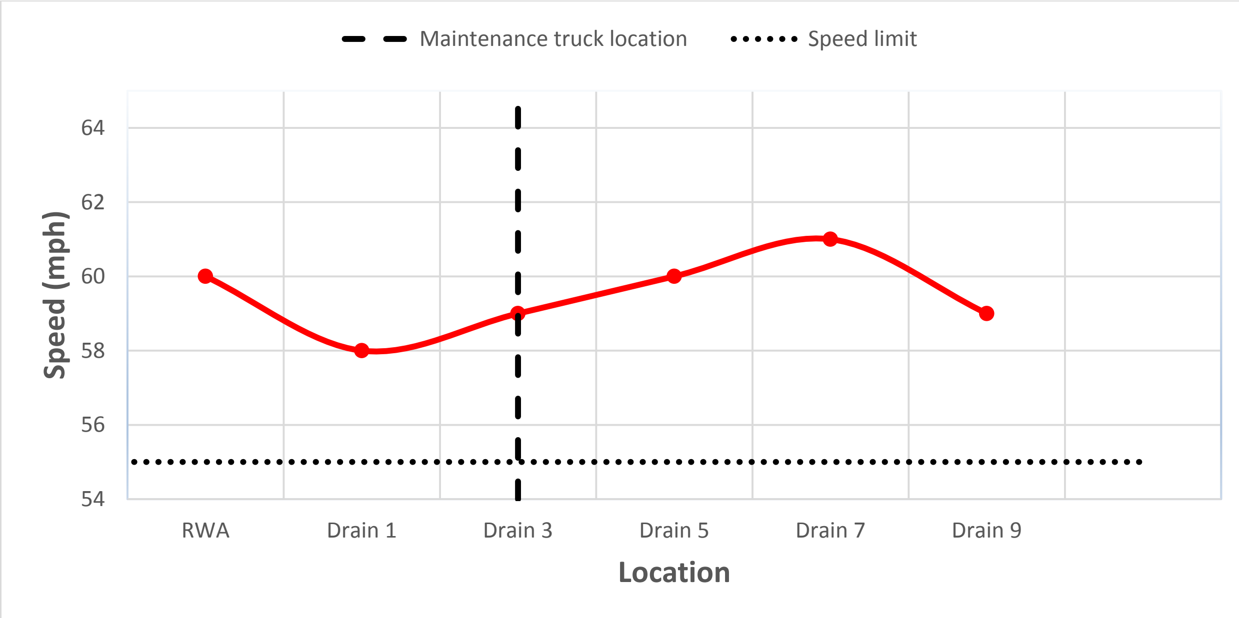


Figure 4.46: Probe Vehicle, I-84, Vactoring, Without RSS (Day 1)

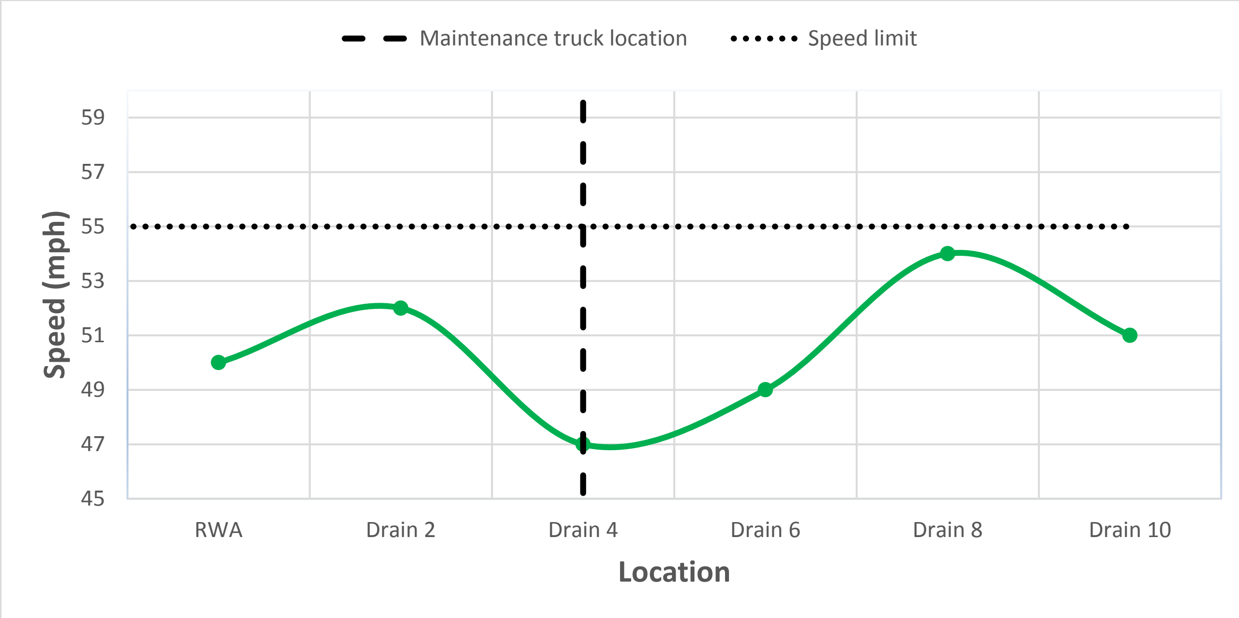


Figure 4.47: Probe Vehicle, I-84, Vactoring, With RSS (Day 2)

4.4 CASE STUDY #4: US-97 SPRAYING

This section of the report presents the results and analysis of the data collected during the spraying operation on US-97 (Case Study #4). The tables and figures provided in this section are similar to that provided for the other case studies above. Discussion of the results shown in each table and figure are also similar to that for the other case studies, and repeated here for clarity. Modifications to the discussion are made to reflect the Case Study #4 data. Only summary tables and figures are provided and discussed below; additional tables and figures related to Case Study #4 are provided in the Appendix.

The spraying work performed on Case Study #4 is a continuously moving operation similar to the sweeping operation in Case Study #2. As with Case Study #2, all of the testing was performed on one day, with the spraying operation making multiple passes both with and without the RSS display turned on. The tables and figures show recorded speeds over the periods of time without the RSS turned on, while the equipment was returning to the starting point to make another pass (free flow), and with the RSS display turned on.

Figure 4.48 presents the recorded traffic volumes during the testing periods on the day of testing. The traffic volume on this case study is significantly lower than that on the other case studies. Total traffic volumes decreased during the course of the testing. The recorded traffic volumes for each time period shown in Figure 4.48 are different in part due to the length of time of each period. Longer periods of time will have greater numbers of vehicles. The percentage of cars (vehicles < 25 feet in length) and percentage of trucks (vehicles > 25 feet in length) vary slightly over the entire test period.

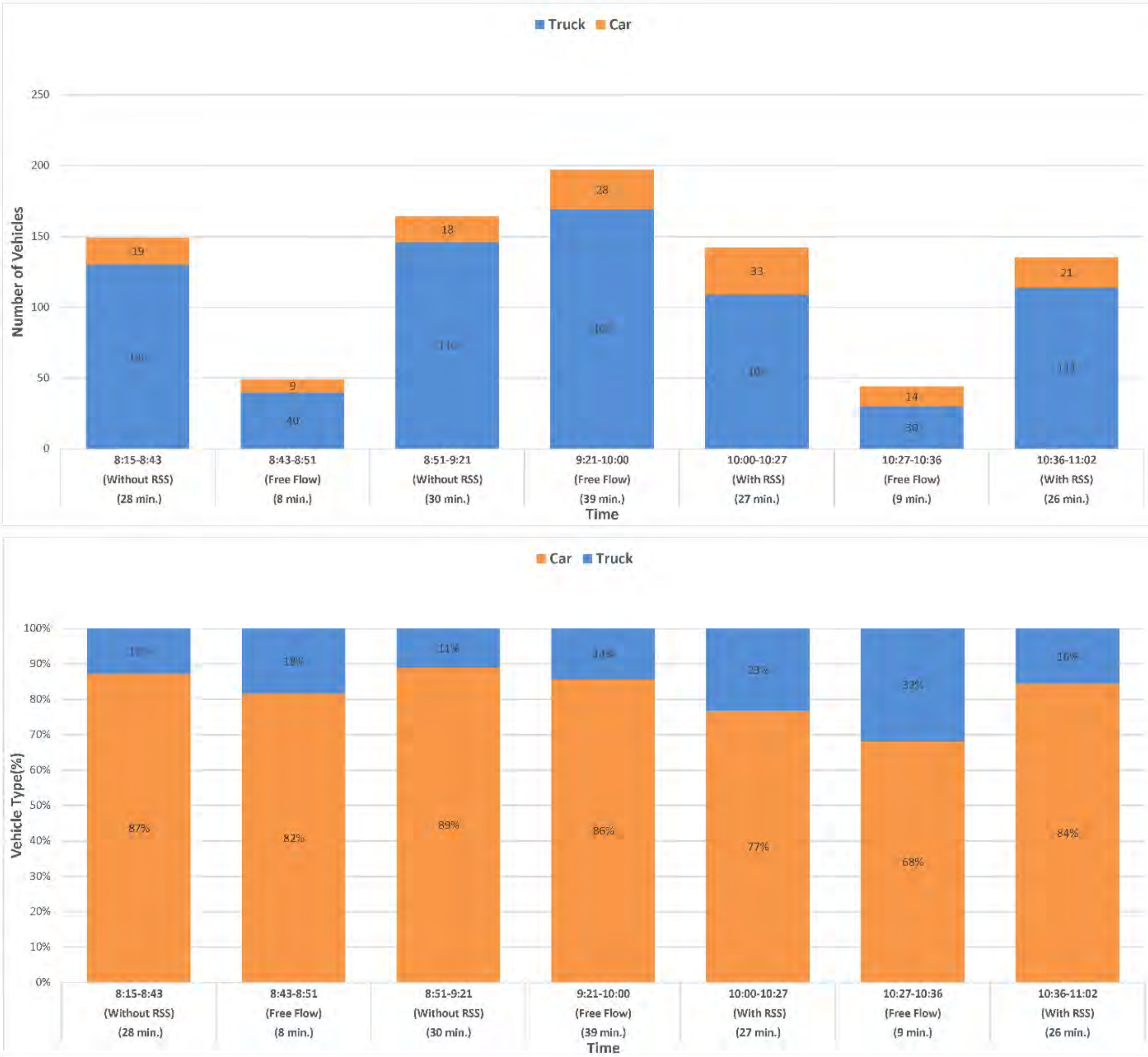


Figure 4.48: Traffic Volume, Number of Vehicles and Vehicle Type Percentage, US-97, Spraying, Location 1

Table 4.46 presents a summary of the vehicle speeds recorded for all vehicles at the RWA sign location during the testing period. For this table, the values represent the data downloaded from the sensors in both the A and B lanes. The 85th percentile speeds for all three timeframes (without RSS turned on, free flow, and with RSS turned on) were 65.3 mph, 63.6 mph, and 64.2 mph, respectively. Similarly, Table 4.47 shows a summary of the vehicle speeds over the same period recorded in the work area, specifically at sensor location #1. The 85th percentile speed decreased to 62.1 mph without the RSS turned on and 61.2 mph with the RSS turned on at this location.

Table 4.46: Hourly Summary of Vehicle Speed, US-97, Spraying, RWA

	Time									
Vehicle Speed (all vehicles)	**Total (without RSS)**	**Total (Free Flow)**	**Total (with RSS)**	8:15-8:43 (without RSS)	8:43-8:51 (Free Flow)	8:51-9:21 (without RSS)	9:21-10:00 (Free Flow)	10:00-10:27 (with RSS)	10:27-10:36 (Free Flow)	10:36-11:02 (with RSS)
MPH										
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.3%	0.4%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	2.3%	0.0%
25-29	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.7%	0.0%	0.0%
30-34	0.3%	0.4%	0.0%	0.7%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%
35-39	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%
40-44	0.3%	3.6%	0.4%	0.7%	0.0%	0.0%	5.2%	0.7%	0.0%	0.0%
45-49	7.3%	7.8%	6.9%	11.2%	0.0%	3.6%	9.9%	7.2%	7.0%	6.5%
50-54	26.2%	26.7%	23.1%	25.7%	26.1%	26.7%	25.5%	28.3%	32.6%	18.0%
55-59	29.7%	33.5%	37.2%	30.3%	34.8%	29.1%	31.8%	37.7%	39.5%	36.7%
60-64	20.2%	16.0%	19.5%	19.1%	19.6%	21.2%	16.7%	13.8%	9.3%	25.2%
65-69	10.4%	6.8%	7.6%	8.6%	10.9%	12.1%	5.7%	7.2%	7.0%	7.9%
70-74	3.5%	1.4%	2.9%	2.6%	2.2%	4.2%	1.6%	3.6%	0.0%	2.2%
>=75	1.9%	2.8%	2.2%	1.3%	6.5%	2.4%	2.1%	0.7%	2.3%	3.6%
Total # of vehicles	317	281	277	152	46	165	192	138	43	139
Average speed	58.4	56.8	58.5	57.3	59.7	59.4	56.1	57.4	56.4	59.6
St. Dev.	7.4	7.8	7.1	6.9	6.7	7.7	7.8	6.5	8.4	7.5
85th percentile	65.3	63.6	64.2	63.2	65.4	66.0	63.2	63.9	62.1	64.3
Min	24.0	25.0	29.3	34.6	50.5	24.0	32.5	29.3	25.0	47.3
Max	91.8	91.7	94.9	81.1	78.2	91.8	91.7	75.8	87.5	94.9
Range	67.8	66.7	65.6	46.5	27.8	67.8	59.2	46.5	62.5	47.6

Table 4.47: Hourly Summary of Vehicle Speed, US-97, Spraying, Location 1

	Time									
Vehicle Speed (all vehicles)	Total (without RSS)	Total (Free Flow)	Total (with RSS)	8:15-8:43 (without RSS)	8:43-8:51 (Free Flow)	8:51-9:21 (without RSS)	9:21-10:00 (Free Flow)	10:00-10:27 (with RSS)	10:27-10:36 (Free Flow)	10:36-11:02 (with RSS)
MPH										
< 10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.3%	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%
35-39	1.0%	1.0%	0.0%	0.7%	0.0%	1.2%	1.5%	0.0%	0.0%	0.0%
40-44	6.1%	7.9%	6.5%	6.0%	8.2%	6.1%	8.1%	6.3%	6.8%	6.7%
45-49	24.0%	23.8%	25.3%	21.5%	28.6%	26.2%	20.3%	25.4%	34.1%	25.2%
50-54	31.3%	26.9%	28.5%	29.5%	30.6%	32.9%	27.4%	33.8%	20.5%	23.0%
55-59	17.3%	18.6%	19.9%	16.8%	16.3%	17.7%	18.3%	11.3%	22.7%	28.9%
60-64	9.9%	12.4%	14.1%	13.4%	10.2%	6.7%	13.2%	15.5%	11.4%	12.6%
65-69	5.1%	5.5%	4.3%	6.0%	4.1%	4.3%	6.6%	5.6%	2.3%	3.0%
70-74	2.6%	2.1%	0.7%	3.4%	2.0%	1.8%	2.0%	1.4%	2.3%	0.0%
>=75	2.6%	1.4%	0.7%	2.0%	0.0%	3.0%	2.0%	0.7%	0.0%	0.7%
Total # of vehicles	313	290	277	149	49	164	197	142	44	135
Average speed	54.4	54.0	54.0	54.7	53.2	54.1	54.4	54.0	53.3	53.9
St. Dev.	8.5	8.0	6.8	8.5	6.8	8.5	8.4	7.2	7.0	6.4
85th percentile	62.1	61.5	61.2	63.0	60.1	60.4	62.1	61.4	60.5	60.2
Min	28.5	32.5	40.5	28.5	41.5	37.5	32.5	40.5	41.5	41.5
Max	91.7	88.9	82.4	82.4	71.3	91.7	88.9	82.4	74.1	77.8
Range	63.2	56.5	42.0	54.0	29.9	54.2	56.5	42.0	32.7	36.4

The traffic analyzers provided the opportunity to view the vehicle speeds through the work zone. Figure 4.49 shows how the 85th percentile speed changed from the RWA signs to the end of the work zone at sensor location #4 for all cases (with and without RSS turned on, and free flow). As seen in the figure, for much of the work zone, the speeds with the RSS turned on were slightly lower than without the RSS turned on. The difference speeds is not as great as that recorded on the other case study projects.

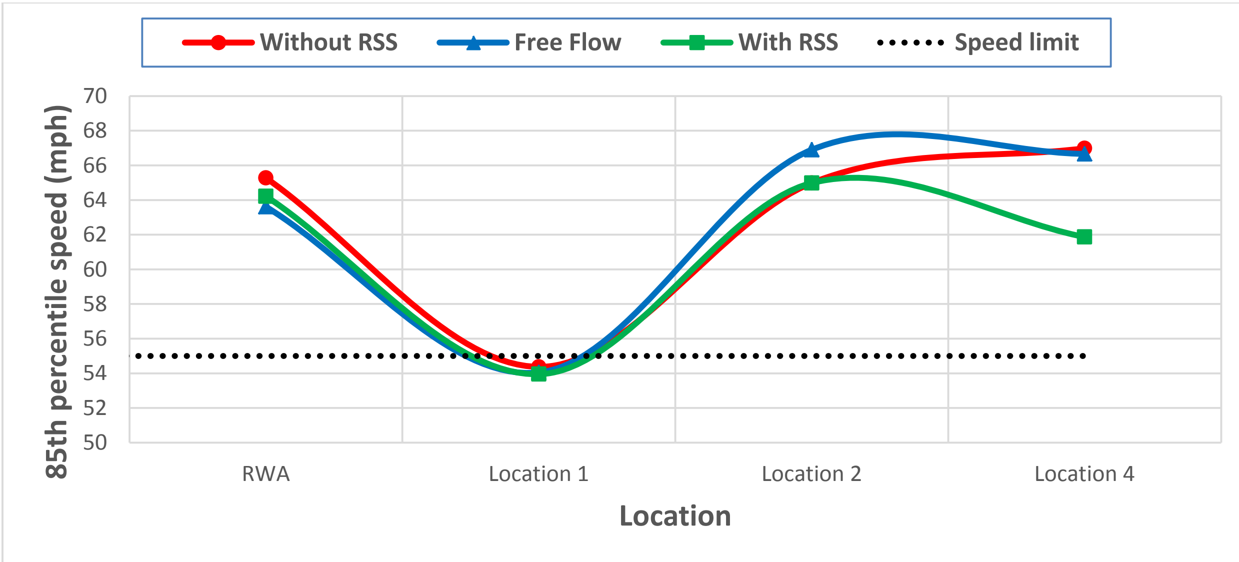


Figure 4.49: Vehicle Speed (85^{th} percentile) at Different Locations during Operation Time, US-97, Spraying

It is likely that the speed in the work zone, at least in the initial portion of the work zone, depends on the speed of the vehicles prior to the work zone. Figure 4.50 shows the 85^{th} percentile speeds at the RWA signs throughout the testing period. Similarly, Figure 4.51 shows the 85^{th} percentile speeds at sensor location #1 during the testing period. Compared to speeds at the RWA signs, in the work zone the speeds were consistently lower during all periods of the work (with and without RSS turned on), excluding the free flow periods. Additionally, Figure 4.51 shows that with the RSS turned on, the 85^{th} percentile speed for both periods combined was lower than without the RSS turned on. Free flow speeds while the sweeping equipment was returning to the start of the work area to make another pass were higher than or about the same as the periods when the spraying operation was taking place.

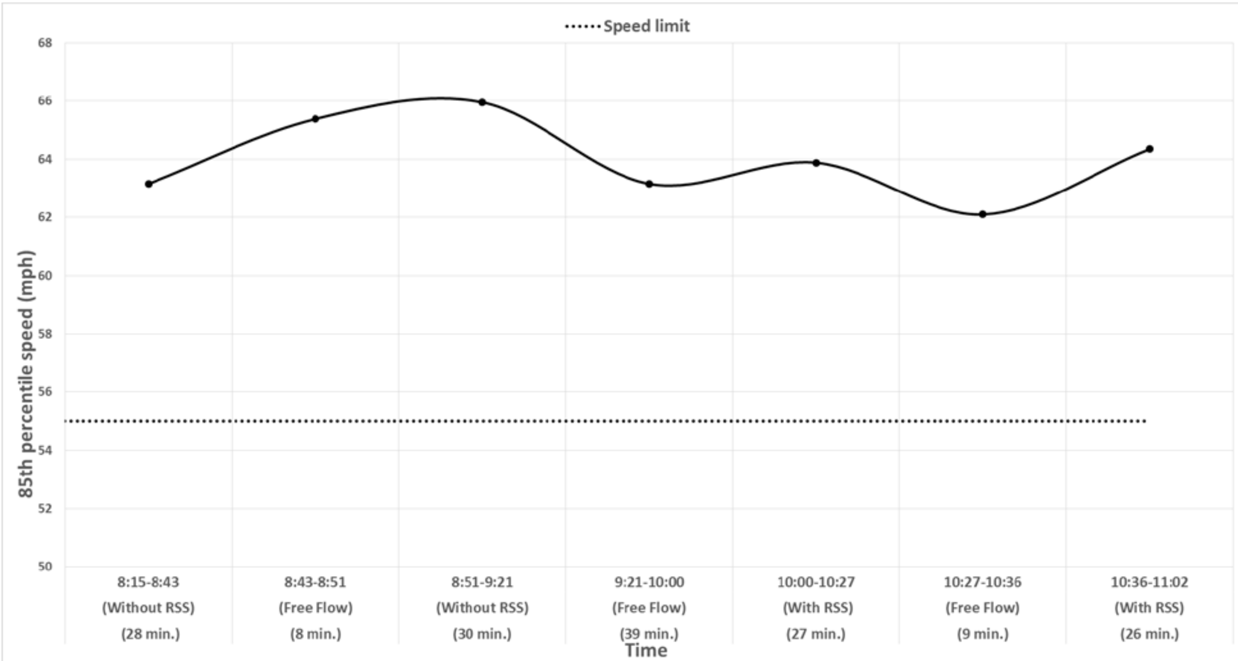


Figure 4.50: Vehicle Speed (85th Percentile) at RWA during Operation Time, US-97, Spraying

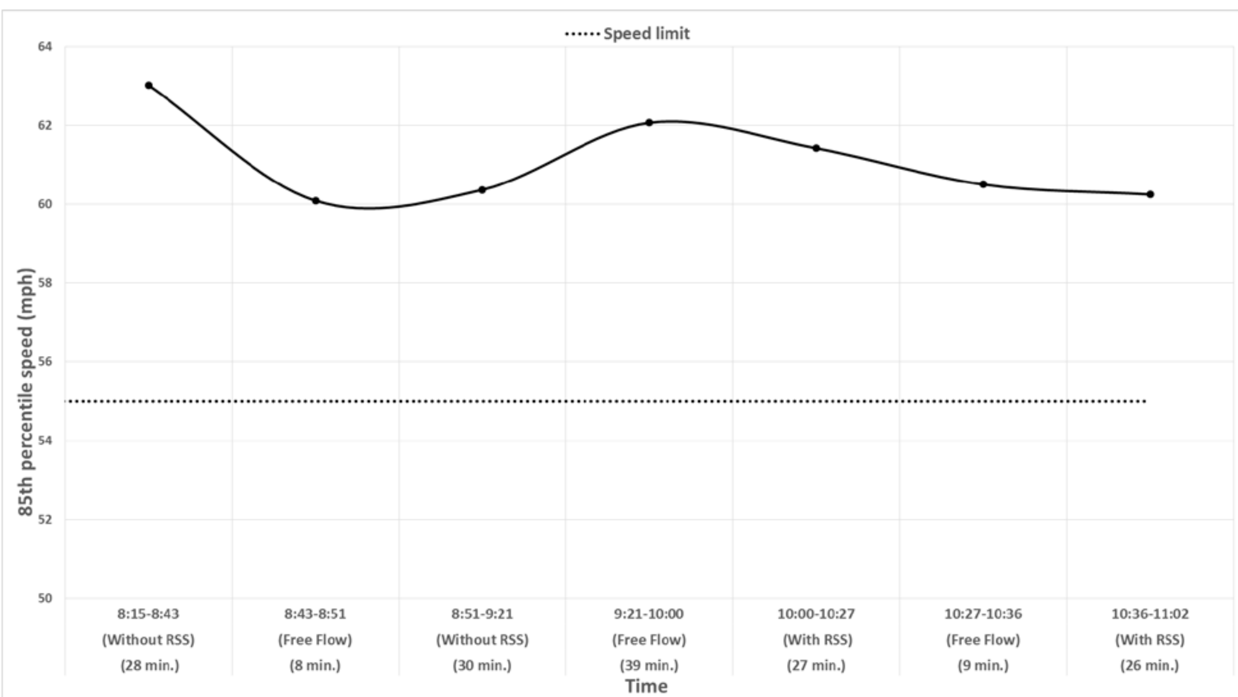


Figure 4.51: Vehicle Speed (85th Percentile) at Location 1 during Operation Time, US-97, Spraying

Similar to the other case studies, as part of the data analysis, comparisons were made between the vehicle speeds during the different work periods. Figure 4.52 shows a comparison of 85th percentile speeds at sensor location #1 with and without the RSS turned on. Sensor location #1 was selected for illustration; similar charts showing comparisons for other locations are provided in the Appendix. The figure illustrates the effect of the presence of the work equipment at location #1. The vehicles slow down as they approach the work operation and then speed up afterwards. The amount of increase after the equipment was greater and earlier without the RSS display turned on. For example, from location #1 to #4, the speeds increased from approximately 60 to 67 mph (7 mph increase) without the RSS turned on. However with the RSS turned on, speed increased from 61 at location #1 to 64 at location #2, and then decreased to 62 at location #4.

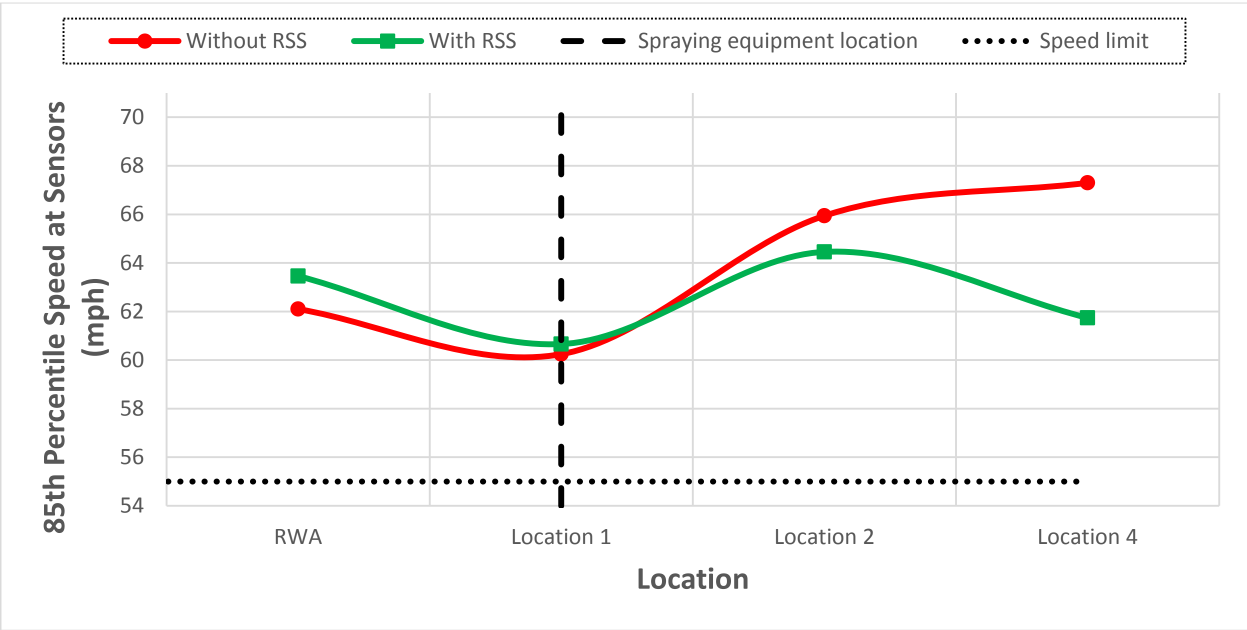


Figure 4.52: 85th Percentile Speed in different Distance from the Operation, US-97, Spraying, Location 1

The vehicle speed data collected provided an opportunity to calculate the amount of decrease in speed from the RWA signs to the work zone for both periods of testing. The speeds in the work zone (WZ) that were used in this analysis were those recorded by all of the traffic sensors at each sensor location. Table 4.48 shows this comparison. For all vehicles, mean speed decreased from 58.4 mph at the RWA signs to 56.2 mph in the work zone, a 3.8% decrease, without the RSS turned on. During the work periods with the RSS turned on, the amount of decrease for all vehicles was greater at 5.4% (from 58.5 mph to 55.4 mph), and the mean speed in the work zone was less (55.4 mph compared to 56.2 mph). When analyzing cars and truck separately, the results were similar for passenger cars (a greater % decrease with RSS turned on). For trucks, the percentage decrease in mean speed was less (0.4%) with the RSS turned on.

Table 4.48: Percentage of Vehicle Speed Decrease in the Work Zone Area, US-97, Spraying

Type of vehicle	Mean Speed (mph) without RSS at RWA	Mean Speed (mph) without RSS at WZ	Decrease in mean speed (%) without RSS	Mean Speed (mph) with RSS at RWA	Mean Speed (mph) with RSS at WZ	Decrease in mean speed (%) with RSS
All Vehicles	58.39	56.16	3.8%	58.51	55.38	5.4%
Passenger Cars	59.20	56.10	5.2%	59.34	55.37	6.7%
Trucks	53.46	56.52	-5.7%	55.66	55.44	0.4%

Table 4.49 shows an additional comparison of mean speeds, this time just comparing the speeds within the work zone. For all vehicles, the mean speed in the WZ during the periods without the RSS turned on was 56.2 mph and the mean speed in the WZ with the RSS turned on was 55.4 mph, a difference of 0.78 mph. This difference was found to be suggestive ($p = 0.077$). No evidence of a difference in mean speeds was found for cars ($p = 0.138$) and for trucks ($p = 0.291$). For this case study, the amount of difference was less for cars (0.73 mph) than for trucks (1.08 mph).

Table 4.49: Effect of Radar Speed Sign on Vehicle Speed, US-97, Spraying

Type of vehicle	Mean Speed (mph) without RSS	Mean Speed (mph) with RSS	Difference in mean speed (mph)	p-value
All Vehicles	56.16	55.38	0.78	0.0769
Passenger Cars	56.10	55.37	0.73	0.1375
Trucks	56.52	55.44	1.08	0.2912

Expanded comparisons of the vehicle speeds are shown in Tables 4.50 and 4.51. The tables show the speed data at the RWA signs and at sensor location #1. Similar tables for other locations are provided in the Appendix. As seen in Table 4.51, the mean and 85th percentile speeds at sensor location #1 are approximately 1 mph less with the RSS turned on for all vehicles combined, for just passenger cars, and for just trucks. Similarly, the standard deviation for all vehicles combined, for passenger cars, and for trucks was found to be less with the RSS turned on.

Table 4.50: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, US-97, Spraying, RWA

Test	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Without RSS	272	65.70	59.20	7.4	45	59.99	53.46	5.1	317	65.27	58.39	7.4
With RSS	215	64.66	59.34	6.7	62	59.83	55.66	7.8	277	64.22	58.51	7.1

Table 4.51: Volume, 85th percentile, Mean and Standard Deviation speed for different types of vehicles, US-97, Spraying, Location 1

Test	Passenger Cars				Trucks				All Vehicles			
	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation	Volume	85th % Speed (mph)	Mean (mph)	Standard Deviation
Without RSS	276	62.37	54.77	8.3	37	56.06	51.43	9.0	313	62.09	54.37	8.5
With RSS	223	61.17	54.59	7.0	54	55.47	51.32	5.0	277	61.17	53.95	6.8

As with the other case studies, analyses were also conducted that focused on the difference in speed between adjacent vehicles and the distance between adjacent vehicles as they passed through the work zone. Figure 4.53 shows the speed difference for vehicles passing sensor location #1 during the work operation time without the RSS turned on. Each dot in the figure represents one vehicle. As seen in the figure, the speed differences vary significantly, with a range of approximately -15 mph to +15 mph, and no particular trend in the data is visible.

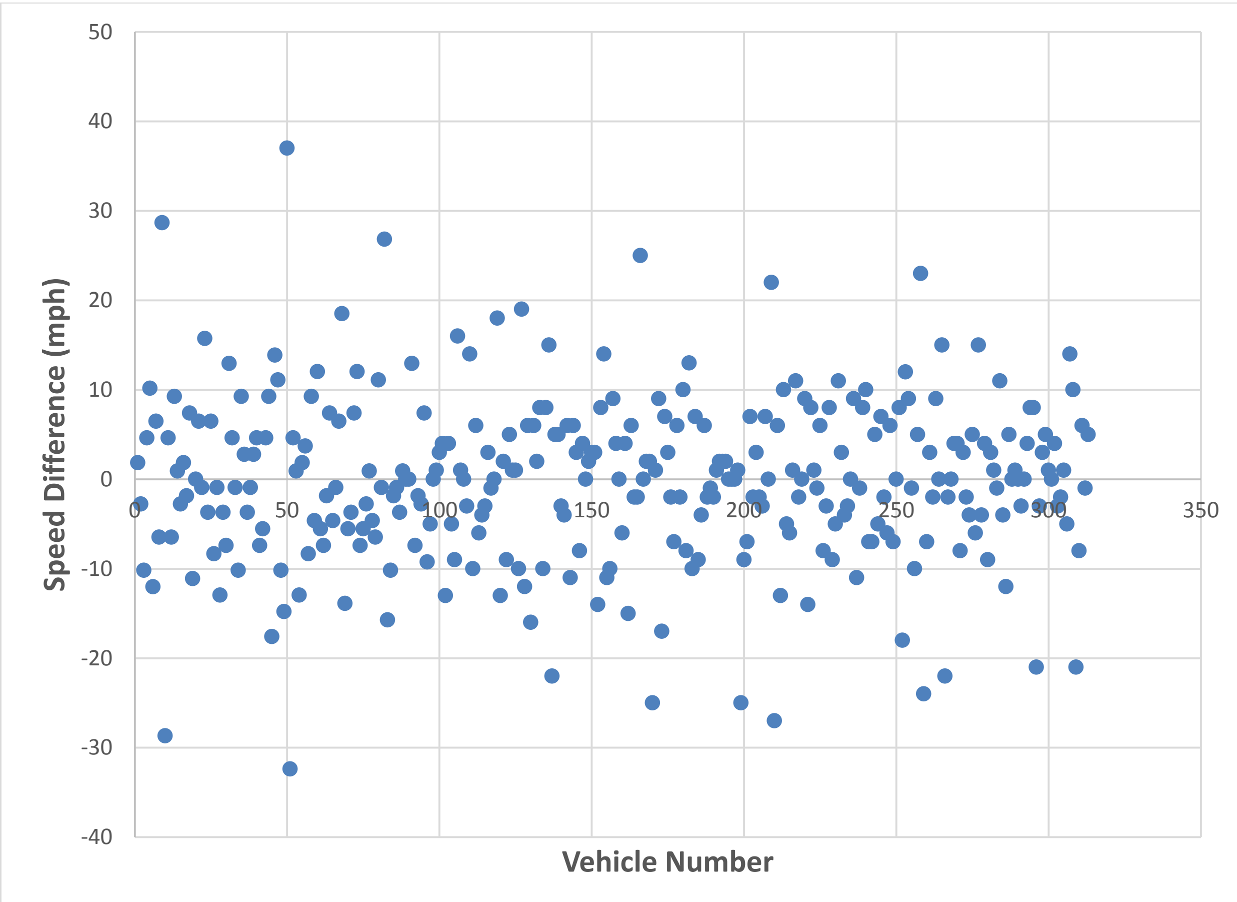


Figure 4.53: Speed Difference for Vehicles Passing Location 1, US-97, Spraying, Without RSS

Figure 4.54 shows the speed differences compared to the actual speed of the vehicle adjacent sensor location #1 during the work operation time without the RSS turned on. The horizontal access contains the speed of the trailing vehicle, and the vertical axis contains the difference in speed between the trailing vehicle and the vehicle in front of it. The figure shows an apparent positive slope; as the vehicle's speed increases, the difference in speed between the vehicle under consideration and the vehicle in front of it also increases. This trend is expected because the two factors are related in nature. Speed difference is calculated from vehicle speed. If the speed for the trailing vehicle is high, there is a greater chance that the speed difference will be high also. Those vehicles represented by the data points in the upper-right portion of the figure are especially of concern because they are travelling at a high rate of speed and at a high rate of speed relative to the preceding vehicle. A reduction of the number of vehicles travelling is this manner is desired in order to improve safety in the work zone.

The posted regulatory speed at this location is 55 mph. During the testing without the RSS turned on, 66% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. During the entire test period, at location #1 within the work zone, 37% of the vehicles were going faster than the posted speed limit. During the time when the maintenance equipment was present at location #1, 35% of the vehicles were travelling faster than the speed limit.

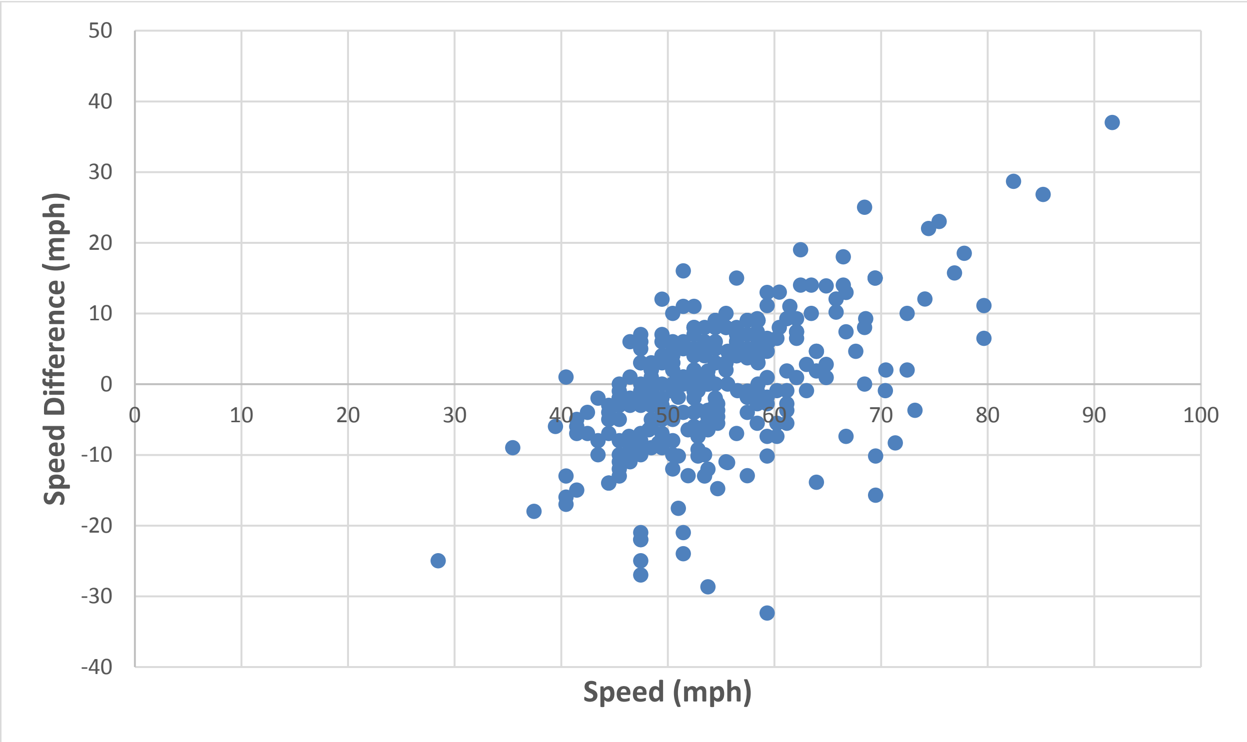


Figure 4.54: Speed Difference vs. Vehicle Speed for Vehicles Passing Location 1, US-97, Spraying, Without RSS

Figure 4.55 is similar to Figure 4.54, however the vertical axis in Figure 4.55 shows the distance between adjacent vehicles rather than the speed difference. Figure 4.55 shows the data for the vehicles passing sensor location #1 during the work operation time without the RSS turned on. While the distance apart varies, the majority of vehicles are less than approximately 1,000 feet apart. The figure does not show a clear trend in distance between adjacent vehicles. The vehicles represented by the data points in the lower-right portion of the figure are especially of concern; they are travelling at a high rate of speed and travelling close to the preceding vehicle. This type of driving behavior can be dangerous; reducing the amount of vehicles travelling in this manner will help improve safety in the work zone.

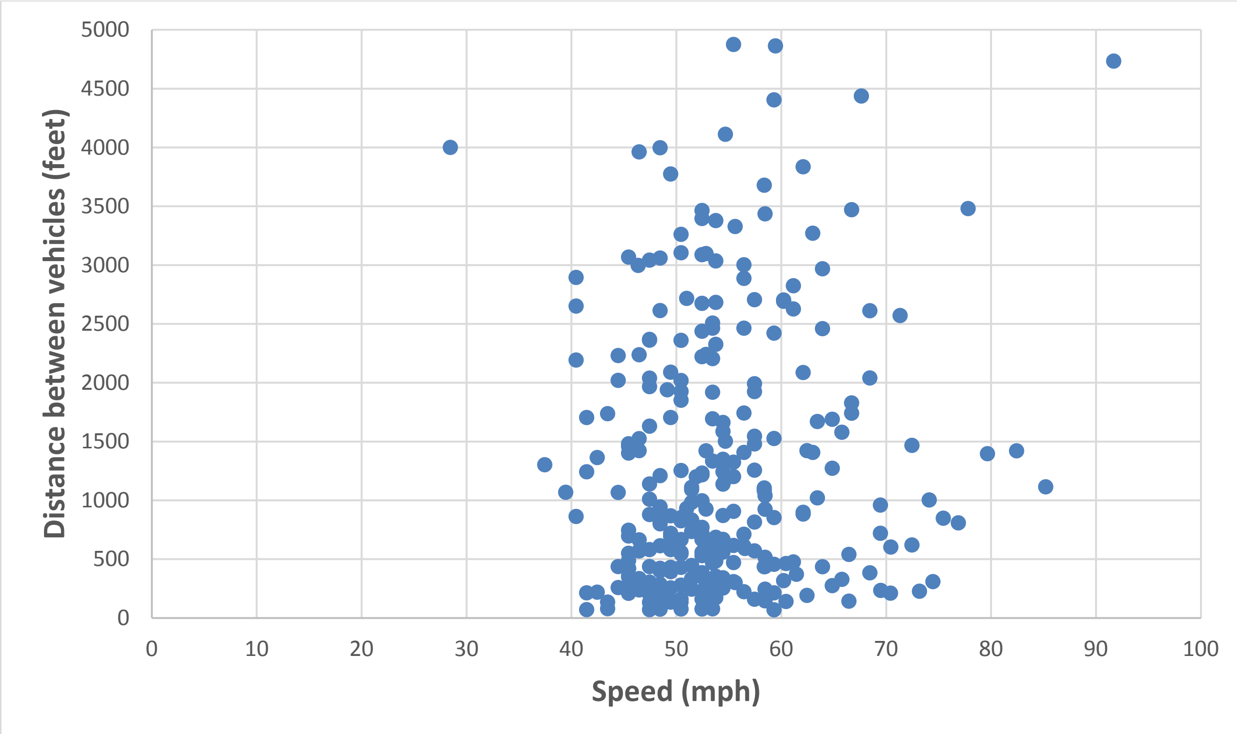


Figure 4.55: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Location 1, US-97, Spraying, Without RSS

The distance between adjacent vehicles compared to the speed difference between vehicles is shown in Figure 4.56. The data is shown for vehicles passing sensor location #1 during the work operation time without the RSS turned on. Again, no particular trend is visible in the figure. . The data points with negative speed difference indicate that the trailing vehicle is slower than the leading vehicle and getting farther away from the leading vehicle as the vehicles travel down the roadway. Those data points on the right side of the figure (higher positive speed difference), especially those with small distance between vehicles, are of concern. To prevent potential rear-end collisions, those vehicles with large positive speed difference (i.e., high speed relative to the vehicle in front of it) and low distance apart (i.e., close to the vehicle in front of it) is undesirable.

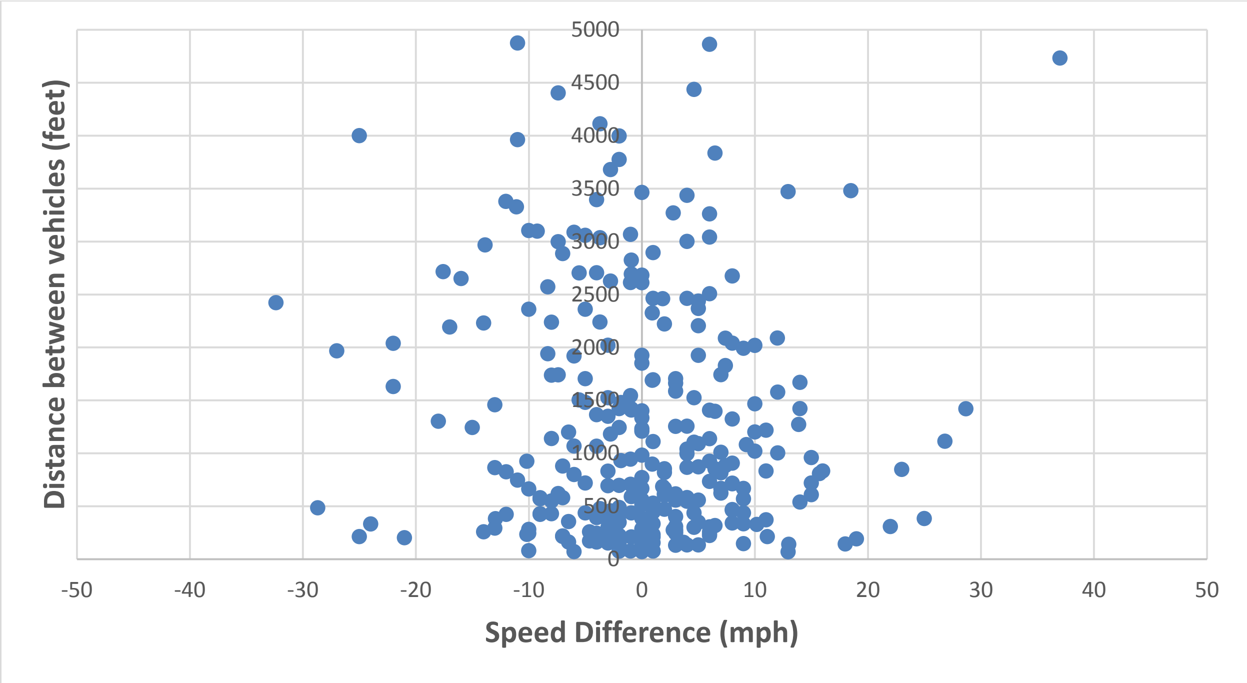


Figure 4.56: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Location 1, US-97, Spraying, Without RSS

For comparison, Figures 4.57, 4.58, 4.59, and 4.60 show similar speed and distance difference charts during the work operation with the RSS turned on. In these figures, the data is based on vehicles passing sensor location #1. Similar charts at the other locations are provided in the Appendix.

During the testing with the RSS turned on, 69% of the vehicles were travelling above the regulatory speed limit at the RWA sign location. This percentage is approximately the same as that recorded without the RSS turned on. During the entire test period with the RSS turned on, at sensor location #1 within the work zone 40% of the vehicles were going faster than the posted speed limit, which is greater than the 37% during the entire test period without the RSS turned on. Although the 40% value with the RSS turned on is greater than the 37% without the RSS turned on, with the RSS turned on the amount of decrease in the percentage of speeders from the RWA sign to the work zone is greater than the amount of decrease without the RSS turned on. Additionally, during the time period when the maintenance equipment was present at location #1, 37% of the vehicles were travelling above the speed limit. Thus, the RSS helped to reduce the speed of a greater percentage of speeders.

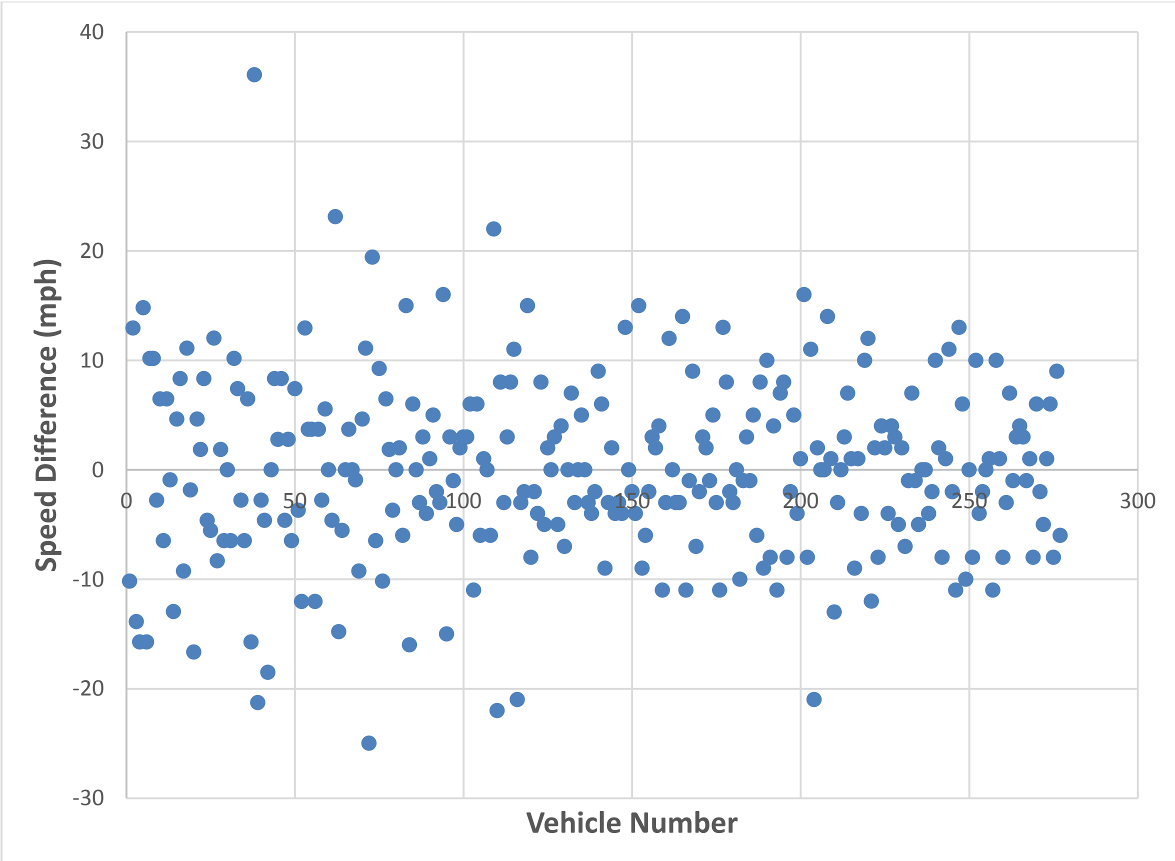


Figure 4.57: Speed Difference for Vehicles Passing Location 1, US-97, Spraying, With RSS

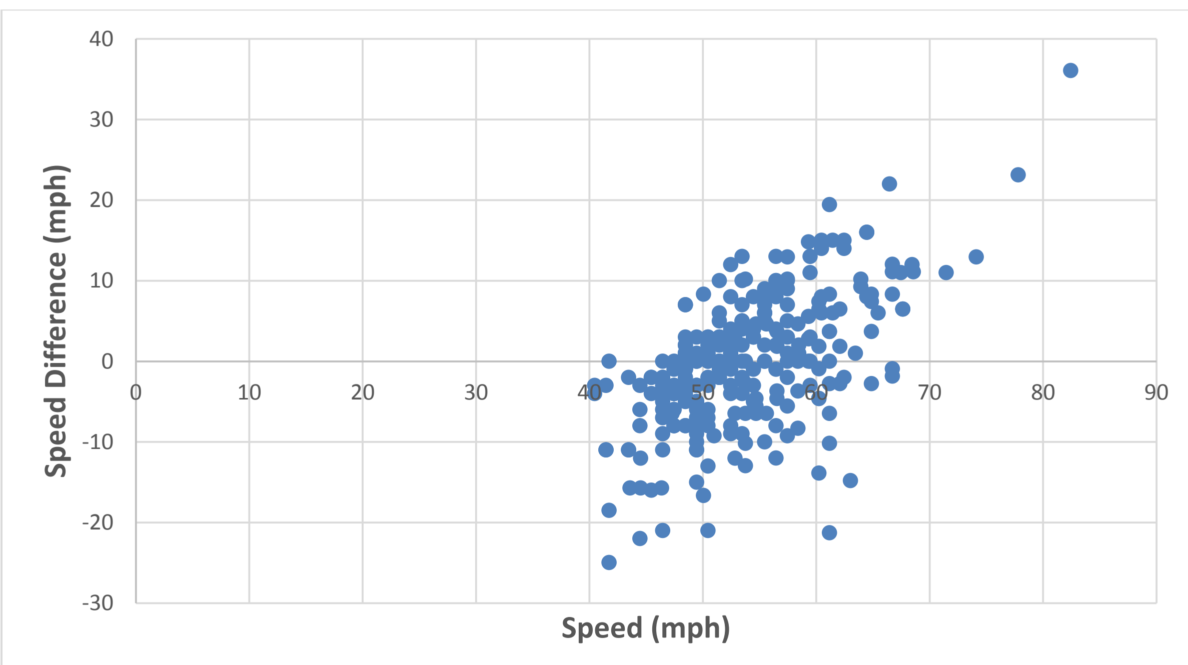


Figure 4.58: Speed Difference vs. Vehicle Speed for Vehicles Passing Location 1, US-97, Spraying, With RSS

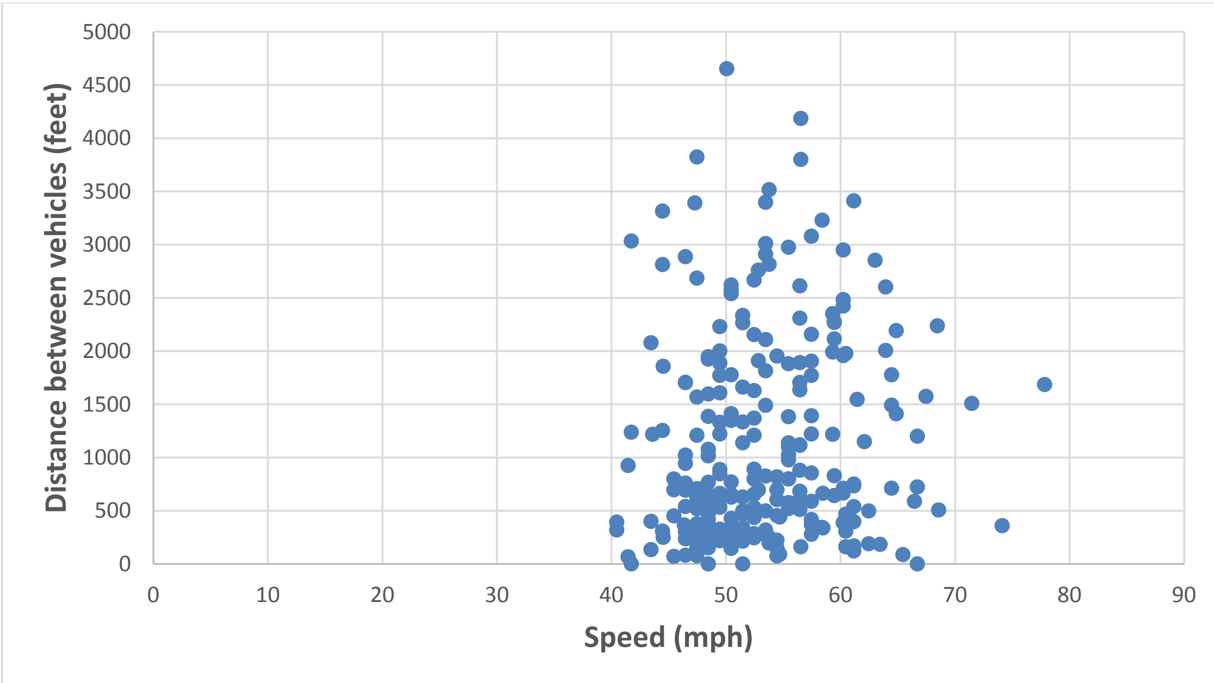


Figure 4.59: Distance between Vehicles vs. Vehicle Speed for Vehicles Passing Location 1, US-97, Spraying, With RSS

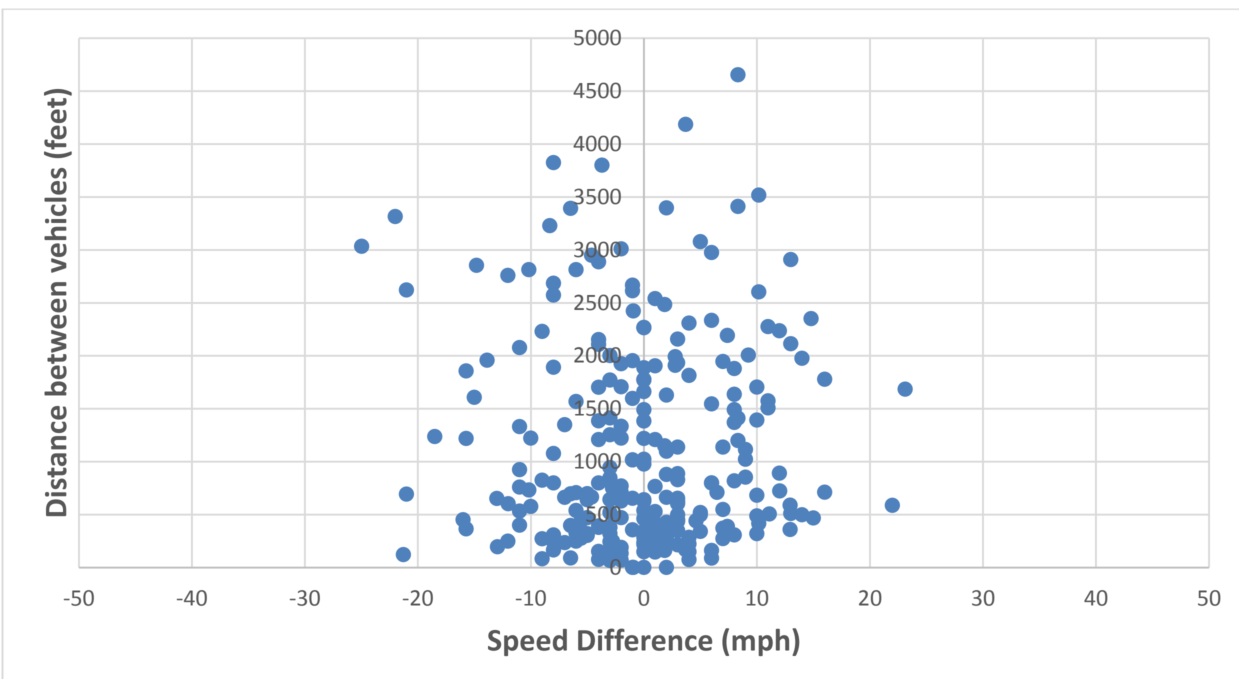


Figure 4.60: Difference between Vehicles vs. Vehicle Speed Difference for Vehicles Passing Location 1, US-97, Spraying, With RSS

Statistical tools were used to analyze the treatment effect of implementing the RSS display in a manner similar to the other case studies. A two-sample t-test was conducted to see whether turning on the RSS display has an effect on the speed difference. In the analysis, the absolute value of speed difference is used as the dependent variable. Absolute value is used due to the fact that, if the speed differences are added together, the negatives and positives will cancel each other and the mean of speed difference will be close to zero. The statistical test was conducted for all vehicles combined, for only passenger cars, and for only trucks. Table 4.52 summarizes the results. The data used to create the table consisted of all of the data recorded at sensor location #1. Similar tables comparing the speed differences at other locations are provided in the Appendix. For all vehicles, the RSS display turned on resulted in a 0.64 mph lower mean speed difference. However, the p-value was high (0.187). Therefore, there is no statistically significant evidence that the means are different. For passenger cars and trucks, the mean differences were greater (0.60 and 0.78 mph, respectively), however the differences were also found to not be significant.

Table 4.52: Effect of Radar Speed Sign on Absolute Value of Speed Differences between Adjacent Vehicles, US-97, Spraying, Location 1

Type of vehicle	Mean of absolute value of Speed difference (mph) without RSS	Mean of absolute value of Speed difference (mph) with RSS	Difference in mean values (mph)	p-value
All Vehicles	6.89	6.25	0.64	0.1871
Passenger Cars	6.89	6.29	0.60	0.2588
Trucks	6.85	6.07	0.78	0.5253

A second statistical analysis was performed using just the positive speed difference values, and omitting those with negative speed difference. Positive speed difference represents a vehicle that is driving faster than the vehicle in front of it. This situation is possibly hazardous as it can lead to rear-end crashes. The results of the analysis, shown in Table 4.53, are similar to the analysis using absolute value of speed differences. There is no statistical evidence that the RSS display has an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it. This result was found for all vehicles, for just passenger cars, and for just trucks.

Table 4.53: Effect of Radar Speed Sign on Vehicles with Positive Speed Differences between Adjacent Vehicles, US-97, Spraying, Location 1

Type of vehicle	Mean of positive value of Speed difference (mph) without RSS (Day1)	Mean of positive value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	7.25	6.92	0.32	0.6450
Passenger Cars	7.20	7.21	0.00	0.9998
Trucks	7.61	5.55	2.06	0.3325

Similar analyses were conducted using the distance between adjacent vehicles as the dependent variable to assess the impact of the treatment (use of RSS display). Table 4.54 shows the results of the analysis. For all vehicles, just passenger cars, and just trucks, there is no statistically significant evidence that the RSS display has an impact on the distance between adjacent vehicles.

Table 4.54: Effect of Radar Speed Sign on Distance between Adjacent Vehicles, US-97, Spraying, Location 1

Type of vehicle	Mean of distance apart without RSS (feet)	Mean of distance apart with RSS (feet)	Difference in mean values (feet)	p-value
All Vehicles	1845.35	1836.66	8.68	0.9666
Passenger Cars	1905.01	1802.24	102.77	0.6487
Trucks	1401.89	1978.19	576.30	0.2967

Additional statistical tests were conducted to explore the effect of vehicle type on mean speed with and without the RSS display turned on. Table 4.55 shows the results of these tests without the RSS display turned on. Similar to the tables above, the values shown in the table are calculated from all of the data recorded by the sensors at sensor location #1. The results suggest that vehicle type does not have an impact on the absolute value of speed difference, positive speed difference, and distance between adjacent vehicles for passenger cars compared to trucks. A lack of distance difference between vehicles may in part be due to the large magnitude of the distance apart between adjacent vehicles.

Table 4.55: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, US-97, Spraying, Without RSS, Location 1

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference (mph)	6.89	6.85	0.04	0.9674
Mean positive speed difference (mph)	7.20	7.61	0.40	0.8056
Mean distance between adjacent vehicles (feet)	1905.01	1401.89	503.12	0.2601

Table 4.56 shows the results for cars and trucks at the sensor location #1 with the RSS turned on. The calculated p-values indicate no statistically significant difference between cars and trucks with respect to absolute value of speed difference, positive speed difference, and distance apart.

Table 4.56: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, US-97, Spraying, With RSS, Location 1

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference(mph)	6.29	6.07	0.22	0.7858
Mean positive speed difference (mph)	7.21	5.55	1.66	0.2001
Mean distance between adjacent vehicles (feet)	1802.24	1978.19	175.95	0.6388

Analyzing all of the data at sensor location #1, the differences between cars and trucks are shown in Table 4.57. The results are similar to that found in the tables above. In all cases, passenger cars have a higher mean speed difference and higher positive speed difference between adjacent vehicles. Similarly, passenger cars travel with a greater distance apart from the vehicle in front of it. However, the statistical analyses show no statistically significant difference between cars and trucks.

Table 4.57: Effect of Vehicle Type on Speed Differences between Adjacent Vehicles, US-97, Spraying, With and Without RSS, Location 1

Type of vehicle	Passenger Cars	Trucks	Difference	p-value
Mean Absolute value of speed difference (mph)	6.62	6.39	0.24	0.7216
Mean positive speed difference (mph)	7.20	6.41	0.80	0.4349
Mean distance between adjacent vehicles (feet)	1859.11	1743.87	115.24	0.6872

In Case Study #43, the RSS unit displayed the approaching vehicle speed when the RSS was turned on. As described above, the RSS unit has the capability of saving the speeds recorded to an internal file. However, this capability was not operable during the case study testing. Therefore, no speeds of approaching vehicles are available for analysis.

As with the prior case studies, the researchers performed multiple probe vehicle passes through the work zones to monitor the nature of the traffic throughout the entire length of the work zone both with and without the RSS turned on. Figure 4.61 shows an example of the speeds recorded by the probe vehicle without the RSS turned on when the work operation was located between sensor locations #3 and #4. Figure 4.62 shows a similar chart with the RSS turned on when the work operation was located between sensor locations #3 and #4. The decrease in speeds as the vehicles approach the work equipment, and the increase downstream of the equipment, are evident in these figures. This driving behavior occurs regardless of the presence of the treatment.

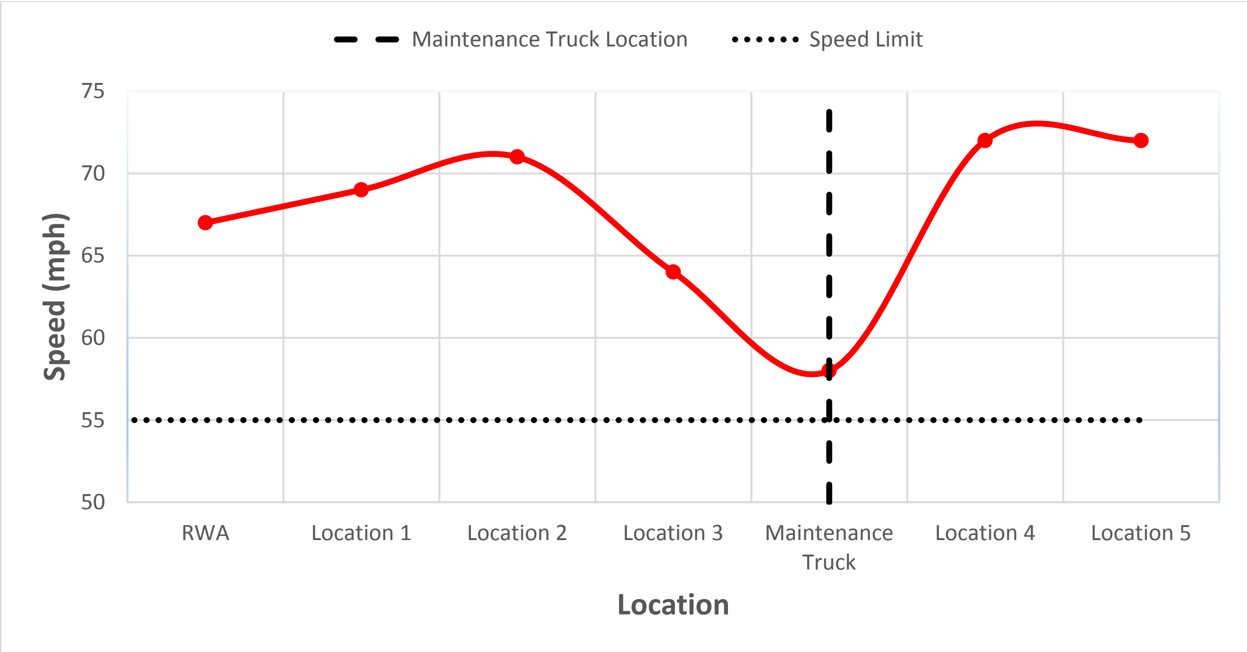


Figure 4.61: Probe Vehicle, US-97, Spraying, Without RSS

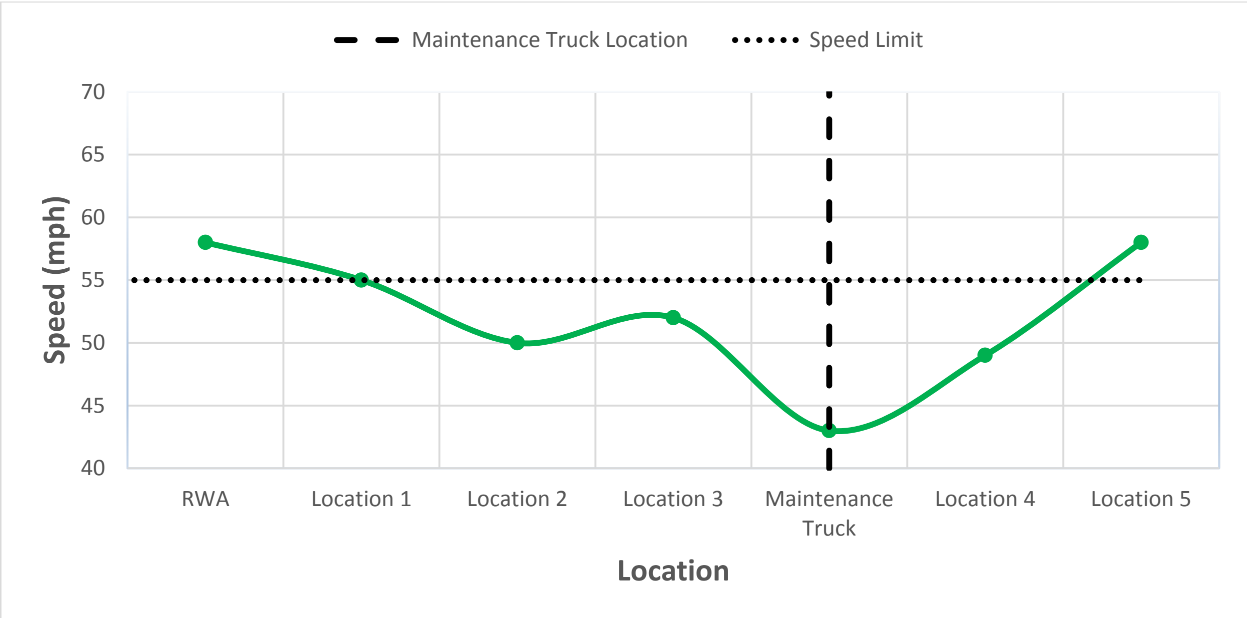


Figure 4.62: Probe Vehicle, US-97, Spraying, With RSS

5.0 CONCLUSIONS

The results of the present study provide helpful insights into the impacts of a truck-mounted radar speed sign on vehicle speeds during mobile maintenance operations on high-speed roadways. Overall, the RSS display proved to be effective in reducing vehicle speeds in the work zone when it displayed the vehicle's speeds compared to when the speeds were not displayed. This impact occurs for both continuously mobile operations (e.g., sweeping and spraying) and intermittent operations (e.g., relamping and vactoring). The magnitude of impact varies from one project to another depending on multiple factors such as the volume and mix of traffic, roadway location and design, and type of work activity. The quantitative analyses of the speed data from the four case study projects included in this research study reveal the following:

- The amount of decrease in vehicle speed between the Road Work Ahead (RWA) signs and the active work area is greater with the RSS display turned on than without the RSS display turned on. For the case study projects evaluated, 85^{th} percentile speeds decreased approximately 2 to 5 mph (4% - 8%) without the RSS turned on and 3 to 13 mph (5% - 23%) with the RSS turned on.

- Vehicle speed is lower as the vehicles approach and pass by the work equipment with the RSS display turned on than without the RSS display turned on. 85^{th} percentile speeds for the case study projects were approximately 2.0 mph less with the RSS display turned on compared to without the RSS display turned on.

- When comparing the percentage of vehicles travelling above the posted regulatory speed limit ("speeders") at the RWA signs to the percentage of speeders in the work zone during the entire test period, there is typically a decrease in the percentage of speeders between the two locations (i.e., fewer speeders in the work zone). The amount of decrease in the percentage of speeders is greater with the RSS turned on than without the RSS turned on. The percentage decrease ranged from 27% to 48% in the case studies when the RSS was turned on, and ranged from 15% to 36% without the RSS turned on. In addition, the decrease in the percentage of speeders is greater in the vicinity of the maintenance equipment than in the other areas of the work zone.

- The mean speed of the speeders in the work zone during the entire test period with the RSS turned on ranged from 59.9 to 61.6 mph, and without the RSS turned on ranged from 59.5 to 62.8 mph. However, the decrease in mean speed from the RWA sign to the work zone is greater with the RSS turn on than without the RSS turned on.

- The difference in speed between adjacent vehicles as the vehicles pass through the work zone is typically less with the RSS display turned on than without the RSS display turned on. For all vehicles, the maximum mean speed difference was approximately 2.0 mph less with the RSS display turned on than without the RSS turned on (approximately 7 mph difference without RSS turned on and approximately 5 mph difference with the RSS turned on).

- The distance apart between adjacent vehicles as the vehicles pass through the work zone is less with the RSS display turned on than without the RSS display turned on. This result and the result mentioned above related to mean speed difference indicate that with the RSS turned on, on average, there is less distance between vehicles and less speed difference.

- The differences listed above vary depending on the type of work being conducted and type and amount of equipment present.

- Vehicle speed decreases as the vehicles approach the equipment and increases after passing the equipment. This change in speeds occurs both with and without the RSS turned on. The amount of decrease upstream of the equipment is greater with the RSS turned on than without the RSS turned on.

Vehicle speed varies throughout the length of the work zone. At the RWA sign location, vehicles travel at normal highway speeds. Passenger cars tend to travel faster than trucks. However, all vehicles begin to slow down as they enter the active work area. There is a gradual decrease in speed to the end of the taper. In the work zone, vehicles typically travel at a lower speed when they pass by the work equipment as described above. After passing the equipment the vehicles typically increase their speed. These results are similar to that observed in previous ODOT studies (e.g., SPR 751 and SPR 769).

Once installed, the RSS unit is fairly easy and convenient to use. The display messages are easily programmed along with the lower and upper speeds limits. There was initially difficulty in downloading the data from the RSS unit, however with detailed instructions, the process is not difficult. Greater detail in the output file from the RSS unit is desired. This greater detail is provided with the newer device installed on the truck in Region 1. The unit now records and stores vehicle speeds with greater frequency (every second) and a CSV file can be downloaded that shows the speeds recorded at this frequency.

The results of this study are promising. A traffic control device that is easy to use, mobile, and multi-functional was found to help slow down vehicle speeds. ODOT should consider expanding availability and use of a truck-mounted RSS unit throughout all regions.

As mentioned in the Literature Review section, however, there are recognized limitations to the use of radar speed displays. Namely, the effectiveness of the speed monitor display decreases over time, and although the displays are an effective speed control countermeasure, speed reductions attained with the radar speed display are usually less than what is desired (SHA 2005). These limitations may be mitigated in part by the mobile and intermittent nature of maintenance work, i.e., the radar speed signs are not stationary and also not present on the roadway when the maintenance equipment is absent. In addition, it should be recognized that use of a RSS unit is not a "silver bullet"; it should be used in combination with other accident prevention and mitigation measures.

6.0 RECOMMENDATIONS FOR RESEARCH AND PRACTICE

The findings of the present study enable making recommendations and providing guidance for future research and practice. The use of truck-mounted RSS displays on mobile equipment during maintenance operations is recommended for ODOT Maintenance operations to help decrease vehicle speeds and speed variability through the work zone. Based on the present case studies, speeds for passenger cars and trucks will be less with the truck-mounted RSS displays present. Lower speeds through the work zone and lower speed variability between passing vehicles are expected to lead to fewer crashes in the work zone. The RSS sign is also expected to get the motorists' attention, make them aware of their speeds, and help prevent distracted drivers.

Truck-mounted RSS displays are applicable to and useful for both continuously moving (e.g., spraying and sweeping) and intermittent mobile (e.g., relamping and vactoring) work operations. Use of truck-mounted RSS signs are recommended for all such operations, and especially those which do not include a lane closure or in which additional support equipment is lacking or minimal (e.g., spraying operation in Case Study #4). Exposed equipment and workers during operations that do not include a lane closure or have additional support vehicles for protection can especially benefit from the reduced speeds and increase in driver attention created by the RSS display.

The following additional guidance regarding use of the RSS unit in practice is based on the findings from the data analyses and discussions with users of the RSS units during the course of the research:

- The RSS signs should be turned on throughout the entire work operation. When the maintenance operation is not being undertaken such as when the truck is traveling to/from the work site, however, the RSS display should be turned off or lowered so as not to confuse the motorists.

- The character font size and brightness should be set such that the message displayed is easy to read and comprehend. The message selected for display, such as "Slow Down", should be able to fit within the display screen. Further guidance on the message is provided in the ODOT Traffic Control Plans Design Manual.

- The display settings on the sign should be determined based on the regulatory speed on the roadway. For example, for a high speed roadway with 55 mph regulatory speed, the following settings are recommended:

    - Below 40 mph: no speed or message displayed

    - Between 40 mph and 55 mph: display the vehicle's speed

    - Above 55 mph: display the vehicle's speed and the message "Slow Down"

The upper speed setting should be set such that it matches the regulatory speed limit (permanent or temporary) in the work zone. If an advisory speed is recommended during the operation, such as was the case with the 45 mph advisory speed sign on the rear of the truck in Case Study #3, the upper speed setting should be set at the advisory speed. When the RSS unit picks up speeds above the upper setting, the display should show both the vehicle's speed and the programmed message (e.g., "Slow Down"), either alternating between the message and speed or at the same time. An alternating or blinking message that does not change too frequently helps to get the motorist's attention.

- Care should be taken to mount the RSS display screen on the truck such that it is visible to on-coming motorists. The screen should not be hidden behind other objects on the truck.
- During the work operation, the truck with the RSS unit should be located such that it is visible to the oncoming traffic at all times and as close as possible to the work operation. On roadways where there are sharp curves or other features that may obstruct an on-coming motorist's view of the RSS display, the truck driver should locate the truck as much as possible to minimize the obstructed view and provide the motorists adequate time to read and react to the sign before encountering the work operation.

The present study also exposed the possibility for additional research to fully understand the impacts of RSS displays and optimize their use. Further research to investigate and evaluate motorist reactions based on different sign settings and different messages is warranted. Standardized messages and RSS speed settings should be developed and used in order to make maintenance work zones appear as consistent as possible throughout the state. In addition, the use of an advisory speed sign with lower speed than the regulatory speed in combination with the truck-mounted RSS display should be studied further. Case Study #3 as part of the present study utilized an advisory speed sign along with the RSS display and appeared to have greater impact on vehicle speeds. However, the present study did not provide sufficient opportunity for in-depth analysis of the impact of the advisory sign.

7.0 REFERENCES

Aarts, L., and I. van Schagen. Driving Speed and the Risk of Road Crashes: A Review. *Accident Analysis & Prevention*, Vol. 38, No. 2, 2006, pp. 215–224.

Benekohal, R.F., and Sun, D. Analysis of Work Zone Gaps and Rear-end Collision Probability. *Journal of Transportation and Statistics*, Vol. 8, No. 2, 2005, p. 71.

Benekohal, R., A. Hajbabaie, J. Medina, M. Wang, and M. Chitturi. *Speed Photo-Radar Enforcement Evaluation in Illinois Work Zones*. Illinois Center for Transportation, 2010.

Blincoe, L.J., T.R. Miller, E. Zaloshnja, and B.A. Lawrence. *The Economic and Societal Impact of Motor Vehicle Crashes, 2010 (Revised May 2015)*. National Highway Traffic Safety Administration (NHTSA), Report No. DOT HS 812 013. 2015.

Bryden, J.E. *Traffic Control Handbook for Mobile Operations at Night, Guidelines for Construction, Maintenance and Utility Operations*. US Department of Transportation, Federal Highway Administration. 2003.

Chen, E., and A. Tarko. Estimating the Effect of Speed Control Strategies on Speed Distribution in Work Zones with Quantile Regression. Presented at Transportation Research Board 93rd Annual Meeting, 2013.

FHWA. *Utility Work Zone Safety Guidelines and Training: State-of-the-Art Synthesis and State-of-the-Practice Synthesis*. Wayne State University Transportation Research Group, Federal Highway Administration, 2007.

FHWA. *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD). United States Department of Transportation (USDOT), Federal Highway Administration (FHWA). 2009.

Fontaine, M.D., P.J. Carlson, and G. Hawkins. *Evaluation of Traffic Control Devices for Rural High-Speed Maintenance Work Zones: Second Year Activities and Final Recommendations.* Texas Department of Transportation in Cooperation with the U.S. Department of Transportation Federal Highway Administration. 2000.

Gambatese, J.A., F. Zhang, and A.M. Vahed. *Implementing Speed Reductions at Specific Interstate Work Zones from 65 mph to 35 mph*. Final Report, SPR 751. Oregon Department of Transportation (ODOT) and U.S. Department of Transportation, Federal Highway Administration (FHWA), 2013. http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2013/SPR751_SpeedReductions.pdf.

Gambatese, J.A., and F. Zhang. *Safe and Effective Speed Reductions for Freeway Work Zones Phase 2*, Final Report, SPR 769. Oregon Department of Transportation (ODOT) and U.S. Department of Transportation, Federal Highway Administration (FHWA), 2014, http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2014/SPR769_HighSpeed_Final.pdf.

Gambatese, J.A. and F. Zhang. *Safe and Effective Speed Reductions for Freeway Work Zones Phase 3*, Final Report, Implementation Research. Oregon Department of Transportation (ODOT), 2015. http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2015/SPR302_SpeedReduction_Phase3.pdf.

Garber, N.J., and M.D. Fontaine. *Controlling Vehicle Speeds in Work Zones: Effectiveness of Changeable Message Signs with Radar*. University of Virginia, Department of Civil Engineering. 1996.

Garber, N.J., and S. Srinivasan. *Effectiveness of Changeable Message Signs in Controlling Vehicle Speeds in Work Zones* Phase II, Final Report. Virginia Transportation Research Council. 1998.

Hildebrand, E.D., and D.D. Mason. (2014). "Effectiveness of Countermeasures to Reduce Vehicle Speeds in Freeway Work Zones". *Canadian Journal of Civil Engineering*, Vol. 41, No. 8, 2014, pp. 686–694.

Lee, B.H.Y., D. Azaria, and S. Neely. *Work Zones and Travel Speeds: The Effects of Uniform Traffic Officers and Other Speed Management Measures*. Vermont Agency of Transporation, Material Research Section. 2014.

Maze, T., A. Kamyab, and S. Schrock. *Evaluation of Work Zone Speed Reduction Measures*. Center for Transportation Research and Education Iowa State University. 2000.

McCoy, P.T., J.A. Bonneson, and J.A. Kollbaum. (1995). Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways. In *Transportation Research Record: Journal of Transportation Research Board*, No. 1509, Transportation Research Board of the National Academies, Washington, D.C., 1995, pp. 65-72.

MDT. *Evaluation of Radar Speed Display (RSD) Trailer-Mounted Device for Speed Reduction for Use in Construction Work Zones*. Montana Department of Transportation (MDT), Research Programs, 2006.

NHTSA. *Fatality Analysis Reporting System (FARS) Encyclopedia*. 2014. http://www-fars.nhtsa.dot.gov/Main/index.aspx. Accessed November 2014.

ODOT. *Oregon Department of Transportation Traffic Control Plans Design Manual*. 2011. http://www.oregon.gov/odot/hwy/traffic-roadway/docs/pdf/tcp_manual/tcp_dm_rev8_cover.pdf. Accessed November 2012.

ODOT. *Oregon Temporary Traffic Control Handbook (OTTCH)*. Oregon Department of Transportation. 2012a.

ODOT. *Work Zone Safety Fact Sheet & Safety Tips*. Oregon Department of Transportation. 2012b.

ODOT. *Oregon Portable Changeable Message Sign Handbook*. Oregon Department of Transportation. 2013a.

ODOT. *Standard Guidelines for Product Review, Radar Speed Trailer*. Oregon Department of Transportation. 2013b.

ODOT. *Traffic Control Plans Design Manual*, 10th Edition. Oregon Department of Transportation. 2014.

ODOT. *Work Zone Safety Fact Sheet & Safety Tips*. Oregon Department of Transportation. 2014.

ODOT. *Qualified Products List*. Oregon Department of Transportation. 2015.

Pigman, J.G., K.R. Agent, and E.R. Green. *Evaluation of Work Zone Safety Operations and Issues*. 2006. Retrieved from http://uknowledge.uky.edu/ktc_researchreports/108/

Ravani, B., C. Wang, D. Ma, W.A. White, and P. Fyhrie. *Evaluation of Methods to Reduce Speeds in Work Zones*, No. CA13-2247. University of California, Davis, Sacramento, CA. 2012.

Sarasua, W., J. Ogle, W.J. Davis, and M. Chowdhury. *Better Management of Speed Control in Work Zones*. SPR 658. South Carolina Department of Transportation, Columbia, SC, 2006.

SHA. *Use of Portable Changeable Message Signs with Speed Display in Work Zones.* Maryland State Highway Administration, Office of Traffic and Safety. 2005.

Skites, D. *Efficacy of Radar Speed Monitoring Displays in Reducing Vehicle Speeds*. 3M Traffic Safety Systems Division. 2004.

Tapecoat. *Tapecoat M860 Pavement Repair Coating*. 2012. Retrieved from http://www.chasecorp.com/products/mesh-backed-tapes/tapecoat-m860. Accessed November 2012.

Tobias, P. *Automated Speed Enforcement Slows Down Drivers in Work Zones*. 2011. Retrieved from http://www.wsdot.wa.gov/NR/rdonlyres/626718B3-A2AE-44FF-9197-79A2F7043493/0/TRBSpeedEnforcement.pdf. Accessed December 2012.

Vaisala. *Vaisala Nu-Metrics Portable Traffic Analyzers NC100/200*. 2012. Retrieved from http://www.vaisala.com/en/roads/products/trafficanalyzers/Pages/NC200.aspx. Accessed November 2012.

Veneziano, D., Z. Ye, and L. Hayden. Guidance for Radar Speed Sign Deployments. In Transportation Research Board 91st Annual Meeting, (No. 12-0806). 2012.

Wertjes, J.M. *Use of Speed Monitoring and Communication Display for Traffic Control*. Diane Publishing Co. 1996.