USE OF FLASHING AMBER-WHITE LIGHTS ON PAVING EQUIPMENT IN WORK ZONES

Final Report

PROJECT ODOT Order No. 19-15

RESEARCH

Oregon Department of Transportation

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by

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16. Abstract:

Safety treatments to mitigate speeding inside work zones is of perennial interest among construction partners. Prior research by ODOT and OSU captured the effect of flashing blue lights on speeding behavior. This study extended that effort to evaluate flashing amber and white lights. Three case studies were conducted on Interstates 5 and 205 during nighttime construction. Using traffic sensors placed on the roadway and GPS sensors placed on paving equipment, vehicle speed, type, volume, headway, and location were recorded. Speed reduction inside the work zone, and speed differential between the road work ahead (RWA) sign and the paver location, were compared statistically using two sample t-test. Results show significant speed reduction for the flashing amber-white lights used in Case Study 2 (2.5 to 10.1 mph inside the work zone, and 1.5 mph between the RWA sign and the paver location). Flashing amber lights showed a speed reduction between the RWA and the paver location in Case Study 1 (4.1 mph). No meaningful difference was observed in Case Study 3. Flashing amber-white lights are recommended for better identification of the paving equipment. Comparison with flashing blue lights suggested a greater impact on speed behavior using the flashing blue lights.

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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

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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.

DISCLAIMER

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1.0 INTRODUCTION

This document is the final report for the "Use of Flashing Amber-White Lights on Paving Equipment in Work Zones" study. It describes the background, overall objectives, and tasks for the study. In addition, it presents the results of all planned and executed research tasks. The report concludes with a summary of the observed impact on vehicle speeds in the presence of flashing amber and amber-white lights mounted to pavement equipment during mainline paving operations in work zones, comparison with a previous study evaluating flashing blue lights in a similar context, and provides recommendations to ODOT and other transportation agencies for further research on the topic.

1.1 BACKGROUND

The research conducted was undertaken to increase ODOT's understanding of the effects of using flashing amber-white lights on the behavior of drivers when the lights are mounted on the paver during night-time mainline paving operations in work zones. A safe and efficient transportation system is a central component of ODOT's mission. In addition, protecting the safety of both the traveling public and ODOT employees and other workers who build, operate, and maintain the state's transportation system is one of ODOT's core values. This research is intended to help ODOT fulfill its mission by identifying the extent to which flashing amber-white lights on a paver impact vehicle speed, and determining whether it is beneficial to use amber-white lights with construction and maintenance equipment/vehicles on future roadway projects.

Several previous studies have examined the effects of various flashing light colors in work zones as treatments to reduce speed (e.g., Kelley, 2018; Gan et al., 2018; Gambatese et al., 2019). These treatments are new to the State of Oregon, and first deployments of flashing colored lights were operated under interim guidance developed jointly by ODOT and other stakeholders. Oregon's statutes and guidance documents, along with the relative novelty of this treatment on the State's roads, provides an opportunity to expand our understanding of the use of flashing amber-white lights on paving equipment as a safety enhancement.

1.2 OBJECTIVES OF THE STUDY

The overall goal of this research was to develop additional knowledge regarding the impact of using flashing amber-white lights on paving equipment in work zones. Specifically, this study aimed to measure the change in vehicle speed, if any, when flashing amber and amber-white lights are used on a paver compared to when amber and amber-white lights are not used on a paver. The research focused on high-speed roadways (e.g., highways and freeways) and on typical nighttime, mobile paving operations that occur on such roadways. The desire to obtain guidance on the research question expeditiously, the study was planned to be an initial evaluation of amber and amber-white lights on three case study projects. The research aims to confirm whether amber and amber-white lights on construction equipment lead to lower vehicle speeds in work zones, and recommend to ODOT whether the use of amber-white lights is a potentially viable long-term safety treatment, and whether this treatment should be studied more closely in a subsequent, more comprehensive study. Specifically, the objectives of the research were to:

1. Collect field data on the speed of vehicles passing through the work zone when flashing amber-white lights are both present and not present on paving equipment;

2. Analyze the field data collected to determine the impact that the amber-white lights have on vehicle speed; and

3. Support ODOT decision making regarding future statutes, rules, policies or guidance related to these lights.

The research plan for meeting the study objectives is illustrated in Figure 1.1. The overall plan contains two overarching phases: Phase 1 to collect speed data from on-going paving operations (Objective 1), and Phase 2 to analyze the data, identify trends, and develop recommendations for ODOT (Objectives 2 and 3). The specific tasks in each phase are described in more detail in Figure 1.1 and in Sections 1.5 and 3 of the report.

	Phase 1: Field Data Collection (Objective 1)	Phase 2: Analysis and Documentation (Objectives 2 and 3)	
Data Needed	• On-going paving projects (case studies) on which to collect vehicle speed data • Characteristics of the roadway and work zones on the case study projects • Scope and schedule for case study projects	• Vehicle speeds in work zone both with and without colored lights turned on • Characteristics of the passing vehicles (e.g., size, volume) • Location of paver containing the colored lights	• Results of vehicle speed data analysis
Research Activities	• With assistance from the TAC, identify three case study projects on which to collect data • Collect scope and schedule information for each project • Collect real-time speed data on case study projects both with and without the colored lights turned on	• Analyze speed data to determine the impact of the colored lights on the speed of passing vehicles	• Develop report explaining methodology, results, findings, limitations and need for further research • Prepare and submit research report • Prepare and submit an archival data file

Figure 1.1: Research Plan for Data Collection and Research Activities

1.3 BENEFITS

Fulfilling the stated objectives provides ODOT with new information about the impact and viability of using flashing amber-white lights on construction equipment in work zones. The output provides quantitative evidence of how speed varies when amber-white lights, located on a paver, are active and inactive. Such information can help determine whether to further pursue the use of flashing amber-white lights for speed reduction in work zones. Each work zone on Oregon roadways exposes drivers and workers to risk of injury. Oregon experiences approximately 500 crashes in work zones each year (ODOT 2017a; 2017b). Each crash has the potential to cause injury or death to a driver and/or worker. The proposed research directly relates to ODOT's safety goal by focusing on reducing crashes and crash severity through encouraging lower vehicle speed in workzones, a driving environment that often creates additional risk to drivers and impacts mobility.

1.4 IMPLEMENTATION

As indicated above, the study output provides evidence to assist ODOT in developing a position regarding the continued use of flashing amber-white lights on construction equipment in work zones on high speed roadways. This output is communicated in the form of this research report submitted to ODOT that desicribes in detail the conduct and findings of the study along with a discussion of the potential benefits and consequences of the expanded use of amber-white lights. The report also identifies future work that may be needed to develop a better understanding of the opperational effects, related human factors, and efficacy of this treatment.

It is expected that the research outputs will be used by the ODOT Transportation Safety Division, Engineering & Technicial Services Branch, and the Regions as they plan and design traffic control for work zones. In addition, the results are expected to be incorporated into the activities of the Statewide Construction Office and implemented through communication and education of the Construction Project Managers statewide.

1.5 RESEARCH TASKS

As described in Section 1.2, the study contained two phases. Phase I of the study entailed initial planning and preparation for data collection, along with the actual collection of field data. Three (3) case study projects located on high-speed roadways in Oregon were selected for the research. The projects took place during a portion of the 2020 construction season (July – September 2020). ODOT personnel and resources were collaboratively used where possible to minimize the need for the researchers to access the right-of-way to collect data. In addition, ODOT and contractor personnel assisted with the placement of the speed sensors on the roadway (traffic control) to collect vehicle speed data.

The outputs of Phase I (i.e., vehicle speed, size, and volume data) was used for Phase II. Phase II included an evaluation of the field data to determine the impacts of amber and amber-white lights on vehicle speeds. The results of this task provide decision support for ODOT as the future use of amber and amber-white lights is considered and if additional research is necessary.

Chapter 2 provides a detailed description of the experimental design of the study, including the tasks undertaken for the data collection, reduction, and analysis.

2.0 EXPERIMENTAL DESIGN

Achieving the goals and objectives of this study required a detailed experimental design. In this chapter, case study selection, equipment preparation, data collection safety and technical training, data acquisition procedure, and methods of data reduction for further analyses are described.

2.1 CASE STUDY SELECTION AND DATA COLLECTION

As stipulated in the study scope, freeways and highways undergoing mainline paving operations were considered for inclusion in the study. The ODOT Research Office, assisted by other ODOT staff, sent emails to ODOT project managers across the state to identify potential projects to include in the study. Responses to the emails, along with a review by the researchers of the current projects being conducted by ODOT that were listed on the ODOT website, resulted in a list of potential case study projects. Among the initial list of projects, three projects, one in Roseburg and one in Oregon City, were selected for the research. These projects were selected because they took place on high-speed roadways, involved mainline paving operations, were conducted by contractors operating flashing amber lights or flashing amber-white lights on the paver, had enough days of mainline paving remaining on the project schedule to observe at least two days with the amber and amber-white lights on and two days with the amber and amber-white lights off, and the contractor was willing to participate in the study. As described in detail below, three case studies were conducted on the two construction projects identified, one case study on the Oregon City project, and two case studies on the Roseburg project.

Prior to the contractor starting the paving operation on each day of data collection, the researchers instructed the contractor to either turn the flashing amber and amber-white lights on or leave them off. The case studies were designed such that there were an equal number of days with the lights on and off. In one case, due to scheduling conflicts across multiple case studies, one day of lights off and two days of lights on data collection was completed. In each case, efforts were made to turn the lights on every other day. When on, the amber and amber-white lights were initially turned on when the paver was moved out to the active work area at the beginning of the work shift, and then remained on during the entire paving operation on that day. Law enforcement vehicles were not actively part of paving operations for these days. Regular patrols were not prevented.

The details for each case study are presented in the subsequent sections.

2.1.1 Case Study 1: I-5 Sutherlin - Garden Valley Blvd., Roseburg

Case Study 1 was located on I-5 between Roseburg and Sutherlin, OR. Land use around this section of the corridor is suburban in the city centers and rural otherwise. Data collection included three days of northbound active work zone from July 21-23, 2020. The flashing amber lights were turned on as a treatment for two days and turned off for one control day. Construction and maintenance operations took place in the northbound slow lane (B lane). To perform the work, the B lane was closed while the fast lane (A lane) remained open to through traffic. Data collection spanned from exit 124 to 129 during the three days. The posted speed limit was 65 mph on this segment of I-5 and the work zone speed limit was 50 mph. On Day 1, the length from the temporary road work ahead sign to the end of the merging section was 3.1 miles, and on days 2 and 3 it was 1.4 miles. Between seven to 11 sensors were placed in the field during data collection. Table 2.1 summarizes details of Case Study 1, and Figure 2.1 displays the location of the study.

Table 2.1: Description of Data Collection for Case Study 1 (I-5 Sutherlin – Garden Valley Blvd., Roseburg)

Details					**Lights**		**Data Collection Range**	
Data Collection Day	**Date**	**Time Frame**	**Paving Lane**	**Travel Direction**	**On**	**Off**	**Start Point**	**End Point**
1	7/21/2020	22:00 to 04:00	Slow Lane (B Lane)	Northbound		X	Exit 127	Exit 129
2	7/22/2020	22:00 to 04:00	Slow Lane (B Lane)	Northbound	X		Exit 124	Exit 127
3	7/22/2020	22:00 to 04:00	Fast Lane (A Lane)	Northbound	X		Exit 124	Exit 127

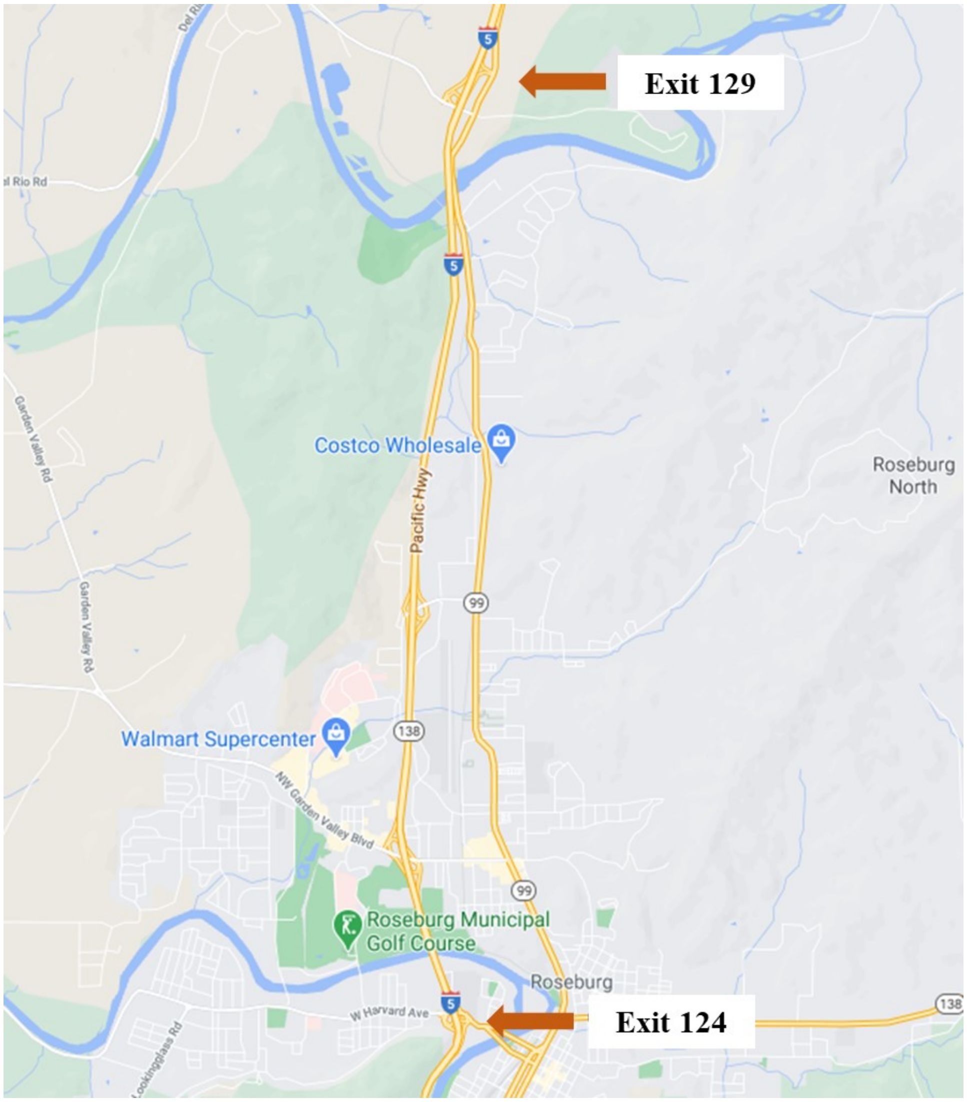

Figure 2.1: Location of case study 1 (Source: Google Maps)

2.1.2 Case Study 2: I-205 Abernethy Bridge – SE 82nd Drive, Oregon City

The paving project used for Case Study 2 was located on I-205 from the Abernethy Bridge to SE 82nd Drive in Oregon City, OR. Case Study 2 was conducted during repaving in the northbound direction of I-205 near the Abernethy Bridge in Oregon City. Data collection for the case study took place in two periods, July 27-28 and August 3-4, 2020. The amber-white lights were turned on for two days and turned off for two days. Amber-white light installation and operation was different than that on Case Studies 1 and 3. Details of the different installations are documented in the equipment section of this report.

The first day of data collection occurred with the flashing amber-white lights off during paving of the fast lane (A lane) in the northbound direction, and alternately turned on and off each day thereafter. Data collection occurred from 23:00 to 03:30. Data collection extended from Exit 9 to Exit 13 on I-205 northbound. The posted speed limit on this section was 55 mph with no speed reduction during construction. Eight to nine sensors were placed in the work zone (starting from the road work ahead sign to the last sensor in the active work area). The distance between the road work ahead sign and the end of taper varied from 1.1 to 1.7 miles. This segment of I-205 could be classified as an urban freeway. Table 2.2 summarizes details of Case Study 2, and Figure 2.2 displays the location of the study.

Table 2.2: Description of Data Collection for Case Study 2 (I-205 Abernethy Bridge – SE 82nd Drive, Oregon City)

Details					Lights		Data Collection Range	
Data Collection Day	**Date**	**Time Frame**	**Paving Lane**	**Travel Direction**	**On**	**Off**	**Start Point**	**End Point**
1	7/27/2020	23:00 to 03:30	Fast Lane (A Lane)	Northbound		X	Exit 9	Exit 12
2	7/28/2020	23:00 to 03:30	Fast Lane (A Lane)	Northbound	X		Exit 10	Exit 13
3	8/03/2020	23:00 to 03:30	Slow Lane (C Lane)	Northbound		X	Exit 9	Exit 11
4	8/04/2020	23:00 to 03:30	Slow Lane (C Lane)	Northbound	X		Exit 10	Exit 13

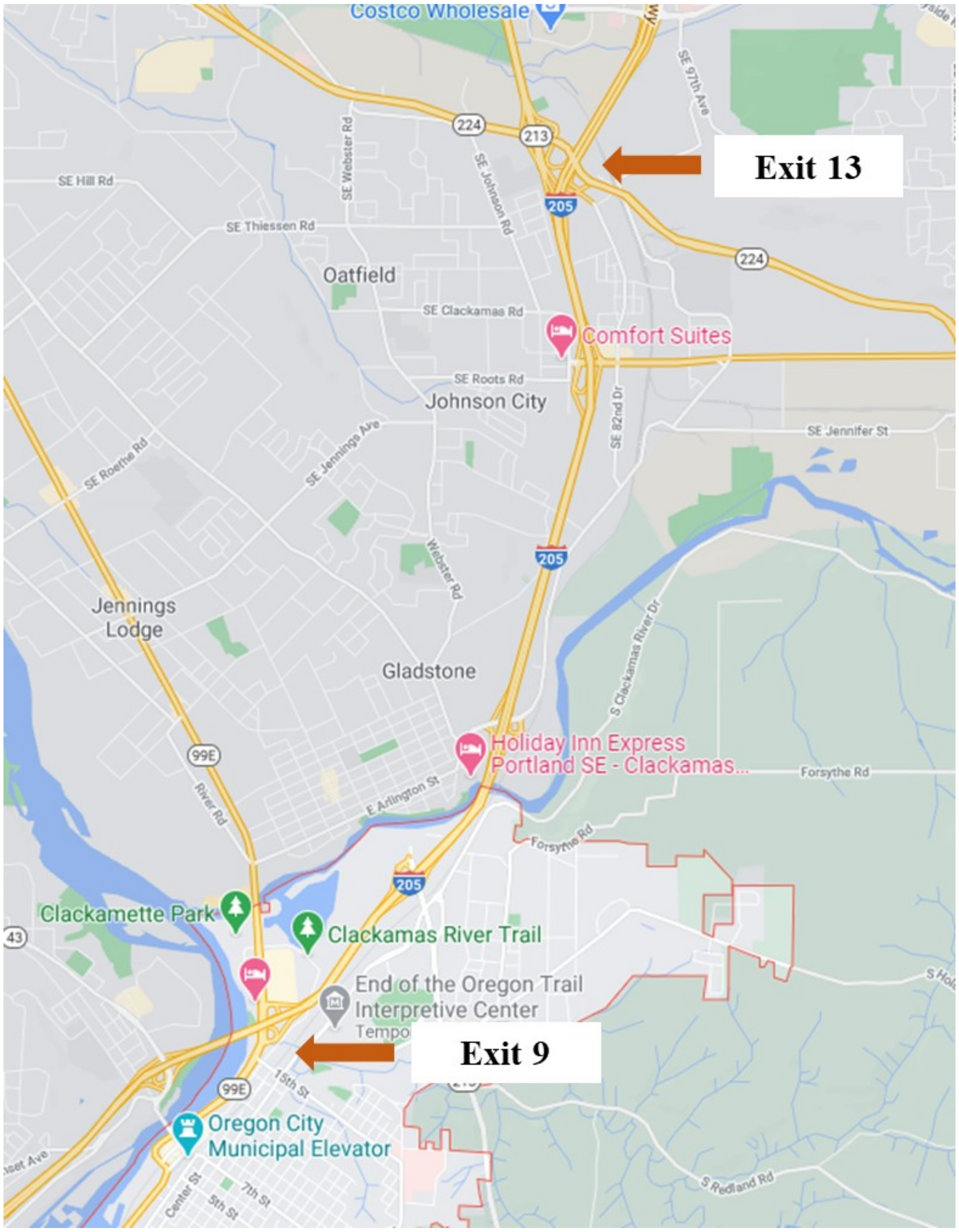

Figure 2.2: Location of case study 2 (Source: Google Maps)

2.1.3 Case Study 3: I-5 Sutherlin – Garden Valley Blvd., Roseburg

The third case study took place on a similar portion of highway as the first case study (I-5 Sutherlin - Garden Valley Blvd., Roseburg). The land use in these two case studies was similar in nature. The difference between the case studies was the direction of paving, as well as the dates of data collection and data collection ranges. The southbound work zone extended from Exit 132 to Exit 136 over four days. On days one and four, the flashing amber lights were turned off. The lights were turned on during the other two days of data collection. The data collection was performed during two consecutive weeks from August 26-27 and August 30-31, 2020. The distance from the temporary road work ahead sign to the end of the taper was 1.1-1.2 miles in length. Nine to 10 sensors were placed during each of the four days of data collection. The location of the case study is displayed in Figure 2.3, and the data collection details are presented in Table 2.3.

Table 2.3: Description of Data Collection for Case Study 3 (I-5 Sutherlin – Garden Valley Blvd., Roseburg)

Details					Lights		Data Collection Range	
Data Collection Day	**Date**	**Time Frame**	**Paving Lane**	**Travel Direction**	**On**	**Off**	**Start Point**	**End Point**
1	8/26/2020	22:00 to 04:00	Slow Lane (C Lane)	Southbound		X	Exit 135	MP* 132
2	8/27/2020	22:00 to 04:00	Fast Lane (A Lane)	Southbound	X		Exit 135	MP 132
3	8/30/2018	22:00 to 04:00	Slow Lane (C Lane)	Southbound	X		Exit 136	MP 133
4	8/31/2018	22:00 to 04:00	Fast Lane (A Lane)	Southbound		X	Exit 136	MP 133

*MP = mile post

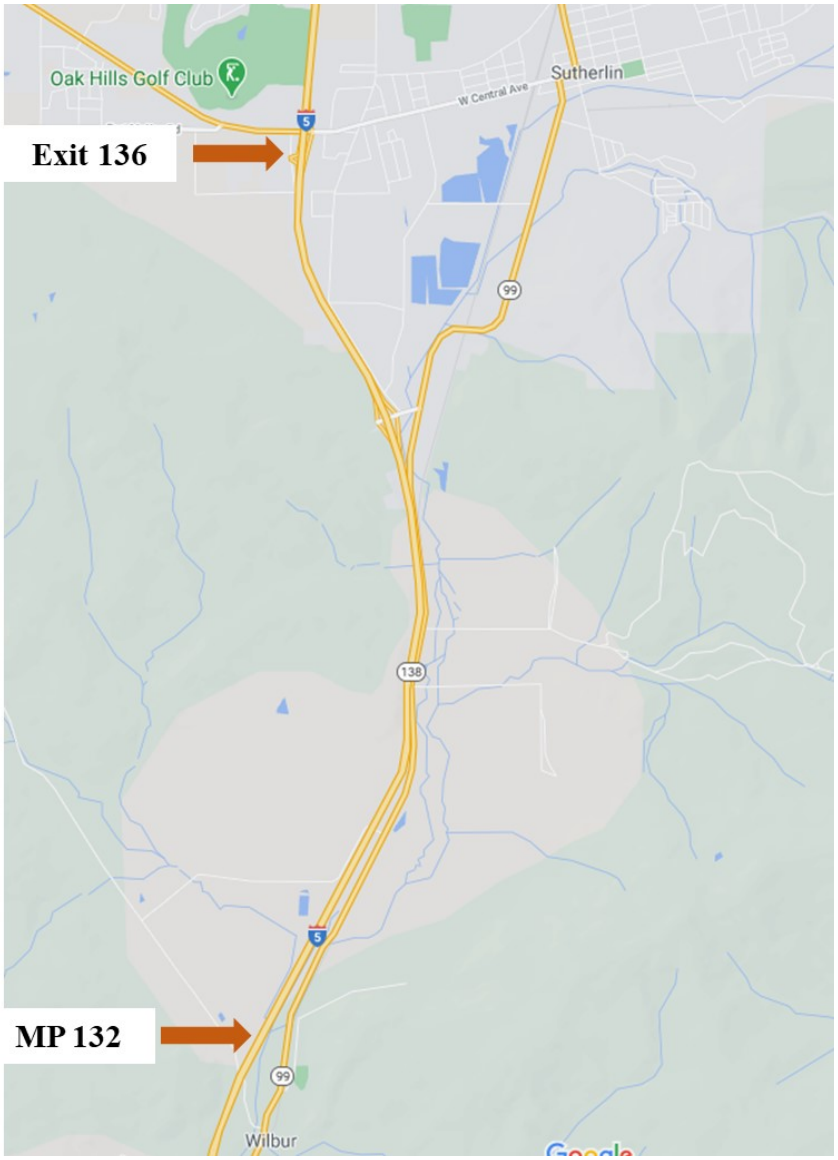

Figure 2.3: Location of case study 3 (Source: Google Maps)

2.2 RESEARCH EQUIPMENT

Data acquisition required a variety of research equipment. Two kinds of sensors were used: portable (in roadway) traffic analyzers (i.e., traffic sensors) to gather traffic data, and GPS sensors to track the paver location with respect to time and to record the locations of the portable traffic analyzers.

2.2.1 Traffic Sensors

2.2.1.1 Product Description

Portable traffic analyzers were used to accumulate vehicle volume, speed, and classification data. The sensors used for this study were produced by MH Corbin, Inc.

Two sensor models were placed on the road surface: NC-200 and NC-350 (Figure 2.4 and Figure 2.5). In terms of precision and accuracy, there are no differences between sensor models. However, the NC-350s have Bluetooth connectivity and a longer battery life.

For their placement on the roadway, a cover made of visco-elastic material is placed over the sensors as a protective buffer from vehicle impacts. To adhere the sensors to the road surface, adhesive tape is then placed over the cover. Figure 2.4 shows an example of the type of cover used along with the sensor. In Figure 2.5, provided by MH Corbin, a cross-sectional view of the NC-350 set-up can be observed.

Figure 2.4: Components of traffic sensor

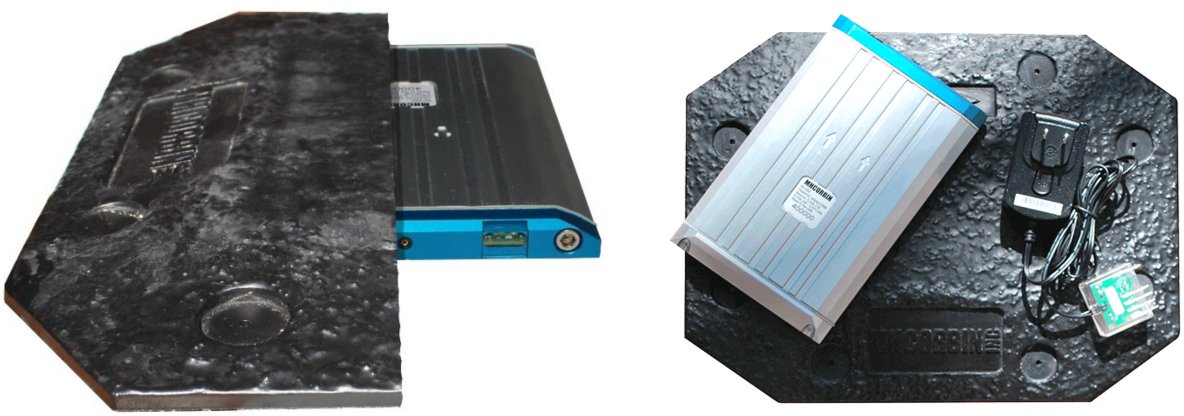

Figure 2.5: NC-350 portable traffic analyzer (M.H. Corbin 2017)

2.2.1.2 Sensor Calibration

A calibration procedure was implemented to confirm the accuracy of the vehicle volume, speed, and classification values recorded by each sensor. In the controlled environment of the Corvallis Municipal Airport, sensors were placed on a roadway and used to collect data relative to multiple vehicles passing over the sensors at preselected speeds. Control speeds of 30, 35, 40, 45, 50, 55, and 60 mph were selected. Test vehicles were driven over the sensors four times at each selected speed after which an analysis using linear regression was performed. In the regression analysis, control speed was considered as the independent variable and the observed speed recorded by the sensor was considered as the dependent variable. This analysis led to an equation relating the recorded speed to the actual speed. While using this equation to calibrate the case study project data, the equation was solved to determine the independent variable x, since the dependent variable y is the observed speed value recorded by the sensor. Figure 2.6 shows an example calibration for sensor 305, and Table 2.4 lists all of the sensors and their calibration equations. Note that in the equations shown in Table 2.4, the variable x represents the speed recorded by the sensor and the dependent variable y represents the actual speed of the passing vehicle.

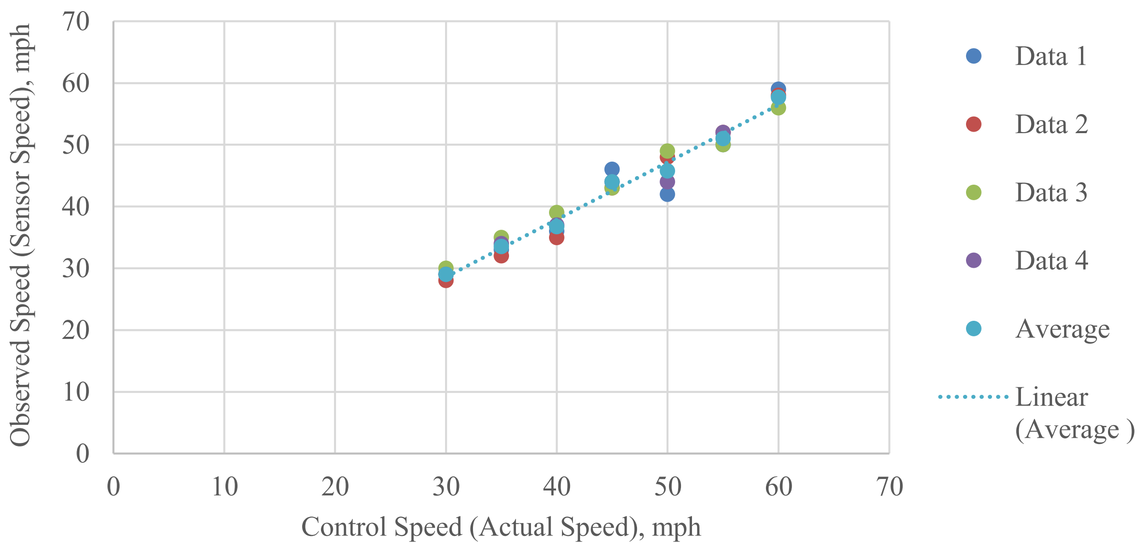

Figure 2.6: Linear regression of calibration data for traffic sensor 305

Table 2.4: Calibration Equations for Sensors

Sensor ID	Adjustment Equation*
101	y = 1.2933x - 9.4113
102	y = 1.0275x - 9.2245
106	y = 1.1789x - 3.6738
107	y = 0.9379x - 5.6308
108	y = 1.4775x - 13.4167
748	y = 1.1452x - 4.6524
774	y = 1.3053x - 9.3586
305	y = 1.0768x - 0.7949
317	y = 0.9523x - 3.7075
318	y = 0.9354x - 0.6793
325	y = 0.8371x - 4.8208
541	y = 0.9046x - 2.9321

*x = speed recorded by the sensor; y = actual speed of the vehicle

2.2.1.3 Sensor Preparation and Data Downloading

Each traffic sensor requires between 2 to 10 hours of charging based on residual battery life. Using the HDM 9.3.0 software package, sensors were programmed for each field installation day to gather data for a particular window of time. After the sensors were removed from the road surface, collected data was downloaded and archived in password protected cloud storage (OSU BOX) for further analysis. After each data collection period, HDM software was used to save data in .mdb format and sequential time stamped data was downloaded in .csv format.

2.2.2 GPS Tracker and Handheld GPS Device

During each data collection period, two iTrail GPS trackers (Figure 2.7) were placed on the light bar of the paver to record the trajectory of the paver during the nighttime paving operations. The GPS data was instrumental in determining the proximity of the paver to the traffic sensor locations where driver speed selection was being collected. GPS trackers were placed on the paver before each data collection period while the paver was parked in the yard, and then removed after the data collection period to download the data for analysis.

Figure 2.7 also shows a hand-held GPS device used in the data collection process. The GPS tracker, which is accurate to 3 m, was used to record the longitude and latitude of the traffic sensors placed on the road. These values were later used during the analysis after the study period to provide a location of the sensors on each day.

Figure 2.7: Handheld GPS device (left), and GPS tracker and casing for GPS tracker (right)

Figure 2.8 shows the GPS sensor placement on the pavers. The 1.5”x1.5” devices were protected using a casing with magnetic attachment that attached the casing to the metal light bar on the paver or on top of the engine cover in front of the operator’s chair. After retrieving the GPS trackers from the paver, time stamped GPS data (longitude and latitude) was downloaded using the iTrail software in .csv format for analysis.

Figure 2.8: GPS sensor location on the paver light bar (left) and on top of paver (right)

3.0 METHODOLOGY

In this chapter, the methods for data acquisition, data cleaning, processing, and data analysis are discussed.

3.1 DATA ACQUISITION

The data acquisition process was comprised of several components. All such components are described in the following sections.

3.1.1 Flashing Amber and Amber-White Lights

As previously described, traffic sensors were placed on the road surface and GPS trackers were placed on the paver. The control was the condition when the flashing amber or amber-white lights on the paver were turned off, and the treatment was the flashing amber lights or amber white-lights turned on (Figure 3.1). The type of flashing amber-white lights was different in Case Study 2 than in Case Studies 1 and 3. In Case Studies 1 and 3, a pair of flashing LED amber lights were installed on the overhead light bar of the paver. The overhead light bar has static white LED lights installed as displayed in Figure 3.1. A close-up view of a pair of the amber lights installed on the light bar of the paving equipment is displayed in Figure 3.2.

Figure 3.1: Paver with flashing amber lights on (left) and amber lights off (right) (case studies 1 and 3)

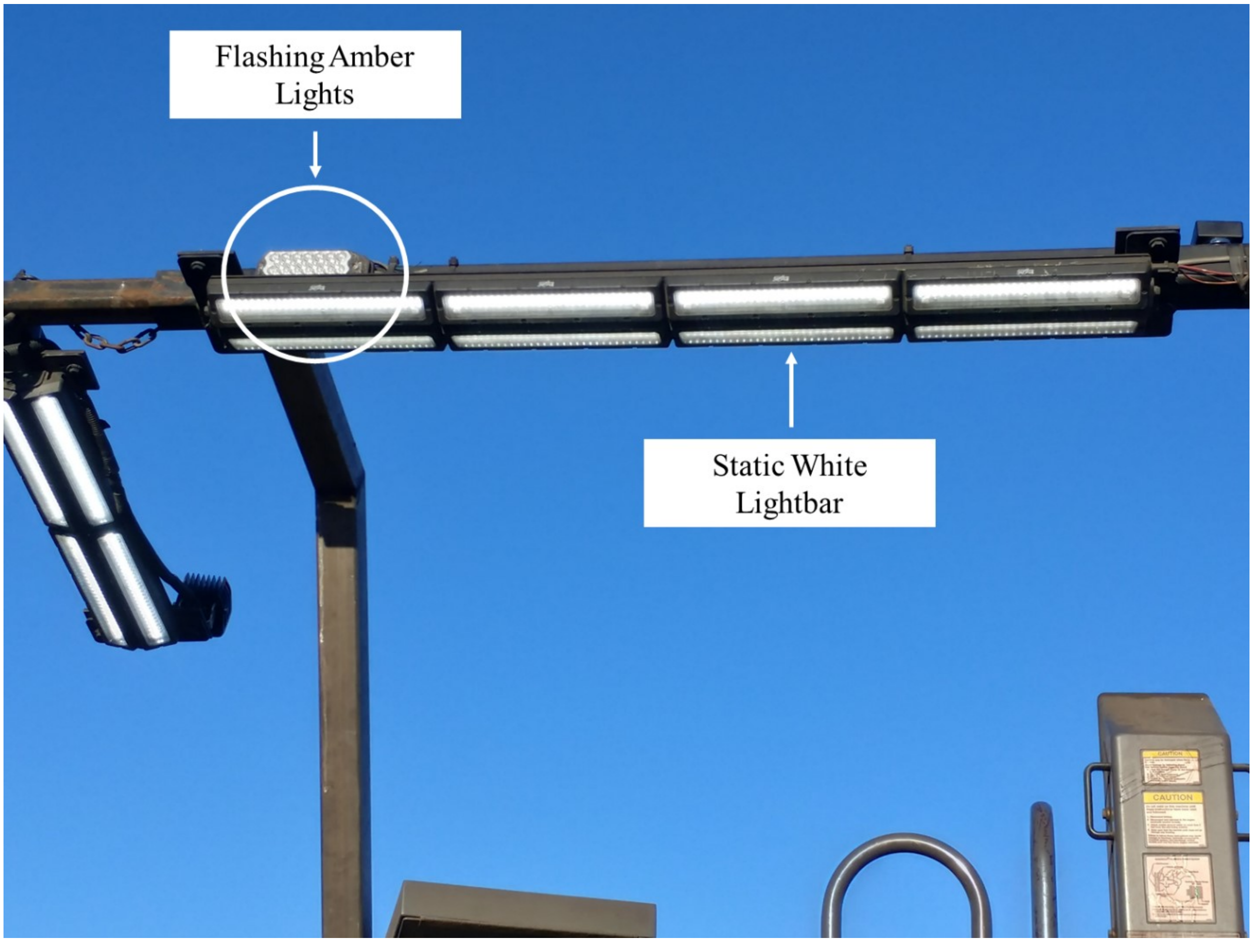

Figure 3.2: Amber light installed on paving equipment with static white lightbar (case studies 1 and 3)

The paving equipment was different in Case Study 2 than Case Studies 1 and 3. In Case Study 2, similar shaped LED alternating amber and white flashing lights were installed on both sides of the paver under the vehicle operators' seats as displayed in Figure 3.3. Alternating amber and white lights flash in this light installation. The paver in Case Study 2 is illuminated with three overhead balloon lights in addition to the amber-white lights (see Figure 3.3). In Figure 3.4, the location of the flashing light is indicated on one side of the paver by the white circle. A similar light is installed on the other side of the paver as well.

Figure 3.3: Only balloon lights on (top-left), amber lights on (top-right), and white lights on (bottom) (case study 2)

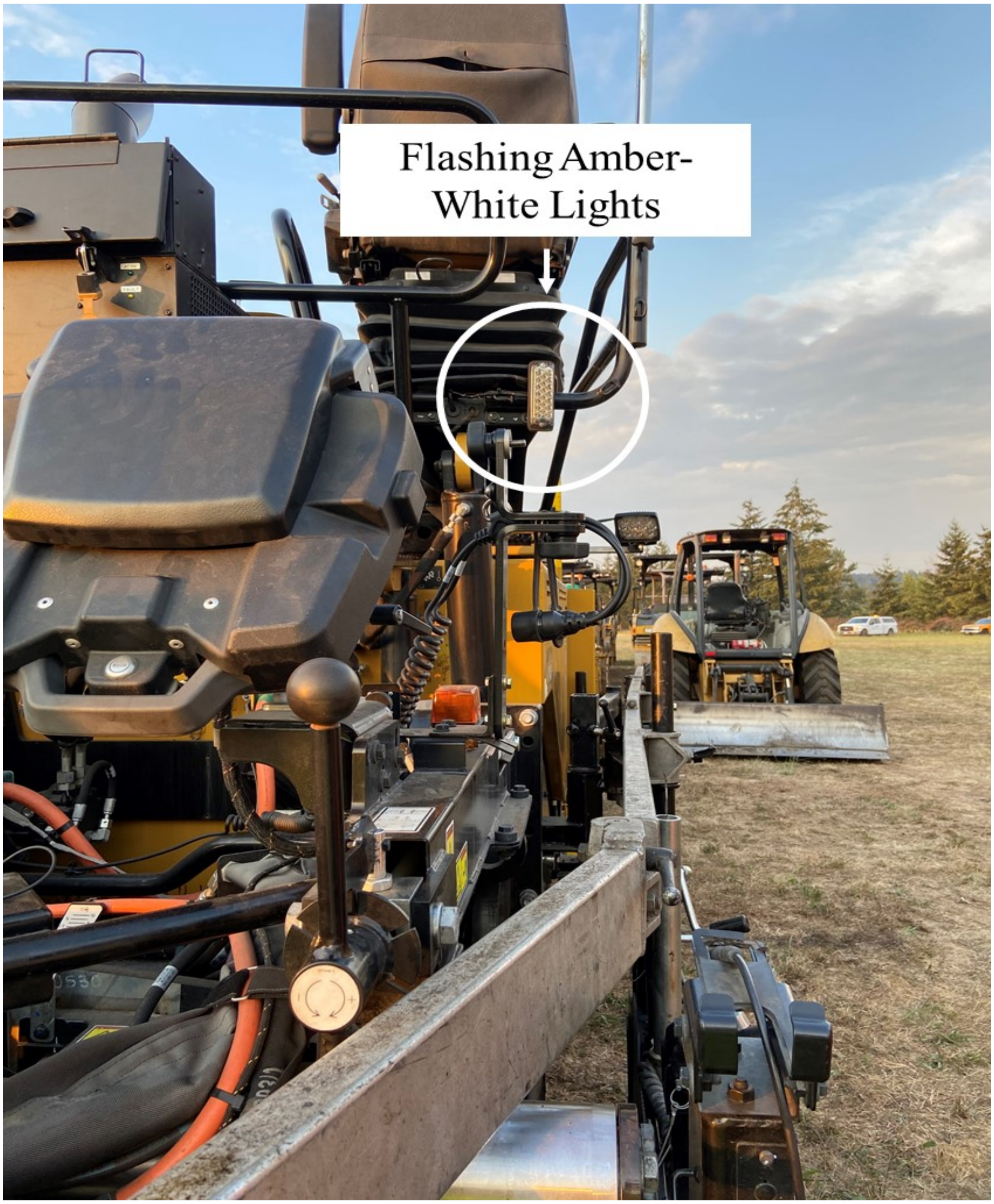

Figure 3.4: Amber-white light installed on paving equipment (case study 2)

3.1.2 Sensor Location Plan

Traffic sensors were placed in the open travel lane(s) upstream of and adjacent to the active work area. Active road paving operations commonly required one- or two-lane closures. One or multiple lanes were kept open for passing traffic based on the number of available lanes in the roadway and the location of the paving operation being performed. Sensors were placed in the lane(s) open to traffic. Figure 3.5 shows a simplistic representation of the sensor placement plan in a generic work zone configuration. Two sensors, one in each open lane, were placed at the location of the Road Work Ahead sign. Typically, the distance from the Road Work Ahead sign to the end of the taper section varied from one to two miles based on the required speed reduction and roadway layout. An additional sensor was placed at the end of the taper. Then, starting at the first paving joint, sensors were place approximately at 0.2 to 0.3-mile intervals along the activity area. The number of sensors placed each day varied from eight to 12 based on the length of paving planned on that day.

Sensors were not placed along the centerline of an open lane; rather they were shifted further away from the closed lane. This action was taken to account for driving behavior through a work zone where drivers tend to position themselves in the lane away from the active work areas (Gambatese & Jafarnejad, 2017).

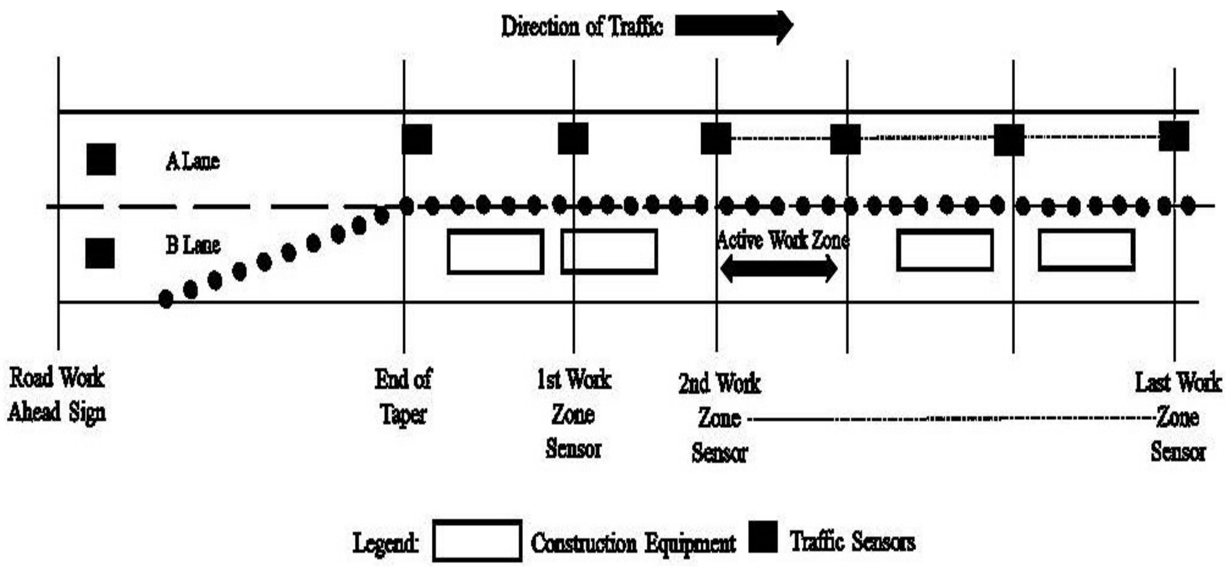

Figure 3.5: Typical sensor placement plan in work zone

3.1.3 Data Downloading and Storage

Using the HDM software for the traffic sensors and the iTrail software for the GPS trackers, raw, sequential, timed-stamped data was saved and stored on a local computer and then uploaded to password protected cloud storage (OSU BOX). Figure 3.6 is an example of data recorded from a traffic sensor.

	A	B	C	D	E	F	G	H	I
1	DateTime	AdviceCode	Speed	Length	StopTime	RoadTemperature	OCCFactor	Gap	Headway
2	8/2/2018 20:00	2	85	23	0	32	0	0	0
3	8/2/2018 20:00	2	68	22	0	32	0	3	299
4	8/2/2018 20:00	2	84	21	0	32	0	3	370
5	8/2/2018 20:00	2	70	20	0	32	0	2	205
6	8/2/2018 20:00	128	254	16	0	32	0	3	1118
7	8/2/2018 20:00	2	66	19	0	32	0	7	678

Figure 3.6: Raw data format from HDM software

3.2 DATA FILTERING

Both sets of data (traffic and GPS location) recorded the date and time. The traffic sensor also recorded the vehicle speed, approximate length of the vehicle, and gap and headway between two consecutive vehicles. The researchers took multiple steps to review the data and filter out faulty measurements and outliers.

The AdviceCode column in Figure 3.6 is a recommendation from the sensor about the degree of confidence in a particular observation. There are three variations of this degree of confidence in the dataset: 2, 4, and 128. Codes 2 and 4 relate the direction of traffic to the direction of the sensor (whether the vehicle was traveling backward or forward) while code 128 indicates a faulty observation. It can be seen in Figure 3.6 that advice code 128 is associated with a recorded vehicle speed of 254 mph, which is an unlikely speed. While filtering the data, data points associated with advice code 128 were removed from the data set.

A second layer of filtering accounted for time periods and headways. For Case Study 2, data was selected specifically between the period from 23:00 to 03:30, a window of 4.5 hours. For both Roseburg case studies (Case Studies 1 and 3), data was analyzed for a six-hour window from 22:00 to 04:00. Sensors were placed on the road at different times on different days based on the times that the contractors were allowed to begin and end lane closures and the availability of support for rolling slowdowns to aid in the safe placement and removal of sensor equipment. This filtering step was taken to introduce more uniformity and consistency in the data analysis.

As this study solely focused on evaluating how individual drivers react to two treatments (amber and amber-white lights off and amber and amber-white lights on) mounted on the light bar of a paver, it was important to remove every possible bias. To isolate the influence of the treatment on driver behavior, only the speeds of free-flowing vehicles (i.e., those not affected by downstream traffic) were targeted for the analysis. Vehicles with less than a 4 second headway were identified as non-free flow vehicles and, therefore, their speeds were removed from the data set (Athol, 1965; Knodler Jr et al., 2008). The researchers also performed a sensitivity analysis, filtering a variety of headways to determine the sensitivity of the mean speed. Based on this additional analysis, the researcher found that filtering based on headways longer than 4 seconds dramatically reduced sample size and had negligible effect on the mean speed.

The length of vehicle parameter recorded by the traffic sensors was used to classify vehicles. For this purpose, vehicles less than 25 ft. in length were counted as passenger cars and vehicles longer than 25 ft. in length were considered to be trucks.

3.3 SPEED DISTRIBUTION AND DESCRIPTIVE STATISTICS

After the data was filtered as described in the previous section, using MATLAB, histograms were produced to show the vehicle speeds at hourly and sub-hourly (15 min) ranges. Figure 3.7 is a portion of an example of hourly distribution statistics produced for one of the traffic sensors on the first day of Case Study 2.

	10:00-11:00			11:00-12:00			12:00-01:00		
Speed_ Range	Passenger Car	Heavy Vehicles	Total	Passenger Car	Heavy Vehicles	Total	Passenger Car	Heavy Vehicles	Total
<10	4	1	5	2	0	2	0	1	1
10-14	2	0	2	0	0	0	1	1	2
15-19	6	0	6	2	2	4	0	0	0
20-24	3	0	3	4	3	7	3	4	7
25-29	1	1	2	4	4	8	4	1	5
30-34	9	4	13	11	3	14	14	4	18
35-39	17	1	18	19	4	23	15	3	18
40-44	26	9	35	21	6	27	17	4	21
45-49	46	6	52	23	7	30	17	8	25
50-54	31	5	36	8	2	10	8	5	13
55-59	15	8	23	5	0	5	8	0	8
60-64	11	0	11	2	1	3	8	3	11
65-69	2	3	5	0	0	0	4	1	5
70-74	1	0	1	3	2	5	2	0	2
75 and above	0	2	2	0	1	1	1	3	4
Total	174	40	214	104	35	139	102	38	140
Average	44.9	49.2	45.7	41.7	40.9	41.5	45.1	45.1	45.1
Std Dev	12.2	14.3	12.7	11.5	15.7	12.7	12.1	19.6	14.4
85th Percentile	56.3	59.1	56.3	50.6	50.9	50.6	57.8	61.5	60.0
Min	3.7	9.4	3.7	6.6	15.0	6.6	11.3	3.7	3.7
Max	70.3	86.3	86.3	74.1	88.2	88.2	80.7	93.8	93.8
Range	66.6	76.9	82.5	67.5	73.2	81.6	69.4	90.0	90.0

Figure 3.7: Speed distribution and descriptive statistics sample

Descriptive statistics such as the mean, standard deviation, minimum, maximum, and 85th percentile speeds were calculated using the dataset as shown in Figure 3.7.

3.4 STATISTICAL ANALYSIS

For the statistical analysis, two datasets, one control (flashing amber and amber-white lights off) and one treatment (flashing amber and amber-white lights on), were compared statistically.

To isolate the influence of the driver behavior with the flashing amber and amber-white lights on, the position of the paver in relation to the traffic sensor needed to be identified. The GPS tracker attached to the paver allowed for the re-creation of the paver’s travel path. The paver travel path could then be overlaid with the location of the traffic sensors. An example of the relationship between the paver location and the sensor locations is shown in Figure 3.8. This example comes from a day when two pavers were active in the work zone. The three-digit numbers indicated in Figure 3.8 are the unique traffic sensor IDs for the sensors placed on the road that particular day.

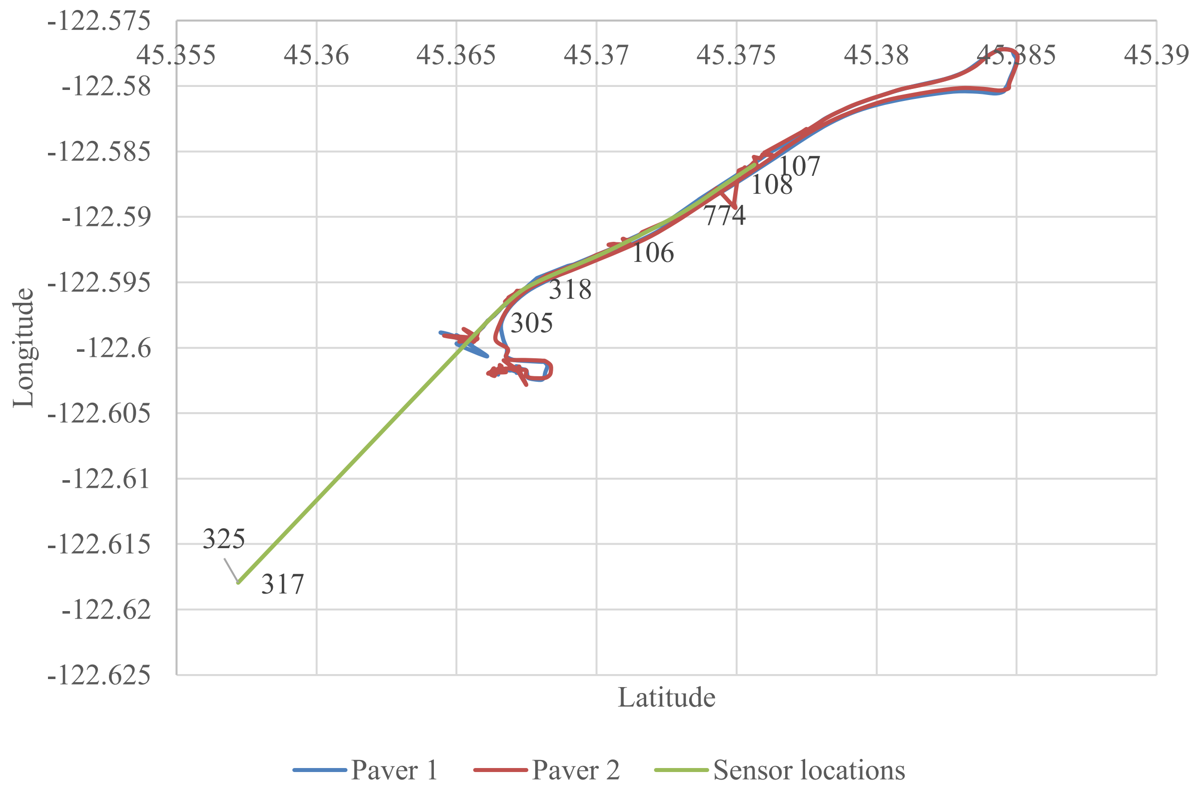

Figure 3.8: Sensor and paver locations

Upon visual inspection of the figure, relative positions of the paver to each sensor of interest were identified. Data recorded at each sensor was filtered to isolate those vehicle measurements that occurred when the paver was within 1,000 ft. upstream and 1,000 ft. downstream of the sensor. This operation was repeated for 250 ft. and 500 ft. intervals, both upstream and downstream of the paver.

Using MATLAB, a two-sample t-test was performed separately for each case study. As the number of samples in each dataset is not the same, a two-sample t-test with a 95% confidence interval was selected to identify statistical significance in the difference between the mean speed measurements collected when the flashing amber and amber-white lights were on, and when the flashing lights were off.

4.0 RESULTS, ANALYSIS, AND DISCUSSION

4.1 SPEED STUDY

This section of the report provides an understanding of the traffic speeds and volumes for both passenger cars and trucks during the data collection periods and the variation in speed through the length of the work zone. To clearly and efficiently convey the data given the large amount of data collected, multiple figures/tables are provided below. For example, free flowing vehicle volumes for Days 1 and 2 are shown in one figure and free-flowing vehicle volumes for Day 3 on the same case study are shown in a separate figure.

4.1.1 Case Study 1: I-5 Sutherlin - Garden Valley Blvd., Roseburg

In this case study, data was collected from 22:00 until 04:00 the next morning on each night, for a total of 3 nights. Figure 4.1 shows the number of vehicles passing through the work zone at each sensor location for the first day of testing when the flashing amber lights were off and the second day when the flashing amber lights were on. The number of heavy vehicles is over represented in this case study. The highest number of heavy vehicles, 479, was recorded at the 5th work zone sensor inside the active work area on Day 1 and the highest number of passenger cars, 460, was recorded at the 1st sensor in the active work area. There are a number of reasons why the volumes may differ from one sensor to another on the same day of data collection. Perhaps the traffic sensor produced a faulty data point and an error code was generated (as described above). The difference in vehicle numbers may also occur when construction vehicles (e.g., asphalt trucks, contractor pickups, and temporary traffic control vehicles) enter the active work area and do not travel across some sensors. If there is a merge/diverge section in or around the work zone, some vehicles may enter/exit the roadway and not travel over all sensors. Also, when a vehicle's wheels drove directly over a sensor, the recorded data showed an error and generated a faulty reading.

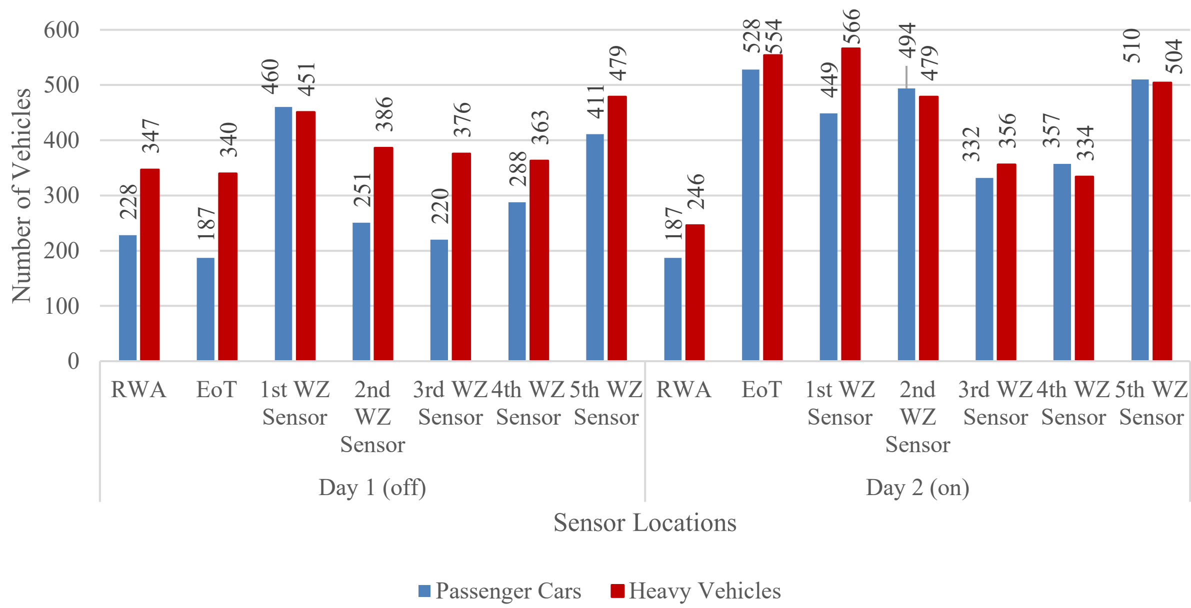

Figure 4.1: Free flow traffic volumes for different vehicle types recorded by WZ sensors for day 1 (lights off) and day 2 (lights on) (case study 1)

Figure 4.2 shows how the number of passenger cars and the number of heavy vehicles have a similar volumetric distribution across sensor locations. Heavy vehicles were more frequently observed than passenger cars. On Day 3 of testing, the amber lights were on. The data was collected from 22:00 to 04:00. The highest recorded heavy vehicle volume, 540, was recorded at the 4th work zone sensor and the highest passenger car volume, 524, was record at the 2nd work zone sensor. Sensors placed at the road work ahead sign and at the end of the taper recorded fewer vehicles than the other sensors.

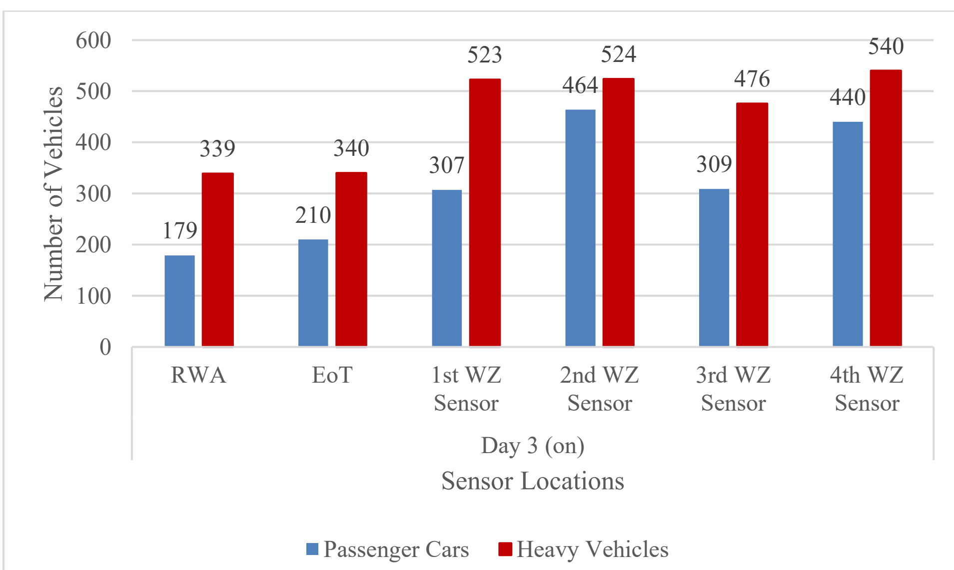

Figure 4.2: Free flow traffic volumes for different vehicle types recorded by active WZ sensors for day 3 (lights on) (case study 1)

The 85th percentile vehicle speed at different locations in the work zone on different days is shown in Figure 4.3. The paver moves through the active work area during the work shift, starting near the 1st work zone sensor and moving downstream towards the last work zone sensor. Therefore, the paver passed each work zone sensor at different times in the work shift. The data presented in the figure represents all of the vehicle speeds recorded at each sensor over the entire work shift.

As shown in the figure, the 85th percentile speeds of the vehicles recorded at the Road Work Ahead (RWA) sign were within 10 mph of the posted speed limit and reduced at the end of the taper. The reduction in speed at the RWA sign is higher on Day 2 (lights on), while the speed on the other two days clustered around the 65-mph speed limit. There is a steady reduction in speed inside the work zone until the 3rd work zone sensor. Days 1 and 2 show an increase in speed at the 5th work zone sensor. The posted speed limit was 65 mph which was reduced to 50 mph in the work zone. Visual inspection of Figure 4.3 suggests that there is no clear pattern regarding the 85th percentile speed. However, many locations inside the work zone had higher 85th percentile speeds than the recommended speed limit in the work zone.

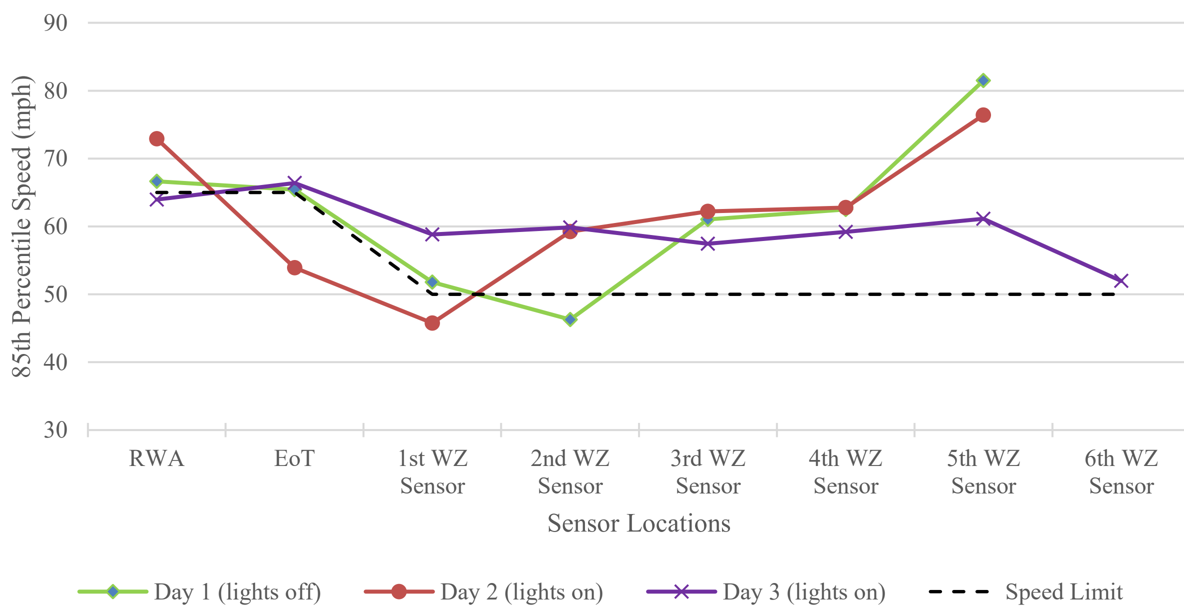

Figure 4.3: Free flow vehicle speed (85th percentile) at different locations for all days (case study 1)

Figure 4.4 shows the 85th percentile speed for each hour of data collection for all days at two locations: end of taper and 2nd work zone sensor. As seen in the figure, at the end of taper location, speeds are higher at all hours as the posted speed limit is 65 mph. Hourly distribution of speed at the 2nd work zone sensor is lower than the end of taper speed and there is no distinctly observable pattern. Similarly, no pattern was observed between days with the flashing amber lights on compared to when the amber lights were off.

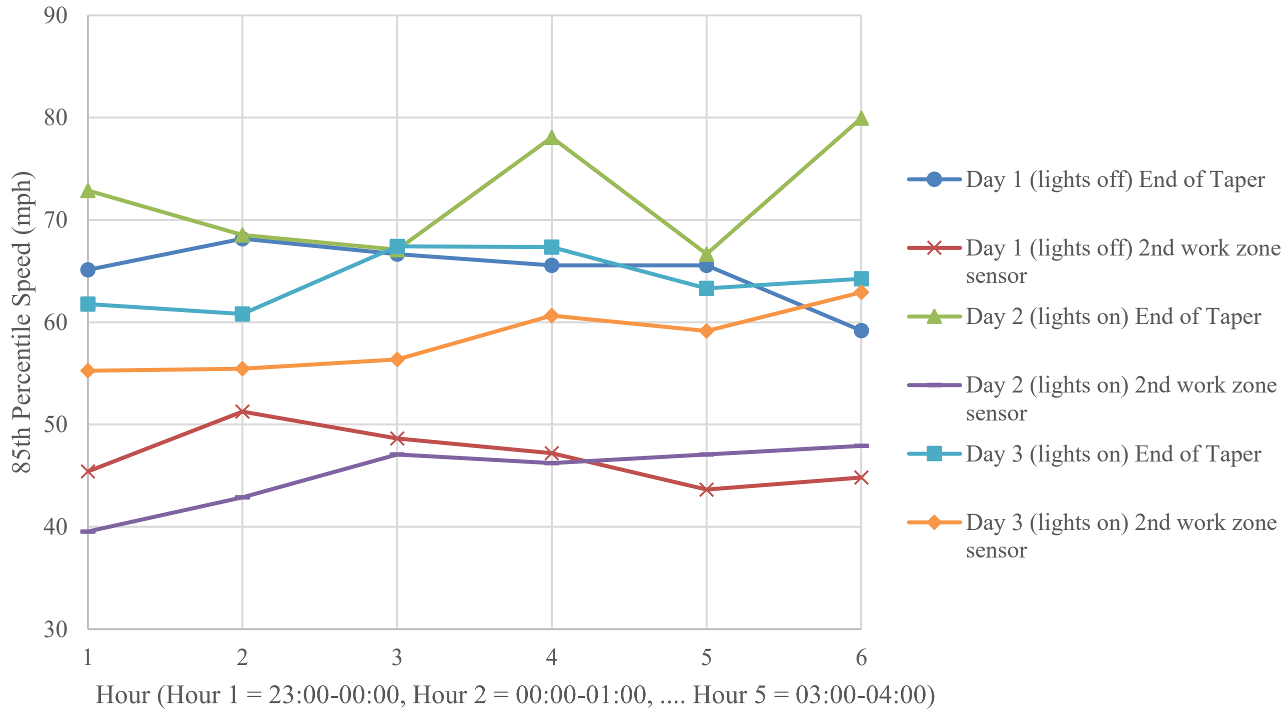

Figure 4.4: Free flow hourly vehicle speed (85% percentile) at end of taper and 2nd work zone sensors for all days (case study 1)

4.1.2 Case Study 2: I-205 Abernethy Bridge – SE 82nd Drive, Oregon City

In this case study, data was collected from 23:00 until 03:30 the next morning on each night of data collection. Figure 4.5 shows the number of vehicles passing through the work zone at different locations for two days of testing when the flashing amber-white lights were first off (Day 1) and then on (Day 2). The data were recorded by different sensors in the middle of the active work area. In general, more passenger cars were observed than heavy vehicles. The highest number of passenger cars, 698, was recorded at the 2nd work zone sensor on Day 1. The highest number of heavy vehicles, 296, was observed at the 2nd work zone sensor on Day 2. Visual inspection yields no distinct pattern in vehicle volumes between lights on days and lights off days.

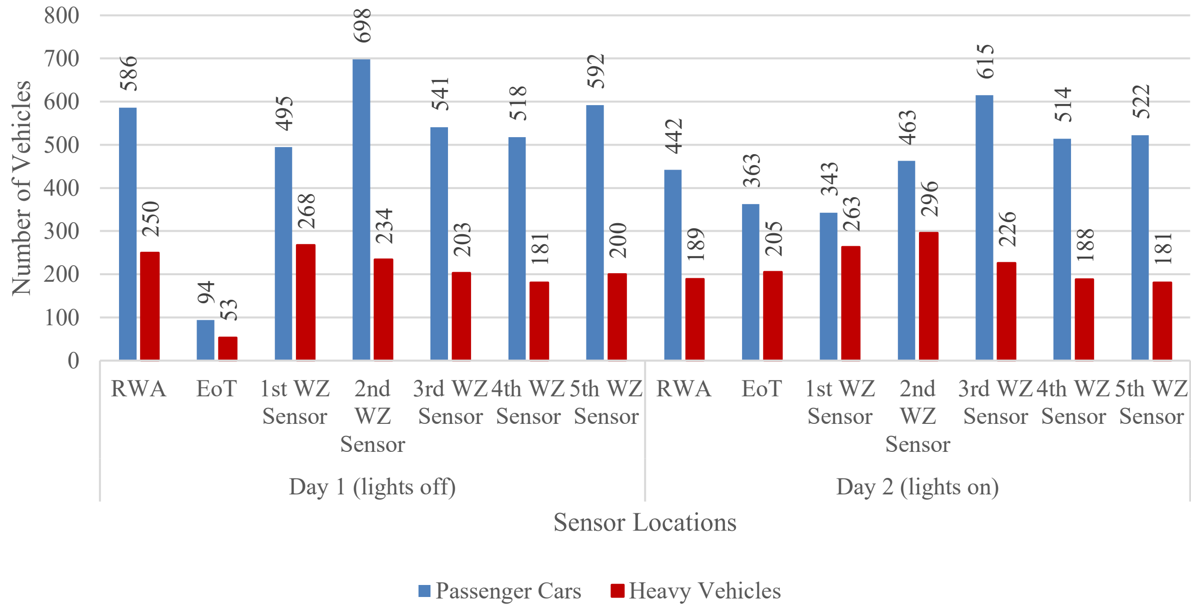

Figure 4.5: Free flow traffic volumes for different vehicle types recorded at work zone sensors for day 1 (lights off) and day 2 (lights on) (case study 2)

Similarly, Figure 4.6 shows how the number of passenger cars and trucks changed in the work zone over the course of each night of data collection for Day 3 and Day 4. The amber-white lights on Day 3 were off and on Day 4 the lights were on. The data collection took place between 23:00 and 03:30 the next morning. There was variation in the volumes recorded by the different sensors. The lowest number of passenger cars was 452 as recorded by the 5th work zone sensor on Day 3, and the highest number of passenger cars was 600 as record by the EoT sensor on Day 4. It is evident that the range is narrow; traffic was somewhat homogenous across the work zone in the two days. As seen in the same figure, the lowest number of heavy vehicles was 147 as recorded by the 6th work zone sensor on Day 4 and the highest number of trucks was 283 as record by the road work ahead sensors on Day 3. The range is narrow for heavy vehicles as well.

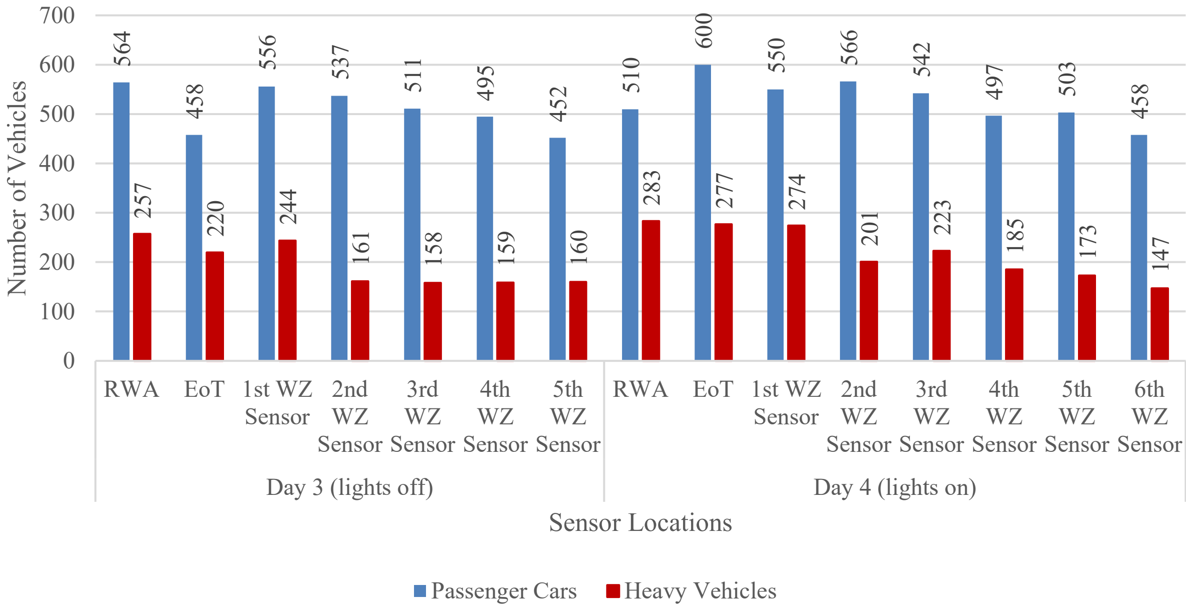

Figure 4.6: Free flow traffic volumes for different vehicle types recorded by active WZ sensors for day 3 (lights off) and day 4 (lights on) (case study 2)

As shown in Figure 4.7, there was variation in the 85th percentile vehicle speed for vehicles recorded at different locations. The figure shows the 85th percentile speed of the vehicles recorded at different locations including at the RWA sign, end of taper, and all of the sensors in the active work area from 22:00 through 04:00 on the four days of testing. The speed limit was 55 mph at the Road Work Ahead (RWA) sign and was not reduced through the work zone. As can be seen in the figure, there was a change in speed from one location to another. For three days (Days 1, 3, and 4), the 85th percentile speed was consistently about 20 mph higher than the posted speed limit at the RWA sign.

For Day 2, when the amber-white light was on, the speed at the RWA was 10 mph lower and increased gradually to the end of taper location. For the other three days (Days 1, 3, and 4), speed variability was reduced inside the work zone. However, at the 4th work zone sensor, speed increased slightly. After this location, there is a decrease in speed at sensor 5. One possible explanation of this behavior is the occasional operation of multiple pavers simultaneously in different locations within the same work zone. However, there is no discerning difference between the lights on and lights off days in this plot.

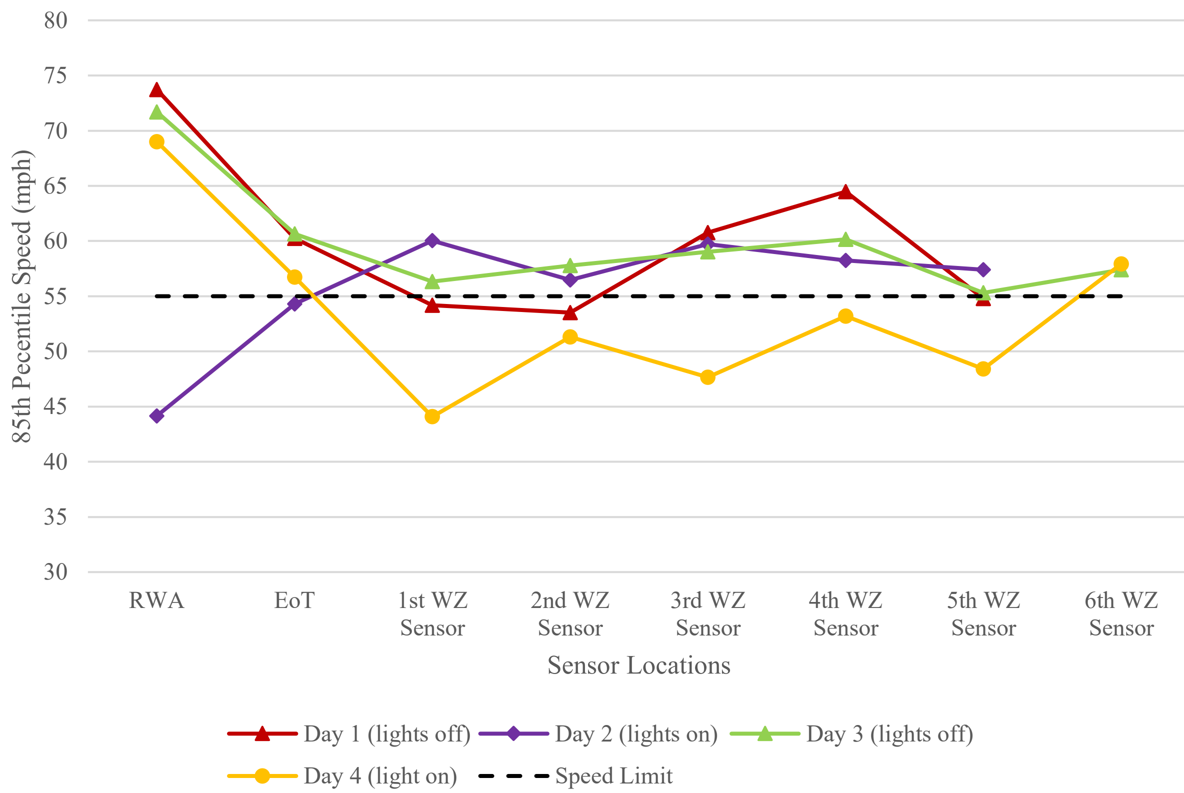

Figure 4.7: Free flow vehicle speed (85th percentile) at different locations for all days (case study 2)

Figure 4.8 shows how the 85th percentile vehicle speed changes over the course of the data collection window. The end of taper sensor location and 2nd work zone sensor location was selected for this analysis. As the speed limit was unchanged for the temporary lane closure, speed reduction inside the work zone after the end of the taper was not anticipated. However, 85th percentile speeds at the end of taper locations were higher than or close to the 2nd work zone sensor speeds. No visual pattern between the amber-white lights on and lights off conditions was detected in this figure.

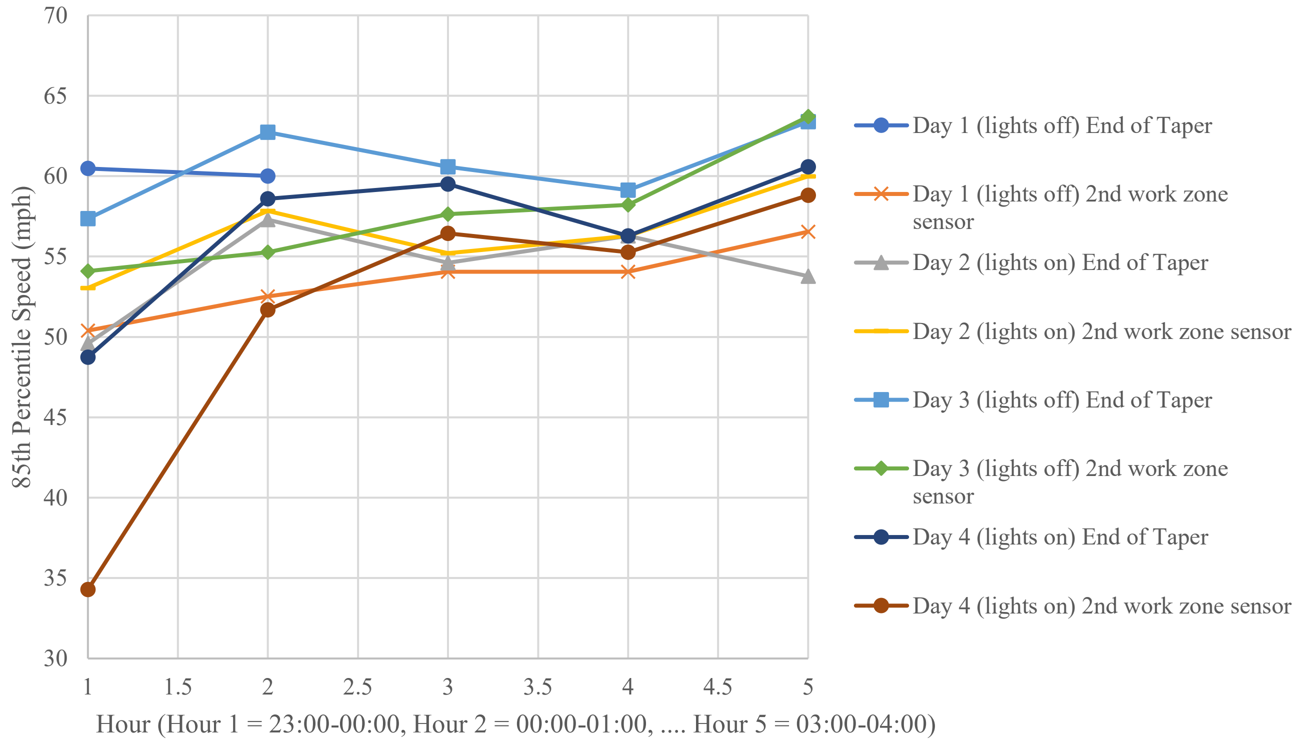

Figure 4.8: Free flow hourly vehicle speed (85% percentile) at active WZ sensors for all days (case study 2)

4.1.3 Case Study 3: I-5 Sutherlin – Garden Valley Blvd., Roseburg

Similar to Case Study 1, for Case Study 3 data was collected from 22:00 until 04:00 the next morning on each night. Figure 4.9 presents the number of vehicles passing through the work zone during Case Study 3 for two days of testing when the flashing amber lights were off (Day 1) and when the lights were on (Day 2). The data were recorded by different sensors in the middle of the work zone. Data from at least 5 active work zone sensors was plotted. There was a difference in the number of passing vehicles on these two days. Heavy vehicle volumes were larger than that of passenger cars at most locations. The largest heavy vehicle volume observed was 417 as compared to 338 for passenger cars. The smallest number of recorded heavy vehicles was 214 on Day 2 at the 1st work zone sensor. The lowest passenger car observation was 158 on Day 1 at the 4th work zone sensor. This range is wider than for Case Study 2, but the vehicle distribution is similar to Case Study 1. Both Case Studies 1 and 3 took place on I-5 near Roseburg, OR.

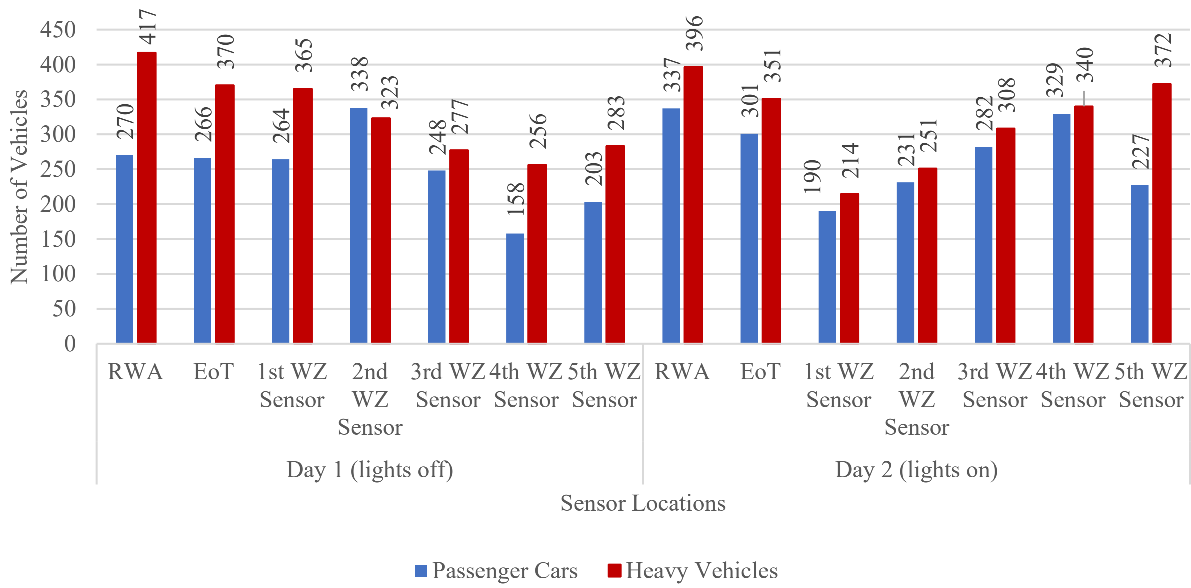

Figure 4.9: Free-flow traffic volumes for different vehicle types recorded by work zone sensors for day1 (lights off) and day 2 (lights on) (case study 3)

Figure 4.10 shows how the number of passing vehicles changed in the work zone over the course of Days 3 and 4 of data collection, in which the flashing amber were lights on and off, respectively. Data collection took place between 22:00 and 04:00, a period of 6 hours. Generally, there was variation in the volume between the different sensors. Volumes of heavy vehicles and passenger cars were similar on Day 3. On Day 4, the difference in volumes is similar to Days 1 and 2 as shown in Figure 5.9. Heavy vehicles are over represented in the figure. However, the highest and lowest volumes are similar.

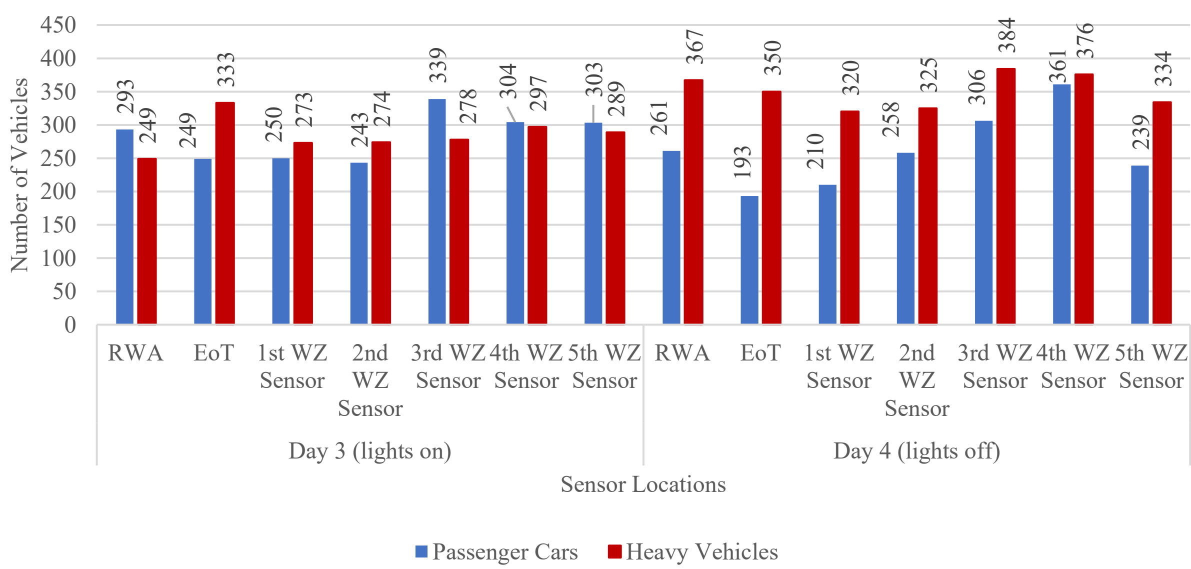

Figure 4.10: Free flow traffic volumes for different vehicle types recorded by active work zone sensors for day 3 (lights on) and day 4 (lights off) (case study 3)

The 85th percentile vehicle speed at different locations in the work zone on different days is shown in Figure 4.11. The figure shows the 85th percentile speed of the vehicles recorded at the RWA sign, end of taper, and all of the sensor locations in the work zone from 22:00 to 04:00 on the four days of testing. The regulatory speed limit was 65 mph at the RWA sign and the temporarily reduced speed limit in the work zone was 50 mph. As seen in the figure, there is variation in the speed between the different locations. The lowest 85th percentile speed of the passing vehicles was 54 mph as recorded by the 1st work zone sensor on Day 2, and the highest 85th percentile speed of the passing vehicles was 78.2 mph recorded by the A lane sensor at the RWA sign on Day 3. The reduction in speed is clear from the EoT to inside the active work area for all days, except Day 3. No distinguishable pattern was observed between flashing amber lights on days and lights off days.

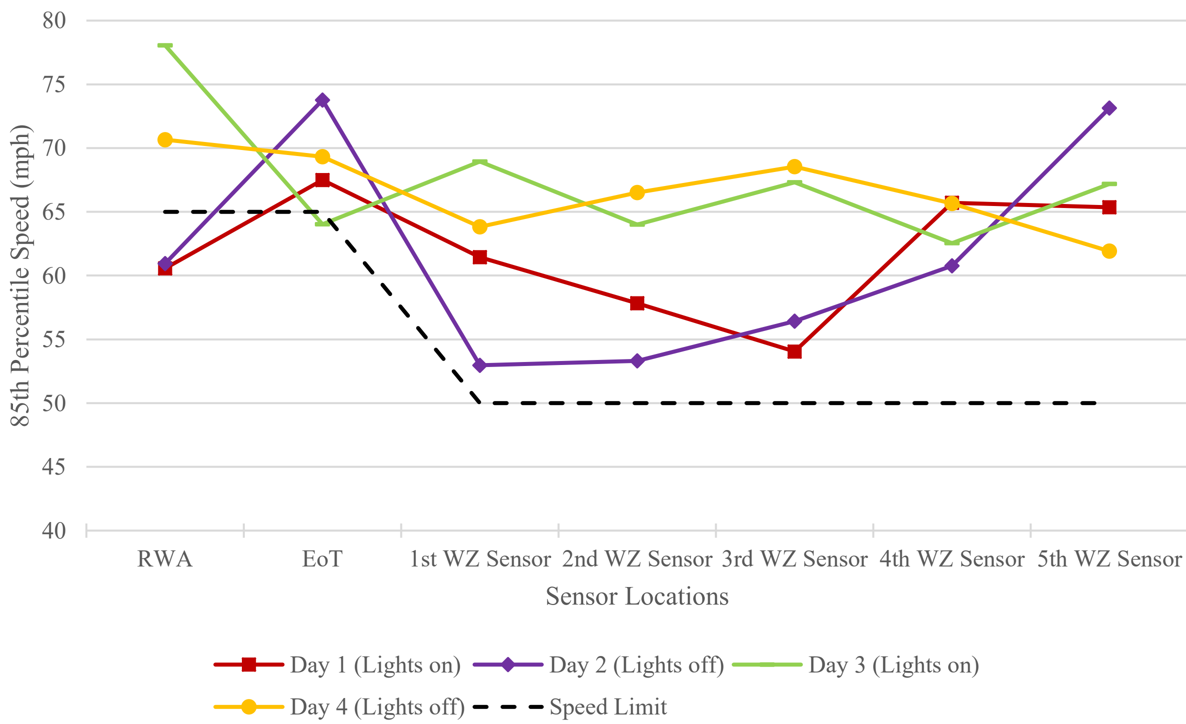

Figure 4.11: Free flow vehicle speed (85th percentile) at different locations for all days (case study 3)

For the third case study, the variation in the hour-by-hour 85th percentile vehicle speed is plotted in Figure 4.12. There is a general trend of speed reduction with hour progression. No distinct pattern could be identified between the EoT to 2nd work zone sensor speeds or between lights on and lights off days.

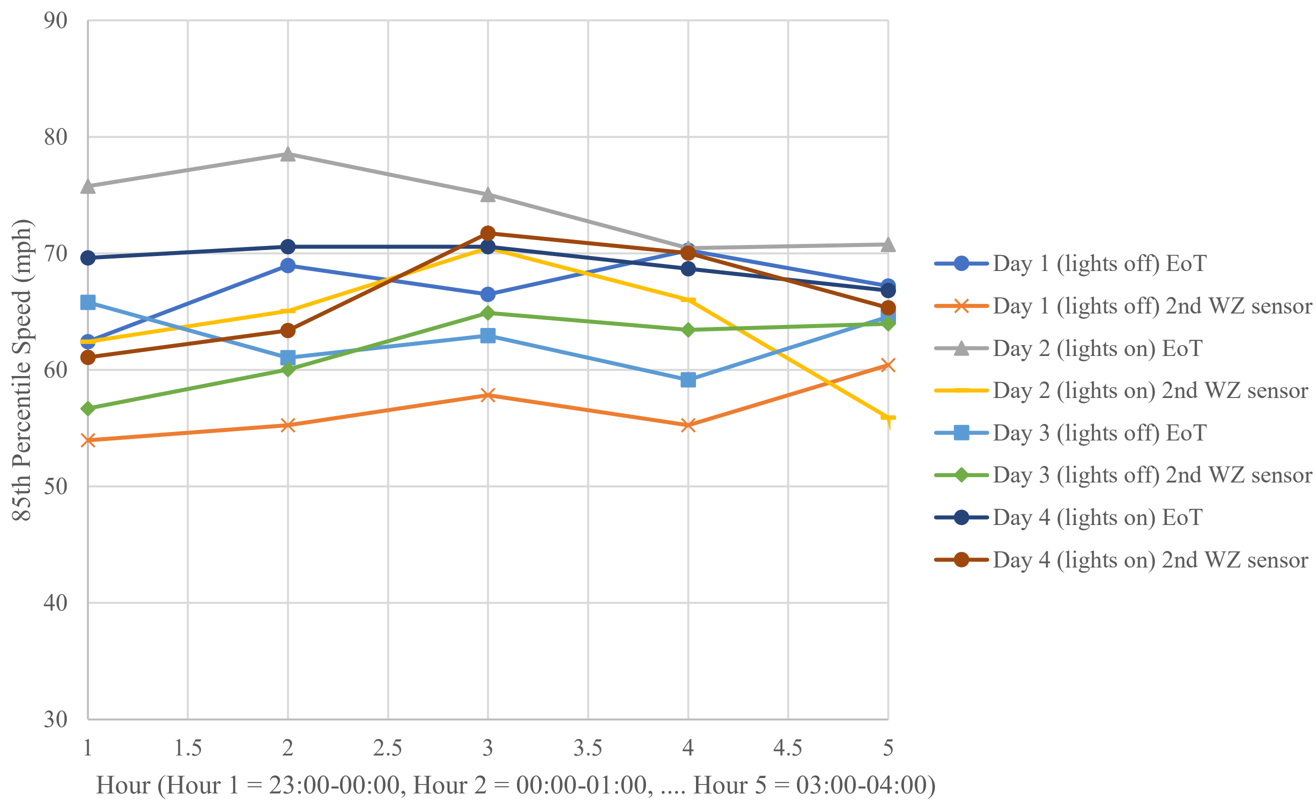

Figure 4.12: Free flow hourly vehicle speed (85% percentile) at active work zone sensors for all days (case study 3)

4.2 DESCRIPTIVE STATISTICS

Descriptive statistics of the data collected, especially vehicle speed in each case study, are calculated that include the mean speed, standard deviation, 85th percentile speed, minimum and maximum speeds, and range. The following section describes the descriptive statistics for the three case studies. Data at two locations is shown for each case study: at the RWA sign and in the middle of the work zone. Similar descriptive statistics were developed at other sensor locations in the work zone for each case study, but not included in the report for brevity.

4.2.1 Case Study 1: I-5 Sutherlin - Garden Valley Blvd., Roseburg

Figure 4.13 presents a summary of the vehicle speeds recorded for all vehicles (passenger cars and heavy vehicles) at the RWA sign location on Day 1 when the flashing amber lights were turned off. PC stands for passenger cars and HV stands for heavy vehicles. The green bars in the Figure that overlay the passenger car and heavy vehicle data depict the frequency histogram. In this figure, data is recorded from one sensor placed near the RWA sign in the fast lane (A lane). As shown in the figure, average speed across the data collection period was 66.7 mph. Average speed varied from 63.1 mph during the period from 00:00-01:00 to 71.2 mph during the period from 22:00-23:00. The posted speed limit was 65 mph at the RWA sign. The 85th percentile speed for the entire recording time was 75.3 mph. The 85th percentile speed value ranged from

66.6 mph to 82.1 mph throughout the test period. It should be noted that the values presented in in Figure 4.13 are different than those presented in Figure 4.3 above. Figure 4.13 shows the hourly speed distribution recorded by one sensor at the RWA sign. Multiple sensors were placed at this location, one in each travel lane. Figure 4.3 presents a weighted average (by traffic volume) of the 85th percentile speed of all hours at all RWA sensors.

Category	22:00-23:00			23:00-00:00			00:00-01:00			01:00-02:00			02:00-03:00			03:00-04:00		
Speed Range	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total
<10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10-14	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
15-19	0	0	0	1	0	1	0	0	0	1	0	1	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
25-29	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0
30-34	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35-39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40-44	0	0	0	1	0	1	0	0	0	0	1	1	0	0	0	0	0	0
45-49	1	1	2	2	0	2	0	0	0	0	0	0	0	0	0	1	0	1
50-54	2	2	4	0	3	3	1	3	4	0	2	2	3	1	4	2	1	3
55-59	9	15	24	6	7	13	2	9	11	2	14	16	2	12	14	3	17	20
60-64	12	29	41	9	30	39	7	31	38	4	32	36	4	30	34	7	25	32
65-69	9	18	27	13	11	24	6	8	14	3	9	12	7	15	22	6	19	25
70-74	10	8	18	8	4	12	5	0	5	4	6	10	4	7	11	10	7	17
75 and above	12	10	22	16	5	21	8	7	15	10	2	12	6	6	12	8	9	17
Total	57	83	140	57	60	117	30	58	88	24	66	90	27	71	98	37	78	115
Average	66.0	66.2	66.1	68.6	65.1	66.8	69.5	65.5	66.9	71.2	63.1	65.3	66.7	66.0	66.2	68.8	66.1	66.9
Std Dev	12.5	9.9	11.0	14.8	7.9	11.9	13.0	11.6	12.2	16.2	6.9	10.7	14.7	8.2	10.3	9.4	8.8	9.0
85th Percentile	76.7	74.6	75.7	81.0	70.3	77.8	81.0	68.1	76.7	82.1	66.6	72.4	79.4	72.3	74.4	78.8	72.4	74.9
Min	12.1	48.7	12.1	15.4	50.9	15.4	27.2	52.0	27.2	19.7	43.4	19.7	13.2	53.0	13.2	45.5	54.1	45.5
Max	97.2	102.6	102.6	108.0	92.9	108.0	102.6	111.2	111.2	113.3	100.4	113.3	96.1	105.8	105.8	92.9	99.3	99.3
Range	85.1	53.8	90.5	92.6	42.0	92.6	75.4	59.2	84.0	93.7	57.1	93.7	82.9	52.8	92.6	47.4	45.2	53.8

Figure 4.13: Hourly summary of vehicle free flow speed, day 1 (lights off) at RWA sign (case study 1)

Similarly, in Figure 4.14, RWA data is tabulated for Day 3 when the flashing amber lights were turned on. As shown in the figure, average speed across the data collection period was 54.1 mph. Average speed varied from 40.8 mph during the period from 22:00-23:00 to 61.7 mph during the period from 02:00-03:00. The posted speed limit was 65 mph at the RWA sign. The 85th percentile speed for the entire recording time was 64.7 mph. The 85th percentile speed value ranged from 54.7 mph to 79.7 mph throughout the data collection period. Both average speed and 85th percentile speed was lower when the flashing amber lights were turned on. However, further analysis is required to confirm this observation.

Category	22:00-23:00			23:00-00:00			00:00-01:00			01:00-02:00			02:00-03:00			03:00-04:00		
Speed Range	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total
<10	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
10-14	1	0	1	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0
15-19	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
20-24	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25-29	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1
30-34	2	1	3	0	1	1	1	0	1	0	0	0	0	1	1	0	0	0
35-39	2	5	7	1	8	9	3	1	4	1	0	1	1	1	2	1	0	1
40-44	4	2	6	8	9	17	4	5	9	0	0	0	1	3	4	3	2	5
45-49	3	3	6	20	17	37	3	11	14	2	4	6	4	3	7	3	3	6
50-54	2	4	6	13	17	30	3	6	9	2	12	14	7	14	21	6	15	21
55-59	6	2	8	4	11	15	2	12	14	7	8	15	8	12	20	11	19	30
60-64	1	0	1	3	2	5	5	4	9	1	8	9	4	7	11	7	9	16
65-69	1	0	1	3	1	4	0	0	0	1	2	3	1	2	3	1	0	1
70-74	0	0	0	2	1	3	1	0	1	2	1	3	1	3	4	3	1	4
75 and above	0	1	1	2	4	6	4	0	4	2	2	4	2	9	11	2	7	9
Total	26	20	46	57	72	129	27	39	66	18	37	55	29	55	84	40	56	96
Average	40.8	45.2	42.7	52.0	51.6	51.8	55.3	51.7	53.2	60.0	58.4	58.9	57.0	61.7	60.1	54.8	60.1	57.9
Std Dev	19.6	13.7	17.3	10.1	14.0	12.4	20.0	6.3	13.7	11.4	8.2	9.3	11.9	16.0	14.8	14.4	12.5	13.5
85th Percentile	58.4	54.7	57.4	62.7	57.4	59.5	73.8	57.4	61.7	74.4	64.9	68.4	65.1	79.7	72.2	66.5	65.6	65.2
Min	0.3	21.8	0.3	25.0	14.3	14.3	13.2	36.9	13.2	36.9	46.6	36.9	38.0	32.6	32.6	10.0	41.2	10.0
Max	68.1	87.5	87.5	81.0	116.6	116.6	115.5	61.7	115.5	80.0	82.1	82.1	101.5	106.9	106.9	82.1	102.6	102.6
Range	67.8	65.7	87.2	56.0	102.3	102.3	102.3	24.8	102.3	43.1	35.5	45.2	63.5	74.3	74.3	72.1	61.4	92.6

Figure 4.14: Hourly summary of vehicle free flow speed, day 3 (lights on) at RWA sign (case study 1)

4.2.2 Case Study 2: I-205 Abernethy Bridge – SE 82nd Drive, Oregon City

Figure 4.15 shows a summary of the vehicle speeds recorded for all passenger cars and heavy vehicles at the RWA sign location on Day 1 when the amber-white lights were turned off. Data shown in the figure is that recorded from one sensor placed near the RWA sign in the slow lane (B lane). As shown in the figure, the mean speed for the entire recording time was 62.3 mph. The mean speed varied from 35.4 mph during the period from 03:00 to 04:00 to 69.0 mph from 23:00-00:00. The posted speed limit on this segment of highway was 55 mph. The 85th percentile speed for the entire recording time was 79.8 mph. The range for this value was from 50.8 mph to 83.5 mph throughout the test period.

Category	22:00-23:00			23:00-00:00			00:00-01:00			01:00-02:00			02:00-03:00			03:00-04:00		
Speed Range	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total
<10	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1
10-14	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15-19	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
20-24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
25-29	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
30-34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35-39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40-44	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
45-49	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
50-54	5	0	5	3	0	3	2	0	2	3	0	3	4	0	4	1	2	3
55-59	6	0	6	6	0	6	4	0	4	2	0	2	2	1	3	0	0	0
60-64	14	1	15	4	0	4	7	0	7	4	0	4	5	0	5	0	0	0
65-69	10	0	10	2	0	2	5	0	5	5	2	7	5	0	5	0	0	0
70-74	9	1	10	8	0	8	4	0	4	10	1	11	5	0	5	0	0	0
75 and above	18	4	22	7	4	11	7	0	7	4	1	5	3	3	6	0	0	0
Total	66	6	72	31	4	35	30	1	31	28	4	32	26	4	30	3	2	5
Average	66.9	86.2	68.5	67.1	84.0	69.0	67.5	0.0	67.5	67.4	73.5	68.1	63.1	80.2	65.4	25.2	50.8	35.4
Std Dev	14.0	14.8	15.0	11.8	9.7	12.7	13.6	0.0	13.6	8.0	9.1	8.3	13.5	14.7	14.7	25.3	0.0	22.7
85th Percentile	79.4	98.8	81.4	77.9	96.7	80.0	80.7	0.0	80.7	74.7	85.0	75.5	72.5	88.1	83.5	50.8	50.8	50.8
Min	14.3	64.8	14.3	43.3	77.9	43.3	29.3	0.0	29.3	50.8	65.7	50.8	16.2	58.3	16.2	0.3	50.8	0.3
Max	101.3	100.3	101.3	100.3	98.5	100.3	97.5	0.0	97.5	78.8	86.3	86.3	84.4	88.2	88.2	50.8	50.8	50.8
Range	87.0	35.5	87.0	57.1	20.6	57.1	68.3	0.0	68.3	28.1	20.6	35.5	68.3	29.9	72.0	50.5	0.0	50.5

Figure 4.15: Hourly summary of vehicle free flow speed, day 1 (lights off) at RWA sign (case study 2)

In the same way, vehicle speeds recorded for all passenger cars and heavy vehicles at the RWA sign location on Day 2 when the amber-white lights were turned on are tabulated in Figure 4.16. Data shown in the figure is that recorded from one sensor placed near the RWA sign in the slow lane (B lane). As shown in the figure, the mean speed for the entire recording time was 55.8 mph. The mean speed varied from 39.9 mph during the period from 03:00 to 04:00 to 62.5 mph from 22:00-23:00. The posted speed limit on this segment of highway was 55 mph. The 85th percentile speed for the entire recording time was 70.1 mph. The range for this value was from 57.7 mph to 74.0 mph throughout the test period.

Category	22:00-23:00			23:00-00:00			00:00-01:00			01:00-02:00			02:00-03:00			03:00-04:00		
Speed Range	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total
<10	0	0	0	0	0	0	1	0	1	2	1	3	1	1	2	0	0	0
10-14	0	0	0	1	0	1	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	2	0	2	0	0	0
20-24	1	0	1	1	0	1	0	1	1	0	0	0	3	0	3	0	0	0
25-29	1	0	1	0	0	0	1	0	1	1	0	1	3	1	4	0	0	0
30-34	1	0	1	1	0	1	2	0	2	3	0	3	1	0	1	2	1	3
35-39	3	0	3	0	1	1	2	0	2	3	0	3	1	1	2	1	0	1
40-44	3	0	3	5	1	6	1	0	1	5	4	9	3	0	3	0	0	0
45-49	7	3	10	3	3	6	7	3	10	7	5	12	2	1	3	0	0	0
50-54	18	6	24	11	6	17	9	8	17	8	6	14	4	8	12	0	0	0
55-59	21	9	30	21	3	24	12	4	16	11	2	13	8	1	9	0	0	0
60-64	31	6	37	25	9	34	6	4	10	13	4	17	10	10	20	0	1	1
65-69	21	4	25	5	2	7	12	1	13	7	2	9	5	5	10	0	0	0
70-74	13	7	20	5	3	8	5	1	6	8	2	10	7	5	12	0	0	0
75 and above	9	13	22	5	11	16	7	5	12	2	3	5	5	3	8	0	0	0
Total	129	48	177	83	39	122	65	27	92	70	29	99	55	36	91	3	2	5
Average	60.9	66.7	62.5	58.8	64.9	60.7	58.7	60.0	59.1	55.5	55.8	55.6	55.0	60.4	57.1	34.5	48.2	39.9
Std Dev	11.0	11.4	11.4	11.3	13.6	12.4	13.9	13.1	13.6	14.9	15.8	15.1	18.8	13.9	17.2	3.7	22.4	13.7
85th Percentile	72.1	80.2	73.9	67.7	81.2	74.0	72.8	77.5	73.7	69.4	74.1	70.0	70.8	71.4	71.1	38.7	64.0	57.7
Min	22.4	48.6	22.4	10.6	38.7	10.6	6.1	24.2	6.1	2.5	3.4	2.5	5.2	9.7	5.2	32.3	32.3	32.3
Max	84.8	87.5	87.5	83.9	87.5	87.5	83.0	83.9	83.9	84.8	84.8	84.8	87.5	79.4	87.5	38.7	64.0	64.0
Range	62.4	38.9	65.1	73.3	48.8	76.9	76.9	59.7	77.8	82.3	81.4	82.3	82.3	69.7	82.3	6.3	31.7	31.7

Figure 4.16: Hourly summary of vehicle free flow speed, day 2 (lights on) at RWA sign (case study 2)

4.2.3 Case Study 3: I-5 Sutherlin – Garden Valley Blvd., Roseburg

Figure 4.17 shows a summary of the vehicle speeds recorded for all passenger cars and trucks at the RWA sign location on Day 2 when the flashing amber lights were turned on. Data shown in the figure is that recorded from one sensor placed near the RWA sign in the fast lane (A lane). As shown in the figure, the mean speed for the entire recording time was 65.2 mph. The mean speed varied from 62.3 mph during the period from 02:00 to 03:00 to 67.5 mph from 23:00-00:00. The posted speed limit on this segment of highway was 65 mph. The 85th percentile speed for the entire recording time was 75.5 mph. The range for this value was from 70.9 mph to 78.7 mph throughout the test period.

Category	22:00-23:00			23:00-00:00			00:00-01:00			01:00-02:00			02:00-03:00			03:00-04:00		
Speed Range	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total
<10	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
15-19	0	0	0	1	0	1	0	0	0	1	0	1	1	0	1	0	0	0
20-24	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
30-34	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
35-39	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
40-44	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0
45-49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50-54	2	1	3	0	0	0	4	1	5	1	0	1	1	0	1	1	0	1
55-59	1	1	2	3	1	4	6	0	6	2	0	2	1	0	1	4	1	5
60-64	9	0	9	7	0	7	7	0	7	4	0	4	4	1	5	3	0	3
65-69	3	0	3	2	0	2	4	0	4	1	0	1	2	0	2	2	1	3
70-74	4	1	5	5	0	5	5	0	5	6	1	7	4	1	5	2	0	2
75 and above	8	0	8	7	2	9	4	1	5	3	0	3	4	0	4	0	1	1
Total	27	3	30	25	3	28	30	2	32	18	2	20	19	3	22	12	3	15
Average	67.9	60.1	67.1	67.2	70.1	67.5	65.2	63.9	65.1	65.8	59.2	65.2	62.9	58.9	62.3	62.9	68.5	64.1
Std Dev	8.4	10.8	8.8	14.0	9.5	13.5	9.8	17.2	10.0	16.5	21.2	16.5	17.5	17.4	17.1	5.6	10.4	6.8
85th Percentile	76.0	72.3	76.0	80.0	76.0	78.7	74.2	76.0	75.5	75.6	74.2	75.1	77.8	73.2	76.6	69.6	79.8	70.9
Min	51.7	51.7	51.7	15.2	59.2	15.2	52.6	51.7	51.7	15.2	44.2	15.2	15.2	39.5	15.2	54.5	59.2	54.5
Max	84.4	72.3	84.4	88.2	76.0	88.2	94.7	76.0	94.7	91.0	74.2	91.0	89.1	73.2	89.1	72.3	79.8	79.8
Range	32.7	20.6	32.7	73.0	16.8	73.0	42.1	24.3	43.0	75.8	29.9	75.8	73.9	33.7	73.9	17.8	20.6	25.3

Figure 4.17: Hourly summary of vehicle free flow speed, day 2 (lights on) at RWA sign (case study 3)

Similarly, vehicle speeds recorded for all passenger cars and trucks at the RWA sign location on Day 1 when the flashing amber lights were turned off are tabulated in Figure 4.18. Data shown in this figure is that recorded from one sensor placed near the RWA sign in the fast lane (A lane). As shown in the figure, the mean speed for the entire recording time was 43.8 mph. The mean speed varied from 31.6 mph during the period from 01:00 to 02:00 to 52.5 mph from 03:00-04:00. The posted speed limit on this segment of highway was 55 mph. The 85th percentile speed for the entire recording time was 47.3 mph.

Category	22:00-23:00			23:00-00:00			00:00-01:00			01:00-02:00			02:00-03:00			03:00-04:00		
Speed Range	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total	PC	HV	Total
<10	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	1	1	0	0	0	0	0	0
15-19	0	3	3	0	3	3	0	2	2	0	5	5	0	0	0	0	1	1
20-24	0	5	5	0	8	8	0	10	10	0	8	8	0	7	7	0	4	4
25-29	0	9	9	0	7	7	0	7	7	0	9	9	0	7	7	0	5	5
30-34	0	10	10	0	9	9	0	3	3	0	2	2	0	10	10	0	6	6
35-39	0	5	5	0	4	4	0	4	4	0	7	7	0	4	4	0	5	5
40-44	0	4	4	1	2	3	0	8	8	0	6	6	0	5	5	0	5	5
45-49	0	1	1	1	1	2	1	0	1	0	2	2	1	2	3	0	2	2
50-54	0	3	3	2	2	4	0	2	2	0	1	1	1	5	6	0	1	1
55-59	1	1	2	0	1	1	0	0	0	1	0	1	0	1	1	0	1	1
60-64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2
65-69	0	0	0	1	0	1	0	0	0	0	0	0	1	0	1	0	1	1
70-74	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
75 and above	0	1	1	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0
Total	1	42	43	5	39	44	1	36	37	1	41	42	4	41	45	1	32	33
Average	55.3	34.3	34.8	52.7	33.8	36.0	46.8	31.5	31.9	56.3	31.0	31.6	60.3	35.1	37.3	60.1	36.7	37.4
Std Dev	0.0	12.0	12.3	9.8	14.6	15.3	0.0	9.1	9.3	0.0	9.8	10.4	12.8	10.3	12.7	0.0	12.0	12.5
85th Percentile	55.3	45.1	46.1	64.9	47.6	51.5	46.8	41.1	41.1	56.3	42.3	43.3	73.7	47.5	51.3	60.1	46.5	50.4
Min	55.3	15.3	15.3	43.9	17.2	17.2	46.8	15.3	15.3	56.3	14.4	14.4	47.7	20.1	20.1	60.1	19.1	19.1
Max	55.3	76.3	76.3	68.7	80.1	80.1	46.8	50.6	50.6	56.3	51.5	56.3	74.4	58.2	74.4	60.1	68.7	68.7
Range	0.0	60.9	60.9	24.8	62.9	62.9	0.0	35.2	35.2	0.0	37.1	41.9	26.7	38.1	54.3	0.0	49.5	49.5

Figure 4.18: Hourly summary of vehicle free flow speed, day 1 (lights off) at RWA sign (case study 3)

4.3 STATISTICAL ANALYSIS

A variety of statistical tests were performed on the datasets to determine whether the flashing amber and amber-white lights have a statistically significant impact on vehicle speed. As a first step, normality tests were performed before moving forward with other statistical tests. Once normality was tested and confirmed for each individual day of each case study, two sample t-tests were performed on the mean speeds to infer whether there is a significant statistical difference in mean speed between two speed groups, control (flashing amber or amber-white lights off) and treatment (flashing amber or amber-white lights on).

With the goal of explaining the drivers' behavior based on speed reduction, a t-test was also performed on the dataset that differentiates the drivers' normal response with no additional speed restrictions (i.e., at the RWA sign) and when the drivers were in the active work zone. This analysis, referred to as speed differential, reflects the impact of the flashing amber and amber-white lights on reducing free-flow speed, and without potential confounding factors associated with downstream work activities.

Each case study was analyzed independently. The differences in location, roadway design, travel lane/paving lane, traffic volumes, dates of data collection, and other factors amongst the case studies were viewed as confounding variables that inhibit making comparisons between the case studies with a high level of confidence. Therefore, the data collected from each case study was analyzed independent of the data from the other case studies.

Within each case study, the data collected was considered comparable from one day to the next. That is, differences in such conditions as day of the week, traffic volumes, roadway segment, and other daily changes in the construction operations were not viewed as being significant factors that create confounding variables. As a result, within each case study, comparisons were made between different days, specifically comparing those days in which the flashing amber or amber-white lights were off (control) and those days with the flashing amber or amber-white lights turned on (treatment).

4.3.1 Data Structuring

A limitation associated with using fixed location traffic sensors is that the sensors do not track individual vehicles throughout the entire work zone. However, as sensors are placed less than 0.5 miles apart within the active work area, it is very likely that each sensor is not independent of the other sensors since a vehicle typically passes over multiple or all of the sensors, especially within the active work area with only one travel lane. To minimize the effect of a lack of independence, the sensors were categorized based on proximity to the paver.

Each sensor at a fixed location will be in proximity to the paver for the complete paving operation, i.e., the paver approaching the sensor (upstream of sensor), the paver at the sensor location, and the paver passed the sensor (downstream of sensor). The flashing amber or amber-white lights on the paver only shine back upstream of the paver. So, for a driver crossing over a sensor with the paver downstream of the sensor, the driver sees and reacts to the flashing amber-white lights on the back of the paver. That is, in this case, the sensor records the vehicle speeds as the driver reacts to the amber-white lights. When the paver is adjacent the location of the sensor, the driver passing over the sensor has seen the amber-white lights on the paver and already reacted to it. For the last case, when sensor is downstream of the paver, the speeds recorded by the sensor represent driver behavior after seeing the amber-white lights and after passing the paver (i.e., the vehicle is downstream of the paver). Therefore, likely reactions of the driver based on location could be recorded in this dataset, namely: (1) preparing to react to the amber-white lights as the driver can see the lights and is approaching the paver; (2) saw the amber-white lights and is reacting to the lights (is adjacent the paver); and (3) travelled passed the paver and reacted to the flashing amber and amber-white lights (is downstream of the paver).

However, for this screening of data to be meaningful, all of the sensors were, logically, not in proximity of the paving equipment during the entire data collection period. Using the location and time data from the GPS trackers placed on the paver, the recorded average speed of the paver was calculated to be 1.6 mph. Therefore, only one sensor with a radius of influence of 1,000 ft was in the vicinity of the paver at one time. Two datasets were created that contained data at different intervals between 1,000 feet upstream and 1,000 feet downstream of the paver, one dataset based on 250 ft intervals and the other based on 500 ft intervals. Each dataset was developed separately for all case studies and included control data (flashing amber or amber-white lights off) and treatment data (flashing amber or amber-white lights on). Each dataset was then used for all further data analyses to determine the difference in speeds between the control days and the treatment days.

4.3.2 Case Study 1: I-5 Sutherlin - Garden Valley Blvd., Roseburg

4.3.2.1 Two Sample t-Test for 250 ft. Interval

To identify statistical significance of the mean speed difference between control (flashing amber lights off) and treatment (flashing amber lights on) days, using the data structuring method described above, two datasets were compiled individually for the control and treatment. The number of data points in each dataset was not equal, therefore, two sample t-tests were performed. Table 4.1 summarizes the results of the t-tests performed on each bin, categorized based on distance of the vehicle from the paver. For example, the bin “Upstream 1,000-750 ft.” had 61 data points (N), meaning that 61 vehicles were recorded at the sensor when the vehicles passing over the sensor were 750 to 1,000 ft. upstream of the paver. The bin “Downstream 250-500 ft” with 17 data points means that the 17 vehicles were recorded by the sensor when the vehicles had already passed the paver and were 250 to 500 ft. downstream of the paver when the flashing amber lights were off.

Table 4.1: t-Test Summary at 250 ft. Intervals (Case Study 1)

Category	Statistics	Distance Upstream of Paver (ft.)				Distance Downstream of Paver (ft.)			
		1,000-750	750-500	500-250	250-0	0-250	250-500	500-750	750-1,000
Flashing amber lights off	Sample Size (N)	61	32	28	35	35	17	17	33
	Average (mph)	46.3	42.3	46.1	45.8	42.7	48.6	42.9	44.1
	Standard Deviation (mph)	11.4	10.2	6.2	8.2	8.0	5.8	9.1	8.5
	Minimum (mph)	21.5	15.2	35.1	30.5	25.1	38.7	26.0	19.7
	Maximum (mph)	86.6	64.0	64.0	64.0	64.0	58.6	59.5	64.9
	85th Percentile Speed (mph)	53.5	51.7	52.8	54.5	50.4	57.4	56.4	52.2
Flashing amber lights on	Sample Size (N)	110	236	316	91	227	182	169	155
	Average (mph)	47.7	46.0	52.6	48.5	49.8	46.2	46.5	53.1
	Standard Deviation (mph)	11.9	14.1	11.0	16.9	14.9	15.7	14.1	10.0
	Minimum (mph)	9.4	5.6	10.0	6.6	4.7	5.6	4.7	15.2
	Maximum (mph)	86.3	97.4	116.0	106.3	109.5	91.0	113.0	86.3
	85th Percentile Speed (mph)	60.4	59.0	61.7	58.1	61.9	62.4	57.7	63.5
Comparison	Average Off speed minus Average On speed (mph)	-1.41	-3.69	-6.50	-2.66	-7.18	2.43	-3.53	-9.05
	t-Stat	-0.753	-1.436	-3.076	-0.886	-2.796	0.632	-1.007	-4.832
	p-Value	0.452	0.152	0.002	0.377	0.006	0.528	0.315	0.000

As shown in the comparison section of the table, the average speed difference was calculated between the average of the flashing amber lights on and off days, and statistical significance of the difference is quantified in terms of t-statistics and significance (p-value). A negative difference indicates that the recorded average speed was higher when the flashing amber lights were on than when the lights were turned off. A positive speed difference indicates that speed was lower when the flashing amber lights were on. In this scenario, it is observed that only one location, 250-500 ft. downstream of the paver, revealed a lower average speed on treatment days. However, this difference was not statistically significant with a p-value of 0.05. At all other locations, days with the flashing amber lights turned on (treatment) showed a higher average speed, but the difference was not significant at all locations. At separate locations e.g., 500-250 ft. upstream of the paver, right at paver, and 750-1,000 ft. after the paver, the difference was statistically significant when treatment days displayed higher average speed.

This finding is plotted in Figure 4.19. The a priori expected pattern is that as the vehicles approach the heavy machinery on the road, speeds will reduce and then will gradually increase as vehicles leave the work area, a halo effect of sorts. No such pattern was seen for any control or treatment day. As discussed from the results reported in the table above, it is generally seen that, except at one location, when the flashing amber lights were on, average speed was higher, although the differences were not statistically significant at most locations.

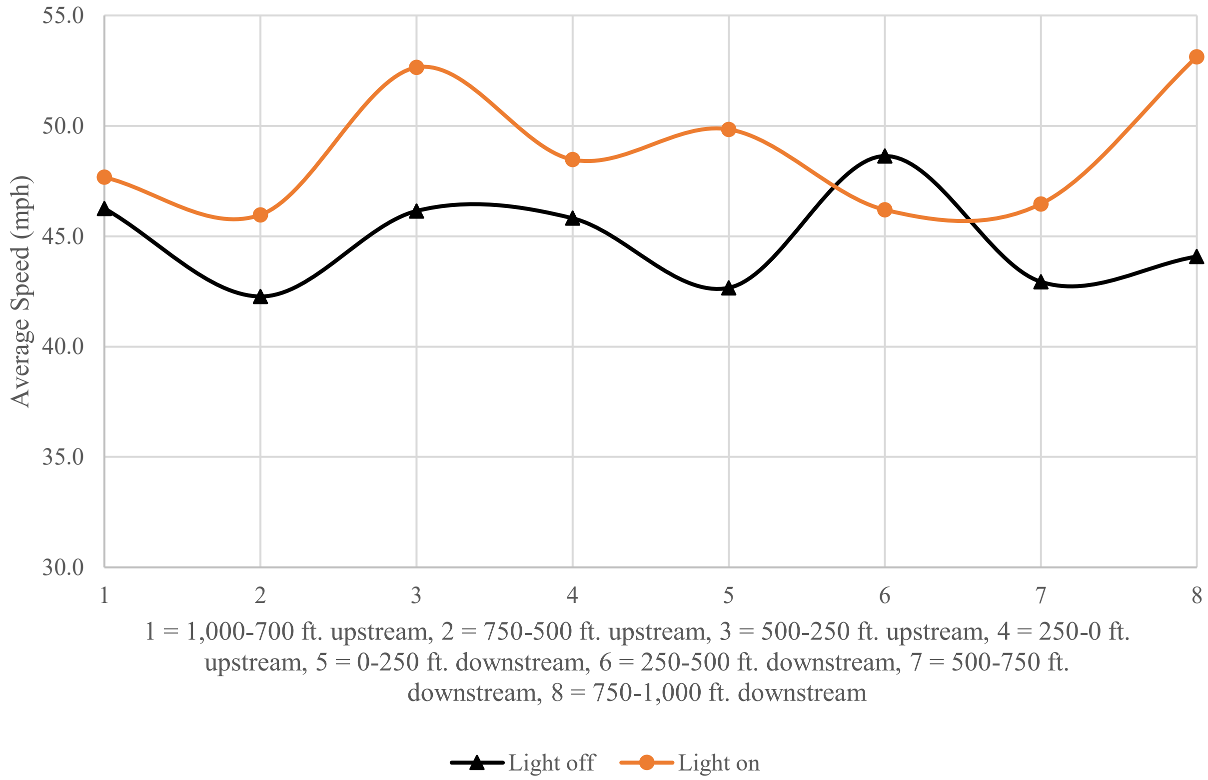

Figure 4.19: Free flow speed distribution across the work zone at 250 ft intervals (case study 1)

4.3.2.2 Speed Reduction Analysis

This test was performed to evaluate whether there is a statistically significant difference between the speed differentials observed for the control and treatment conditions, between the RWA sign and right at the paver (0-250 ft. upstream and 0-250 ft. downstream of the paver). In an ideal scenario, this test should be performed in pairs. However, due to limitations in the equipment used for the data collection, the speed of a specific vehicle could not be identified at both locations. To overcome this obstacle, data points of similar proximity to the paver were aggregated and a t-test was performed. This speed differential dataset was created by subtracting the speed of vehicles at 250-0 ft. upstream and 0-250 ft. downstream of the paver location from the speed of vehicles at the RWA sign. These results are presented in Table 4.2. It can be observed that the speed reduction on treatment days, when the amber lights were flashing, was higher than on days without the lights at a statistically significant level. Traveling from the road work ahead sign to the paver, the average speed reduced by 15.6 mph without the lights on and 19.7 mph with the flashing lights on. Therefore, a 4.1 mph higher speed reduction was credited to operation of the flashing amber lights.

Table 4.2: Speed Reduction Significance Test (Case Study 1)

Light Status	Mean Speed Differential (mph)	N	p-Value	t-Value	Degrees of Freedom	Standard Deviation (mph)
Off	15.6	623	0.000	-8.023	2445	11.2
On	19.7	1824				

4.3.3 Case Study 2: I-205 Abernethy Bridge – SE 82nd Drive, Oregon City

4.3.3.1 Two Sample t-Test for 250 ft. Interval

Similar to the analysis for Case Study 1, a comparison of speed between control and treatment was performed for Case Study 2. The results are tabulated in Table 4.3. In the upstream locations, when drivers were approaching the paver inside the active work area, none of the speed differences were found to be statistically significant. Right at the paver (0-250 ft. downstream), the difference in speed was 8.97 miles lower when amber-white lights were flashing. This trend continues downstream of the paver. The greatest amount of speed reduction, 10.14 mph, occurred after passing the paver and reaching the 250-500 ft. range downstream of the paver. All differences in speed in this range are statistically significant. Recall that Case Study 2 used a different lighting design and sequence than Case Studies 1 and 3.

Table 4.3: t-Test Summary at 250 ft. Intervals (Case Study 2)

Category	Statistics	Distance Upstream of Paver (ft.)				Distance Downstream of Paver (ft.)			
		1,000-750	**750-500**	**500-250**	**250-0**	**0-250**	**250-500**	**500-750**	**750-1,000**
Flashing amber-white lights off	Sample Size (N)	444	113	179	289	276	231	154	377
	Average (mph)	41.5	42.0	45.2	40.2	48.3	43.3	49.8	49.7
	Standard Deviation (mph)	15.3	14.2	12.2	15.9	12.4	13.3	12.1	13.0
	Minimum (mph)	5.8	5.0	17.5	3.1	8.7	7.5	21.1	13.2
	Maximum (mph)	104.8	69.0	93.8	91.9	104.8	93.0	79.4	122.5
	85th Percentile Speed (mph)	56.3	55.9	57.1	54.7	60.0	57.1	61.6	60.9
Flashing amber-white lights on	Sample Size (N)	494	201	212	219	105	158	232	412
	Average (mph)	40.6	43.0	42.6	42.5	39.3	33.2	47.4	42.5
	Standard Deviation (mph)	13.3	14.2	14.2	12.7	14.1	18.8	11.6	14.4
	Minimum (mph)	4.3	4.8	3.1	4.3	2.8	1.2	5.9	0.3
	Maximum (mph)	89.6	121.2	91.8	71.6	112.2	69.4	93.8	94.7
	85th Percentile Speed (mph)	53.3	54.0	55.0	55.9	49.4	52.7	57.4	55.0
Comparison	Average Off speed minus Average On speed (mph)	0.81	-0.98	2.60	-2.30	8.97	10.14	2.45	7.25
	t-Stat	0.866	-0.597	1.929	-1.759	6.061	6.233	1.997	7.401
	p-Value	0.387	0.551	0.054	0.079	0.000	0.000	0.047	0.000

The results presented in Table 4.3 are depicted in Figure 4.20. It can be observed that the lights on and lights off curves cross each other at various locations until location 4 (0-250 ft. upstream of the paver). After that location, the difference becomes larger and continues the trend of flashing amber-white lights having lower average speed. The common "halo effect" relative to the paving equipment is somewhat observed with the amber-white lights on plot.

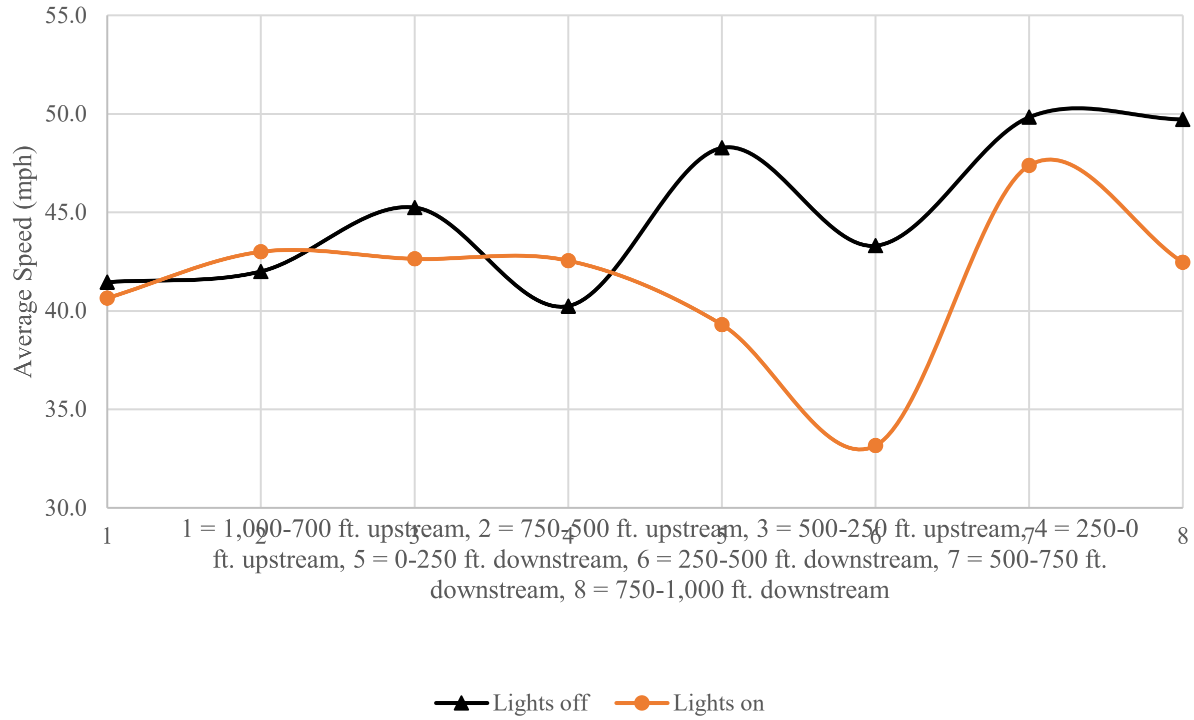

Figure 4.20: Free flow speed distribution across the work zone at 250 ft intervals (case study 2)

4.3.3.2 Speed Reduction Analysis

Similar to Case Study 1, speed reduction analysis was performed for Case Study 2 using a t-test. The analysis was performed using the speed differential between the mean speed at the RWA sign and the speed right at the paver, comparing the differentials with the amber-white lights turned on (treatment) and with the amber-white lights turned off (control). Table 4.4 summarizes the outcome of the test. Based on the p-value, it can be inferred that at a level of confidence of 95%, speed reduction on days with the lights turned on was higher than on days with the lights turned off. The speed reduction from the road work ahead sign to the location of the paver was 17.9 mph when the flashing lights on the paving equipment were kept off, and the reduction was 19.4 mph with the flashing lights turned on. Therefore, a 1.5 mph higher reduction was observed under the condition when the flashing amber-white lights were turned on.

Table 4.4: Speed Reduction Significance Test (Case Study 2)

Light Status	Mean Speed Differential (mph)	N	p-Value	t-Value	Degrees of Freedom	Standard Deviation (mph)
Off	17.9	1656	0.000	-4.497	3483	9.7
On	19.4	1829				

4.3.4 Case Study 3: I-5 Sutherlin – Garden Valley Blvd., Roseburg

4.3.4.1 Two Sample t-Test for 250 ft. Interval

In Case Study 3, at the first three distances approaching the paver, from 1,000-500 ft. upstream, the speed was lower when the flashing amber lights were on. This difference in mean speed is statistically significant. All differences at locations other than 250-0 ft. upstream and 750-1,000 ft. downstream were not statistically significant. Results of this analysis are presented in Table 4.5.

Table 4.5: t-Test Summary at 250 ft. Intervals (Case Study 3)

Category	Statistics	Distance Upstream of Paver (ft.)				Distance Downstream of Paver (ft.)			
		1,000-750	750-500	500-250	250-0	0-250	250-500	500-750	750-1,000
Flashing amber lights off	Sample Size (N)	399	134	274	103	139	243	197	210
	Average (mph)	50.64	41.26	43.33	41.70	45.87	48.18	46.33	50.63
	Standard Deviation (mph)	13.62	12.30	15.35	15.71	14.29	13.86	11.65	15.04
	Minimum (mph)	15.16	4.82	2.08	3.52	5.00	10.22	16.13	19.09
	Maximum (mph)	110.73	70.77	84.10	106.43	90.01	107.74	82.62	140.24
	85th Percentile Speed (mph)	61.13	53.96	57.53	53.75	59.30	57.23	56.51	61.77
Flashing amber lights on	Sample Size (N)	573	153	248	148	136	132	146	445
	Average (mph)	46.47	38.90	42.31	48.47	46.20	49.48	47.72	51.68
	Standard Deviation (mph)	13.52	11.63	15.64	13.32	10.36	14.82	14.59	14.62
	Minimum (mph)	1.87	10.31	4.31	5.79	26.26	11.28	10.22	7.50
	Maximum (mph)	109.42	62.91	93.79	97.40	90.40	121.04	108.12	127.70
	85th Percentile Speed (mph)	58.15	50.50	56.55	58.52	55.40	60.93	59.07	61.90
Comparison	Average Off speed minus Average On speed (mph)	4.17	2.35	1.02	-6.77	-0.32	-1.30	-1.38	-1.04
	t-Stat	4.719	1.669	0.752	-3.679	-0.217	-0.846	-0.980	-0.842
	p-Value	0.000	0.096	0.452	0.000	0.828	0.398	0.328	0.400

The results shown in Table 4.5 are depicted in Figure 4.21. It can be observed visually that the two plots progress within a narrow margin of each other. At location 4 (150-0 ft. upstream of the paver), a greater difference in mean speed is observed, and higher mean speed was observed for the days in which the flashing amber light was on. No halo effect was observed for either of the progressions.

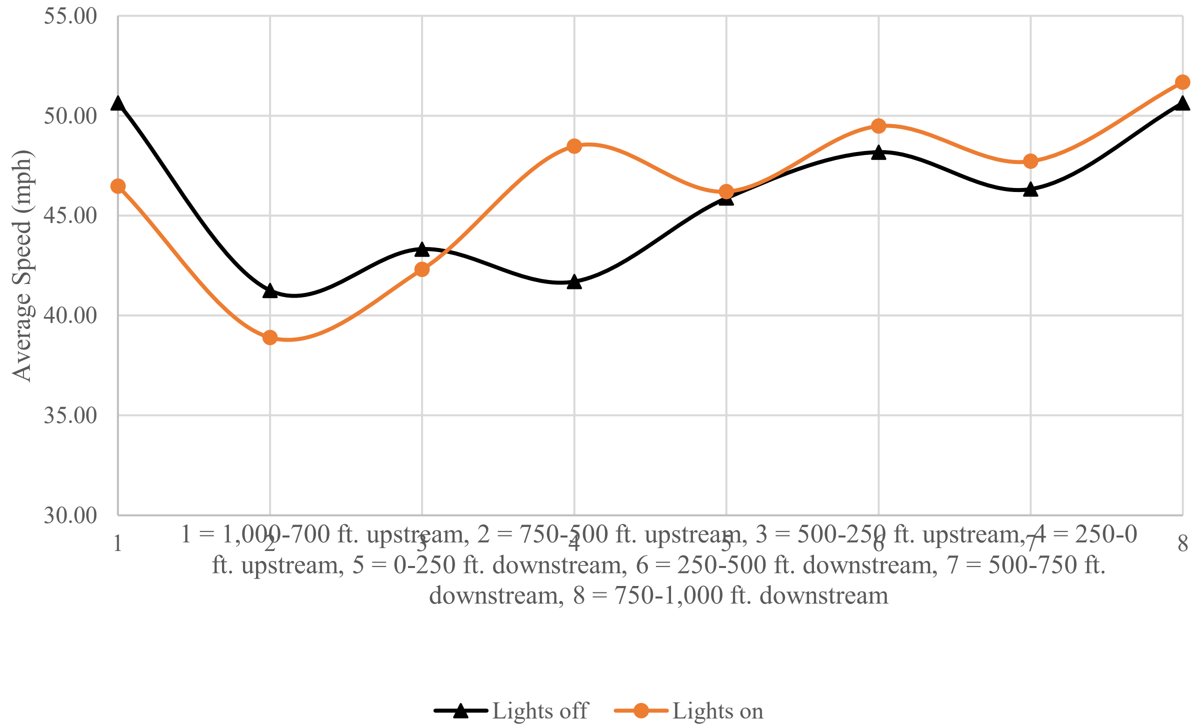

Figure 4.21: Free flow speed distribution across the work zone at 250 ft. intervals (case study 3)

4.3.4.2 Speed Reduction Analysis

For Case Study 3, there is a statistically significant difference observed in speed reduction. The results are presented in Table 4.6. When the flashing amber lights were kept off, a speed reduction of 20.7 mph occurred from the road work ahead sign to at the paver location. During the treatment days with the lights on, the reduction was 18.4 mph. Therefore, this case study revealed a 2.2 mph greater speed reduction during the flashing amber light turned off days. This result is contradictory to the assumption made regarding the treatment effect.

Table 4.6: Speed Reduction Significance Test (Case Study 3)

Light Status	Mean Speed Differential (mph)	N	p-Value	t-Value	Degrees of Freedom	Standard Deviation (mph)
Off	20.6	1504	0.000	5.922	2703	9.4
On	18.4	1201				

4.4 COMPARISON OF FLASHING BLUE LIGHTS AND FLASHING AMBER-WHITE LIGHTS

In Table 4.7, results from the previous study conducted by the research team of the effect of the flashing blue lights on paving equipment are shown and compared to the results of the present study. It can be observed that when the blue lights on the paving equipment are turned on, the reduction in speed differential was higher (7 to 7.9 mph), whereas the reduction in speed is 1.5 to 4.1 mph for the amber-white lights. In the active work area, more locations inside the work zone show lower speeds with the flashing blue lights than the amber-white lights.

Table 4.7: Comparison of Flashing Blue Lights and Flashing Amber-white Lights

Category		Flashing blue lights	Flashing amber or amber-white lights
Impact inside the work zone	Case study 1	3.6 to 15.95 mph slower with blue lights on at locations greater than 500 ft. upstream and greater than 250 ft. downstream	2.4 mph lower speed with amber lights on at 250-500 ft. downstream of the paver
	Case study 2	3.6 to 4.7 mph slower with blue lights on at the following locations: 500-750 ft and 0-250 ft upstream of the paver, and 0-250 ft and 500-750 ft downstream of the paver	2.5 to 10.1 mph lower speed with amber-white lights on at locations greater than 0-250 ft. downstream of the paver
	Case study 3	2.4 to 10.2 mph slower with blue lights on at the following locations: 250-750 ft upstream of the paver, and 0-750 ft downstream of the pave	4.7 mph lower speed with amber lights on at 1,000-750 ft. upstream location
Impact from road work ahead sign to at paver location	Case study 1	No difference	4.1 mph gain in speed differential
	Case study 2	7 mph gain in speed differential	1.5 mph gain in speed differential
	Case study 3	7.9 mph gain in speed differential	2.2 mph loss in speed differential

5.0 CONCLUSIONS AND RECCOMENDATIONS

The research study provided an opportunity to investigate the effectiveness of flashing amber and white lights mounted on construction equipment during mainline paving operations on high-speed roadways in Oregon. The study specifically assessed the impact that the lights have on the speed of vehicles passing through the work zones. The following conclusions and recommendations are drawn from the analyses of the data collected as well as the literature review, researchers' observations while on the case study sites, and conversations with those involved in the case study projects.

Conduct of the research study focused on three case studies, involving paving on two construction projects, one on Interstate 5 and the other on Interstate 205 in Oregon. The construction projects were selected due to their inclusion of paving work on a high-speed roadway, the timing of the work relative to the study timeline, and the presence of flashing amber and white lights on the paver used in the paving operations. Data collection efforts successfully recorded passing vehicle data (speed, length, location, and time) on three to four separate paving days for each case study, one or two days with the flashing amber or amber-white lights on and two days with the lights off. As described previously, each case study was analyzed independently.

It should be noted that vehicle speeds at different locations relative to the paver may also be impacted by other traffic and work zone features besides the flashing amber or amber-white lights. For example, the presence of other construction equipment and workers in the active work area, an active radar speed sign in the work zone, and asphalt trucks entering/exiting the work area have been identified in prior work zone research as impacts to vehicle speed, and all of these elements were present in the case studies in this research project. The dynamic nature of the mobile paving operation and the traffic conditions, along with unknowns related to driver behavior (e.g., distractions), characteristics (e.g., age), and conditions (e.g., fatigue) limit the ability to eliminate these confounding factors. These impacts cannot be controlled within the selected experimental design given the available study time and resources. Therefore, the speed reductions measured at a specific location in a work zone may differ from project-to-project, from day-to-day, and during different stages of the paving operation. In addition, two different types of lighting configurations (flashing amber lights and flashing amber-white lights) were used in the case studies. The results obtained provide an acceptable initial assessment of the impact of the two configurations on vehicle speed that can be used to guide and inform decisions about the use of flashing amber-white lights as well as future research to study microscopic driving behavior. However, the other configuration (flashing amber lights attached to static white light bar) did not show significant results to recommend use of amber lights for such configuration.

Analyses of the data reveal that vehicle speed was affected by the presence of flashing amber-white lights in Case Study 2, and was unaffected by the flashing amber lights in Case Studies 1 and 3. Experience collecting field data from these work zones validated that the visibility window of 1,000 ft. is sufficient even within curvilinear segments of the roadway. In Case

Studies 1 and 3, no meaningful speed reduction could be quantified from the presence of the flashing amber lights. In several instances, small increases in mean speed with the amber-white lights turn on were observed at a statistically significant level. The presence of amber or amber-white lights mounted to the paver causing drivers to accelerate is not logical. Therefore, even though two-sample t-tests in Case Studies 1 and 3 demonstrated such results, the numerical difference does not carry any significance to the operation of the flashing amber lights. The result is likely to be the same if data from two "no amber or amber-white lights" nights are compared. The expectation was that the flashing effect of the amber light in conjunction with the white light bar would attract higher visual attention to reduce speed. Such a conclusion could not be made from the analysis of the results.

For the amber-white light combination shown in Figure 3.3 and 3.4, immediately adjacent to and downstream of the paver, there was a statistically significant reduction in speed when the lights were turned on. The amount of reduction in mean speed varied from 2.5 to 10.1 mph right at the paver (250-0 ft. to 0-250 ft.). At a statistical confidence level of 95%, these differences were all found to be significant. The research team concludes from this finding that the flashing amber-white lights contributed to sustained speed reduction throughout the work zone activity area.

A two-sample t-test was used to compare the effect of flashing amber or amber-white lights inside the active work zone (between lane drop and lane reopening). Using the data collected at the road work ahead sign, a second analysis was performed on the speed differential between control and treatment days. Speed differential was defined as the difference between the mean speed at the RWA sign and the mean speed at the paver location. The mean speed differential with the flashing amber or amber-white lights on was then compared to the mean speed differential with the lights off. The results are summarized below:

- Case Study 1: The speed differential was found to be statistically significant (flashing amber lights off differential = 15.6 mph, and lights on differential = 19.7 mph). 4.1 mph speed reduction was gained during the use of the flashing amber lights on the paver.

- Case Study 2: The speed differential was found to be statistically significant (amber-white lights off differential = 17.9 mph, and flashing amber-white lights on differential = 19.4 mph). 1.5 mph speed reduction was gained during the use of the flashing amber-white lights on the paver.

- Case Study 3: The speed differential was found to be statistically significant (flashing amber lights off differential = 20.6 mph, and amber-white lights on differential = 18.4 mph). 2.2 mph speed differential was lost during the presence of the flashing amber lights. The hypothesis that the presence of additional flashing amber lights can cause drivers to speed up is unsubstantiated. Therefore, this correlation was not counted as meaningful.

As mentioned above, generalization of the results to all projects with a high level of confidence is limited given the low number of case study projects and the presence of confounding variables. While some differences in mean speeds may have been found to be statistically significant for Case Study 2, average speed reduction from 2.5 to 10.1 mph inside the work zone and 4.1 mph higher speed reduction when the flashing amber-white lights were turned on, the practical difference may be minimal. This magnitude may not be discernable on the jobsite, and may not result in any difference in the frequency and/or severity of crashes. It is recommended that, if a flashing amber-white light configuration is to be implemented, the flashing colors are amber-white and the lights are mounted high enough so as not to flash directly in the eyes of the workers on and around the paver.

Lastly, as shown above and similar to prior work zone research studies involving other traffic control measures, the difference in mean speed is not constant throughout the entire length of the work zone. The difference in mean speed is typically greatest at/near the traffic control measure and then diminishes at distances farther from the traffic control measure.

The conclusions gained from the present study provide additional information about the impacts of flashing amber or amber-white lights on vehicle speeds. However, given the limitations of the study and confounding variables, further research is recommended to capture the impacts of the flashing amber or amber-white lights with greater confidence. This research team conducted previous research on flashing blue lights (Gambatese et al., 2019). Even though the comparison identifies many different confounding factors, a rough estimate was produced for qualitative comparison of two light installations. The flashing blue light installation was similar in nature to the flashing amber or amber-white lights used in Case Studies 1 and 3 of the present research. While the use of blue lights revealed a statistically significant difference in observed speeds between treatment and control, no such conclusion was made for Case Studies 1 and 3 of the present research. More consistent reduction in speed was observed in the blue lights study. The potential cause of the consistent reduction can be attributed to the association of blue lights with a police vehicle which drivers responded to by reducing their speed. The speed differential between the RWA sign and the paver was higher when flashing blue lights were used as well.

The following are recommended topics for additional research on the topic:

- Evaluation of driver behavior in response to the flashing blue and flashing amber or amber-white lights, such as the extent to which drivers are distracted by the lights, their glance patterns and durations, and their response to repeated exposure to the lights on equipment.

- Evaluation of vehicle speeds and driver behavior when flashing blue lights and flashing amber or amber-white lights are located on multiple pieces of equipment in the work zone (e.g., on the finish roller, paver, tack truck, and grinder).

- Evaluation of vehicle speeds and driver behavior when flashing blue lights and flashing amber or amber-white lights are located on permanent and/or temporary infrastructure in the work zone (e.g., roadway signs, radar speed signs, PCMS trailers, and barrels).

- Evaluation of vehicle speeds for the configuration used in Case Study 2 of the flashing amber or amber-white light using flashing blue-white lights.

- Evaluation of different combinations of lights with different colors (e.g., blue, white, and amber) to identify optimal combinations.

- Assessment of the impact of flashing blue lights and flashing amber or amber-white lights in other roadway and work settings, such as during stationary operations and in combination with blue lights flashing on law enforcement vehicles present in the work zone.

Future research studies on the topic would benefit from a mixed methods approach consisting of case studies on actual construction projects along with assessment of drivers in a simulated environment. A driving simulator enables the evaluation of driver behavior in response to the presence of flashing amber or amber-white lights in a laboratory setting where variables can be controlled and alternative designs can be safely tested.

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APPENDIX A

CASE STUDY DATA

Raw data collected from the case studies, along with corresponding figures and tables that are not included in this report, are available in electronic format. Please contact the researchers to obtain the data and figures/tables.