USE OF BLUE LIGHTS ON PAVING EQUIPMENT IN WORK ZONES

Final Report

ODOT ORDER NO. 19-03

Oregon Department of Transportation

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by

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16. Abstract: Vehicle speed in work zones is a significant concern to ODOT and construction partners. Prior national research shows that law enforcement vehicles located within a work zone with active flashing blue lights result in reduced vehicle speeds. Placement of flashing blue lights on construction equipment has been identified as a potential control measure to further reduce speeds. The goal of this research study is to conduct an initial evaluation of the impact of flashing blue lights located on construction equipment on the speed of passing vehicles in work zones. The research design consisted of a controlled experiment involving flashing blue lights mounted on the rear of the paver during mainline paving operations on three case study projects on high speed roadways in Oregon. Vehicle speed data was collected during multiple work shifts on each case study, both with and without the flashing blue lights on. The experimental results reveal that vehicle speed is affected by the presence of flashing blue lights. Speed differentials between the road work ahead sign and the first exposure to the paver resulted in greater speed reductions in all three case studies when the flashing blue lights were on. Additionally, within the active work area at distances upstream of the paver where the driver can see and react to the blue lights, mean vehicle speeds tended to be lower when the blue lights were on. Closer to, immediately adjacent, and downstream of the paver, the amount of reduction in mean speed was typically less or none at all with the blue lights on; in some cases the mean speeds were higher with the blue lights on. 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.

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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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This research study was funded by the Oregon Department of Transportation (ODOT). The authors thank ODOT for its support and input provided to conduct the research. The authors would also like to thank all the ODOT Research and field personnel, and the contractor employees from Oregon Mainline Paving, who participated in the case studies. Without their input and assistance, the valuable information received from the research would not be available. Further appreciation is expressed to the many additional OSU graduate students who assisted with data collection, reduction, and analysis for the study including: Bahar Abiri, Mohammed Azeez, Zachary Barlow, Lukas Bauer, Ali Jafarnejad, Ali Karakhan, and Khandakar Rashid.

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 Blue 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 blue lights mounted to pavement equipment during mainline paving operations in work zones, and provides recommendations to ODOT and other transportation agencies for further research on the topic.

1.1 BACKGROUND

Road construction and maintenance equipment is commonly used within the highway right-of-way and is equipped with a variety of work lights to illuminate the activity area for the workers and warning lights to alert drivers and pedestrians of a potential hazard. The color and arrangement of the warning lights are often dictated by legislation. In Oregon, ORS 816.350 allows for the use of "public vehicle warning lights" for such equipment, and Section 4 of the statute states:

> "Vehicles operated by a police officer and used for law enforcement may be equipped with any type of police lights, but *only these vehicles may be equipped with blue lights*" (italics added).

However, ORS 816.370 states that road machinery is exempt from the lighting equipment prohibitions in ORS 816.350. This exemption leads to a question of the appropriateness of using blue lights on road construction and maintenance equipment.

The research conducted is expected to increase ODOT's understanding of the effects of using flashing blue lights on the paver during mainline paving operations in work zones during night-time operations. 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 blue lights on a paver impact vehicle speed, and determining whether it is beneficial to use blue lights with maintenance equipment/vehicles on future roadway projects.

Several previous studies have examined the effects of work zone light colors as treatments in other states. These prior (and current) treatments are new to the State of Oregon, and 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 blue 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 blue lights on paving equipment in work zones. Specifically, this study aimed to measure the change in vehicle speed, if any, when flashing blue lights are used on a paver compared to when blue 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. Given the present use of blue lights on paving equipment during the summer 2018 construction season, and the desire to obtain guidance on the research question expeditiously, the study was planned to be an initial evaluation of blue lights on three case study projects. The research aims to confirm whether an initial investigation of blue lights on construction equipment may lead to lower vehicle speeds in work zones, and recommend to ODOT whether the use of blue lights is a potentially viable long-term safety treatment that 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 blue lights are both present and not present on paving equipment;

2. Analyze the field data collected to determine the impact that the blue 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 Section 3 of the report.

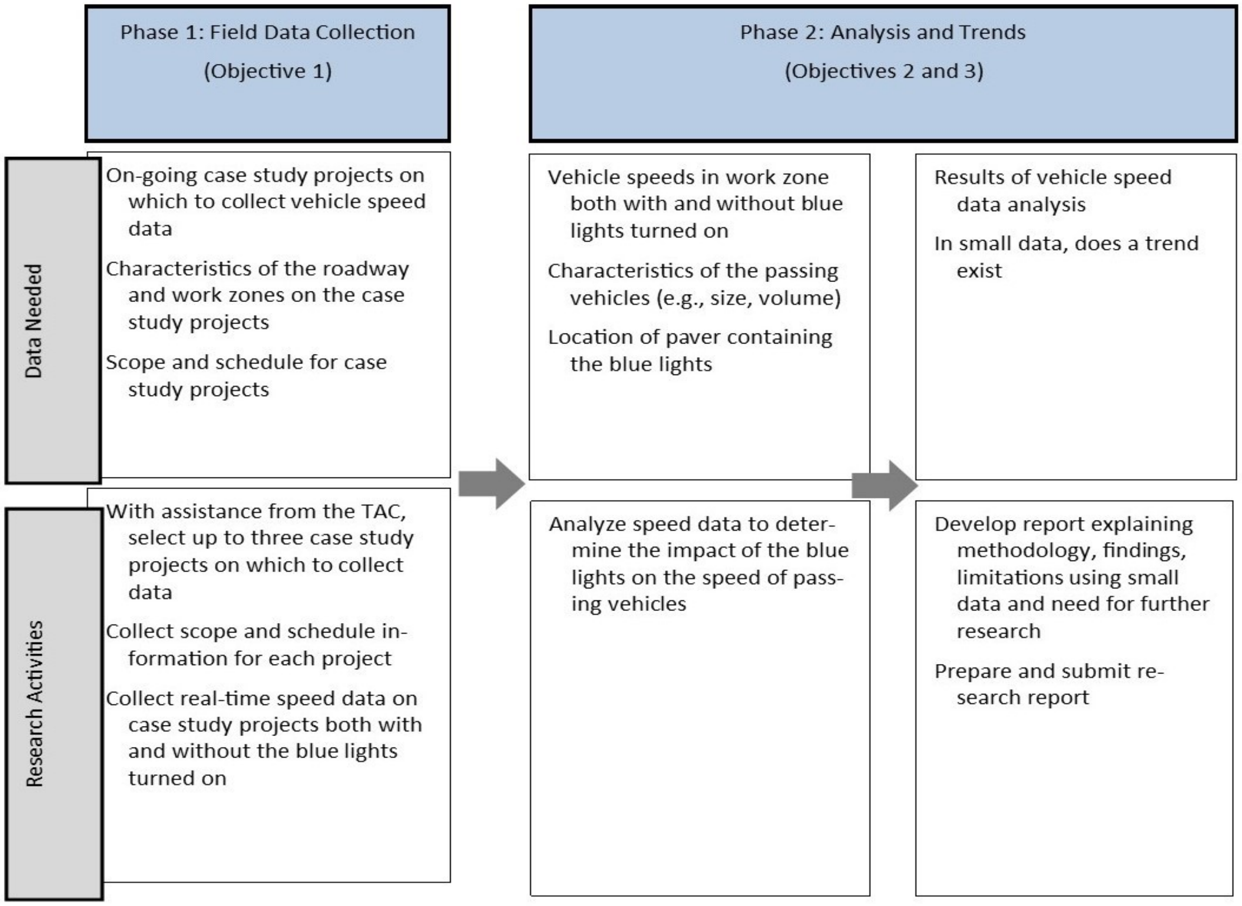

Figure 1.1: Research plan for data and research activities

1.3 BENEFITS

Fulfilling the stated objectives provides ODOT with new information about the impact and viability of using flashing blue lights on construction equipment in work zones. The output provides quantitative evidence of how speed varies when blue lights, located on a paver, are active and inactive. Such information can help determine whether to further pursue the use of flashing blue 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 through encouraging lower vehicle speed in workzones, particularly in areas close to workers, 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 interim use of flashing blue lights on construction equipment in work zones on high speed roadways. The study 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 blue lights. The report also identifies fuure work that may be needed to develop a better understanding of the opperational effects, human factors, and short term efficacy of this treatment.

It is expected that the research outputs be used by the ODOT Transportation Safety Division and the Region Transportation Safety Coordinators in each Region 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 2018 construction season (July – September 2018). 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 (through traffic control) to collect vehicle speed data.

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

Section 3 provides a detailed description of the experimental design of the study, including the tasks undertaken for the data collection, reduction, and analysis.

2.0 LITERATURE REVIEW

Roadway construction and maintenance work in the right-of-way is necessary to expand and maintain the roadway system and to ensure safe and efficient operations over time. To perform the work, the right-of-way is typically restricted to construction and maintenance activities, most commonly by closing individual lanes or segments of entire roadways for the duration of the work. Safety and traffic operation issues remain a point of concern in work zones due to atypical and unexpected conditions and rerouting of the passing traffic.

Over the years, researchers and DOT personnel have realized that only a tapered lane closure with cones and barrels to enable work to be performed on the roadway is not sufficient on its own to maintain safety and mobility through the work zone. Further traffic control measures are necessary to maintain drivers' attention, manage vehicle speeds, and protect workers on the roadway (TEEX, 2011). Many such examples include, but are not limited to, the introduction of radar speed signs, variable message signs, speed humps, mobile automated speed enforcement, work zone amber lights, presence of law enforcement vehicles, etc. Recently, the use of flashing warning lights installed on heavy machinery, e.g., rollers, in a work zone has gained popularity. Most states, including Oregon, have a provision regarding the installation of special lights in their bylaws (ORS 816.370) (Wilt, 2018). This chapter briefly discusses attempts to install such lights across the country and draws attention to the reported outcomes.

A survey conducted by the Texas Transportation Institute (TTI) in 1998 reported that 50 states were using amber warning lights on construction vehicles in highway work zones. Twelve states used additional blue, red, or white hazard warning lights. Even though TxDOT allowed blue lights in conjunction with amber lights in work zone at the time of the survey, more recent policy documents suggest limited use of this combination (Ullman & Lewis, 1998).

A study funded through the Florida DOT (Gan, Wu, Orabi, & Alluri, 2018) in early 2018 evaluated the effect of a stationary police car present in a work zone. The study was extended by using wildlife conservation commission vehicles with flashing blue lights. Based on the data collected, the researchers report that the presence of the police vehicle reduced average speed more than the wildlife conservation service vehicle. For example, for the case study situated on I-4, work zone speed was reported to be reduced by 4.4 mph. In both cases, average speed was reduced through a stationary work zone.

According to the National Cooperative Highway Research Program (NCHRP) Report 624 (Gibbons & Lee, 2008), researchers determined that between amber, blue, red, and white lights, the combination of amber and white lights had the greatest impact on speed compliance. As a result, the researchers recommend this combination of light colors if additional lights are needed on construction and maintenance vehicles operating in a work zone. This study also reported that if only one type of light is used, four-way flashers have the highest impact for providing accurate information to drivers. Addition of the same light multiple times or changing the light location did not have reportable influence on the outcome; drivers seemed to extract the same amount of information.

When measuring speed compliance, a psychological study on emergency lighting previously reported that in the daytime, red light has the most significant effect, while during the nighttime blue lights are more effective (Howell, Pigman, & Agent, 2019). Amber light falls somewhere in between red and blue light in terms of effectiveness (Howell et al., 2019). Another study reported that, blue lights are easily detectable during nighttime (Anderson & Plecas, 2010) and that rates of braking are higher for flashing blue lights.

In 2010, psychologists from Fraser Valley University in Canada reported that habituation or prolonged exposure to certain types of warning lights impacts rate of compliance (Anderson & Plecas, 2010). As a result, the researchers conclude that perennial exposure to amber lights mounted on the construction work fleet may prove to have reduced effect on speed reduction over a prolonged period of time. It is assumed that a similar reduction in the intervention's impact would be present for flashing blue lights as well.

The Iowa DOT has recently gained approval from the state legislature to implement flashing blue and white lights on their snowplows for a 3-year trial period. The goal of the trial is the evaluate the impact of the additional lights on reducing high impact rear-end crashes associated with snowplow operation (Curtis, 2018). This decision was based on research finding that attaching such hazard warning lights could successfully modify driving behavior to avoid aforementioned collision type. The blue and white lights are mounted on the top of the snowplows, shine only to the rear of the snowplow, and are turned on along with the rotating amber lights on the snowplows. The implementation of the blue and white lights was coordinated with a wide-ranging public information campaign to inform people of the blue and white lights on snowplows. To date, the preliminary data reveals a significant reduction in vehicles impacting snowplows when the blue and white lights are flashing.

The review of prior research reveals that the presence of flashing lights, including flashing blue lights, has an impact on speeds and crashes in work zones. With respect specifically to flashing blue lights, previous studies have been conducted when the lights are located on law enforcement vehicles and snowplows. Prior research has not investigated the impacts of blue lights mounted on construction equipment in mobile work zones. The impacts of blue lights on equipment in mobile work zones are expected to be different than those observed in prior research studies. Anecdotal input received regarding the current use of blue lights on pavers over the past couple construction seasons in Oregon suggests that the lights help to reduce vehicle speeds. Further research is needed to confirm these initial observations and provide quantitative evidence of the impacts that flashing blue lights located on construction equipment have on vehicle speeds and driving behavior. Such additional evidence is intended to support ODOT's decisions regarding the use of blue lights mounted on construction and maintenance equipment in work zones.

3.0 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.

3.1 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 – Hassalo, Grants Pass I, and Grants Pass II – were selected to be case studies for the research. These projects were selected because they took place on high speed roadways, involved mainline paving operations, were conducted by contractors operating blue lights on the paver, had enough days of mainline paving remaining on the project schedule to observe at least two days with the blue lights on and two days with the blue lights off, and the contractor was willing to participate in the study. The researchers contacted the ODOT and contractor personnel on each case study project to confirm its inclusion in the study. Once confirmed, the researchers began planning for and conducting the data collection in coordination with the project personnel.

For each case study project, the paving work was performed at night, starting from approximately 7:00pm and ending at typically 6:00am the next morning depending on the specific 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 blue 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 each case, efforts were made to turn the lights on every other day. However, other factors were also taken into consideration when determining whether to turn the blue lights on for a specific day, such as the lane being paved that day, segment of roadway being paved, and planned length of paving, which may have altered the initial lighting schedule. When on, the blue 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.

Standard patrolling of the roadway by Oregon State Police (OSP) was not restricted. However, OSP was instructed by the contractor to not park in the work zone on the data collection days. On some data collection days on each case study, OSP vehicles were observed travelling through the work zone without their blue lights on. On Case Study 1, OSP and emergency vehicles were observed passing through the work zone with their flashing lights on to attend to an emergency situation. The speeds of the OSP vehicles were not filtered out from the data since the exact time when the vehicles passed over the sensors is not known and their speed is indistinguishable from surrounding vehicles in some cases.

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

3.1.1 Case Study 1: Hassalo, Portland

The first case study (Case Study 1), named the Hassalo project, and was located on I-5 passing through Portland, Oregon. Land use around this section of the corridor is urban in nature. Data collection included four days of northbound active work zone in two segments (August 1-2 and August 8-9, 2018). The blue lights were turned on as a treatment for one day in each segment. Construction and maintenance operations took place in the northbound C (slow) lane. To perform the work, both the B (middle) and C lanes were closed during the paving operation while the A (fast) lane remained open to through traffic. The off and on ramps were closed in the active work area where paving took place; other ramps outside the active work area remained open if they did not interfere with traffic control. Data collection spanned from exit 302 to 306 during the four days. The posted speed limit is generally 55 mph on this segment of I-5. Table 3.1 summarizes details of Case Study 1, and Figure 3.1 displays the location of the study.

Table 3.1: Description of Case Study 1 (Hassalo, Portland)

Details					**Blue Lights**		**Data Collection Range**	
Data Collection Day	Day/Date	Time Frame	Paving Lane	Travel Direction	On	Off	Start Point	End Point
1	Wed., 8/1/2018	23:00 to 04:00	C (slow) Lane	Northbound	X		Adjacent exit 302A	Killings-worth St. Overpass
2	Thurs., 8/2/2018	23:00 to 04:00	C (slow) Lane	Northbound		X	Exit 302B	Exit 305B
3	Wed., 8/8/2018	23:00 to 04:00	C (slow) Lane	Northbound		X	1,000 ft. north of I-5 and I-405 Junction near Mississippi Avenue	Near Exit 306A
4	Thurs., 8/9/2018	23:00 to 04:00	C (slow) Lane	Northbound	X		Exit 302B	Rosa Parks Overpass

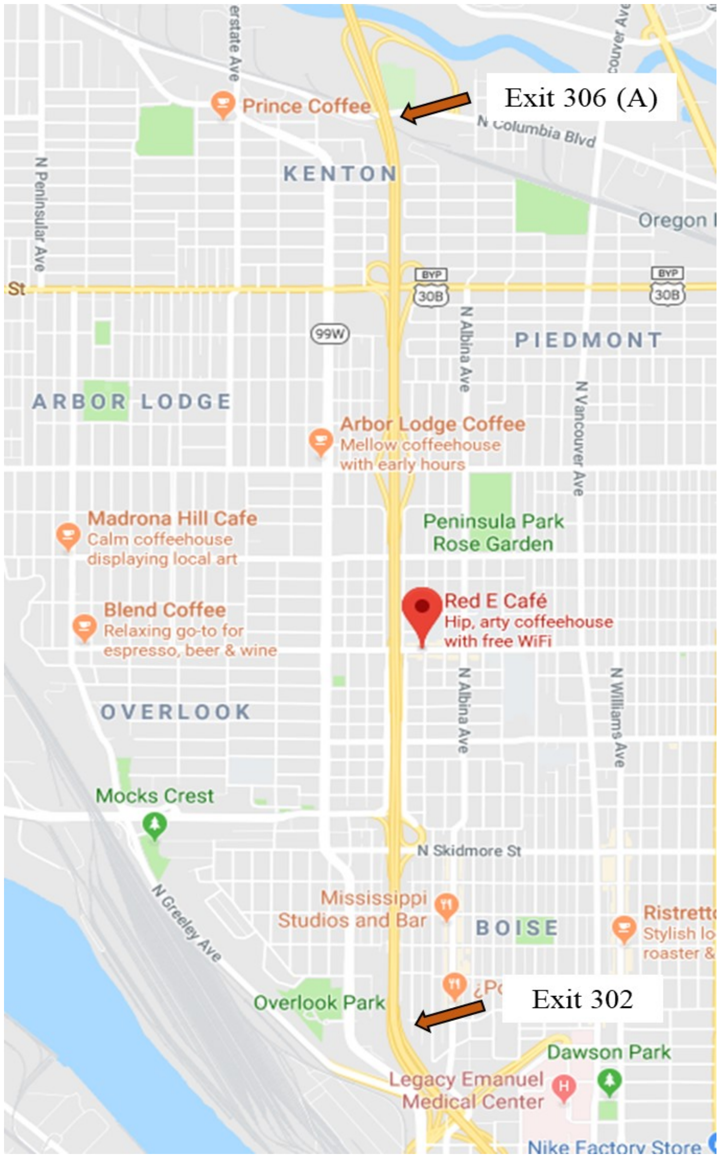

Figure 3.1: Location of case study 1 (Source: Google maps)

3.1.2 Case Study 2: Grants Pass I

The paving project in Case Study 2 (Grants Pass I) included repaving in the A (fast) lane in both directions of I-5 between Grants Pass and Evans Creek. Data collection for the case study took place from August 12-15, 2018, and extended from Grants Pass to Evans Creek, primarily in the northbound direction. The first day of data collection was with the flashing blue lights off during paving of the A (fast) lane in the southbound direction. Data collection occurred over six hours (from 22:00 to 04:00). Data collection on Days 2, 3, and 4 covered northbound paving operations extending from exit 48 to 55. Although I-5 is a north-south facility, this particular segment of the roadway is oriented in the east-west direction. Based on the location of this particular segment of Interstate 5, geometric properties like lane width, number of lanes, shoulder width, posted speed limit, etc. and land-use were similar in both directions. In addition, the work zone set-up and construction work process were the same in each direction and performed by the same crews. A gradual speed reduction was also kept homogenous for all days. Based on these conditions, northbound and southbound direction driving behavior were expected to be similar and not impacted by travel direction. The posted speed limit of this section was 65 mph, with a temporary reduction to 50 mph during construction. This segment of I-5 would be considered a multi-lane freeway. Table 3.2 summarizes details of Case Study 2, and Figure 3.2 displays the location of the study.

Table 3.2: Description of Case Study 2 (Grants Pass I)

Details					**Blue Lights**		**Data Collection Range**	
Data Collection Day	Day/Date	Time Frame	Paving Lane	Travel Direction	On	Off	Start Point	End Point
1	Sunday, 8/12/2018	22:00 to 04:00	A (fast) Lane	Southbound		X	1,000 ft. north of Foothill Rd. Underpass	Exit 48
2	Monday, 8/13/2018	22:00 to 04:00	A (fast) Lane	Northbound	X		Station 510+00	Station 440+00
3	Tuesday, 8/14/2018	22:00 to 04:00	A (fast) Lane	Northbound		X	Exit 48	Exit 52
4	Wednesday, 8/15/2018	22:00 to 04:00	A (fast) Lane	Northbound	X		Station 436+00	Station 240+00

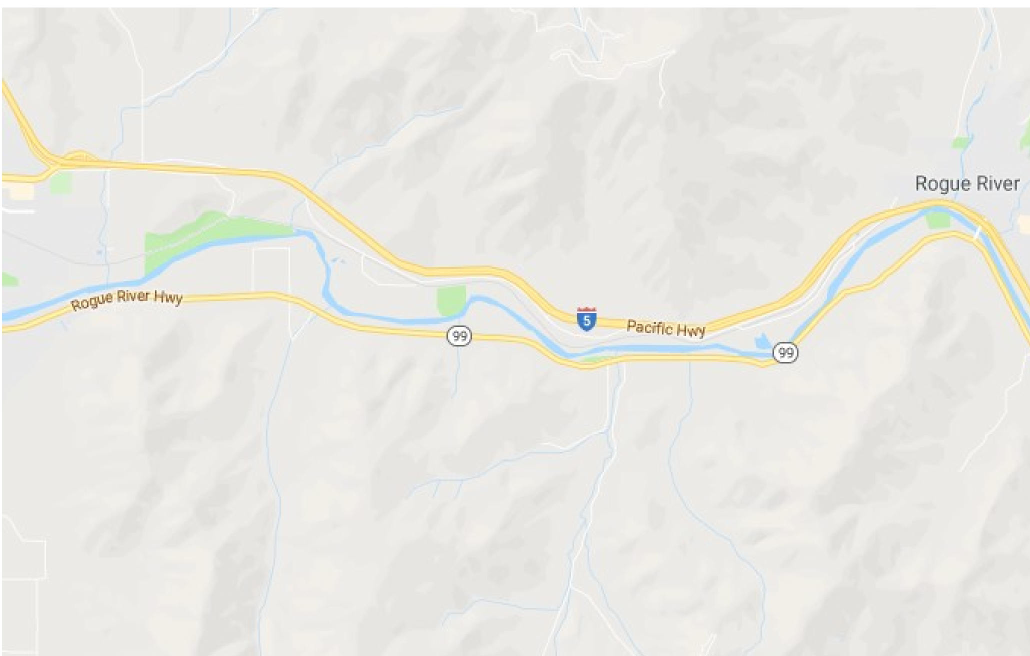

Figure 3.2: Location of case study 2 (Source: Google maps)

3.1.3 Case Study 3: Grants Pass II

The third case study project (Grants Pass II) took place on a similar portion of highway as the second case study (Grants Pass I). The difference between the case studies is the paving lane (A lane vs. B lane), as well as the dates of data collection and data collection ranges. On the first day of data collection, with the blue lights off, paving operations took place in the B (slow) lane in the southbound direction extending from exit 53 to 48. On the other three days of data collection, paving operations took place in the northbound B (slow) lane with the blue lights on and off on alternate days. This segment of road had a posted speed limit of 65 mph (temporarily reduced to 50 mph during construction) and was relatively rural in character. Table 3.3 provides detailed information about this case study. The location of the case study is the same as that of Case Study 2, displayed in Figure 3.2.

Table 3.3: Description of Case Study 3 (Grants Pass II)

Details					**Blue Lights**		**Data Collection Range**	
Data Collection Day	Day/Date	Time Frame	Paving Lane	Travel Direction	On	Off	Start Point	End Point
1	Monday, 8/27/2018	22:00 to 04:00	B (slow) Lane	Southbound		X	Exit 53	Exit 48
2	Tuesday, 8/28/2018	22:00 to 04:00	B (slow) Lane	Northbound	X		Exit 47	1,000 ft. south of Foothill Rd. Underpass
3	Wednesday, 8/29/2018	22:00 to 04:00	B (slow) Lane	Northbound		X	1,000 ft. south of Foothill Rd. Underpass	Exit 55
4	Thursday, 8/30/2018	22:00 to 04:00	B (slow) Lane	Northbound	X		Station 268+00	Station 64+00

3.2 EQUIPMENT

Data acquisition required a variety of equipment. Two kinds of sensors were used: portable (in roadway) traffic analyzers 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.

An attempt was made to use a portable intelligent transportation system (ITS) trailer, provided by ODOT, in the work zone to supplement the data gathered from the in-lane sensors. The trailer captured video of the roadway, along with vehicle count and speed data, and sent the data to ODOT for storage and processing. A sample of the data was then sent to OSU for possible inclusion in the analysis. Upon review of the data, the format of the data and the location of the trailer relative to the other sensors and paving operation limited the value of the ITS data for use in the present study. Therefore, the data was not used in the analysis. However, use of the ITS trailer has merits, especially for longer-term applications and where placement of in-lane sensors is not possible or unsafe, and the ITS trailer should be considered for future studies.

3.2.1 Traffic Sensors

3.2.1.1 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. Highway Information System. Two sensor models were placed on the road surface: NC-200 and NC-350 (Figure 3.3 and Figure 3.4). In terms of precision and accuracy, there are no differences between sensor models. However, the NC-350s have Bluetooth connectivity (not used for this study) 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. First figure shows an example of the type of cover used along with the sensor. In Figure 3.4, provided by MH Corbin, a cross-sectional view of the NC-350 set up can be observed.

Figure 3.3: Components of traffic sensor

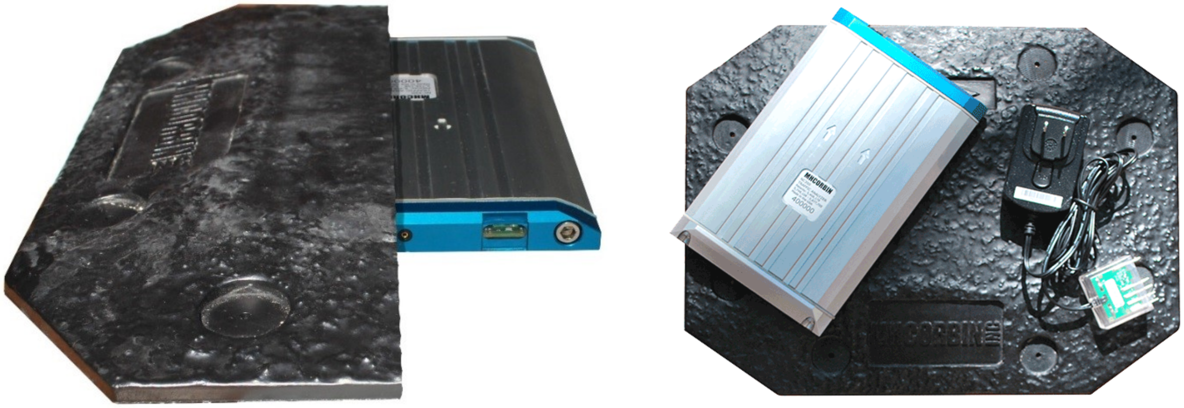

Figure 3.4: NC-350 portable traffic analyzer (M.H. Corbin 2017)

3.2.1.2 Sensor Calibration

A calibration procedure was implemented to confirm the accuracy of the recorded vehicle volume, speed, and classification values from 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 20, 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 this regression, control speed was considered an independent variable and the observed speed recorded by the sensor was considered a dependent variable. This analysis led to an equation relating the recorded speed to the actual speed. However, while using this equation to calibrate the case study project data, the equation was solved to determine the x value as y is the observed speed value recorded by the sensor. Figure 3.5 demonstrates an example calibration for sensor 101, and Table 3.4 lists all of the sensors and their calibration equations. Note that in the equations shown in Table 3.4, the variable x represents the speed recorded by the sensor and the dependent variable y represents the actual speed of the passing vehicle.

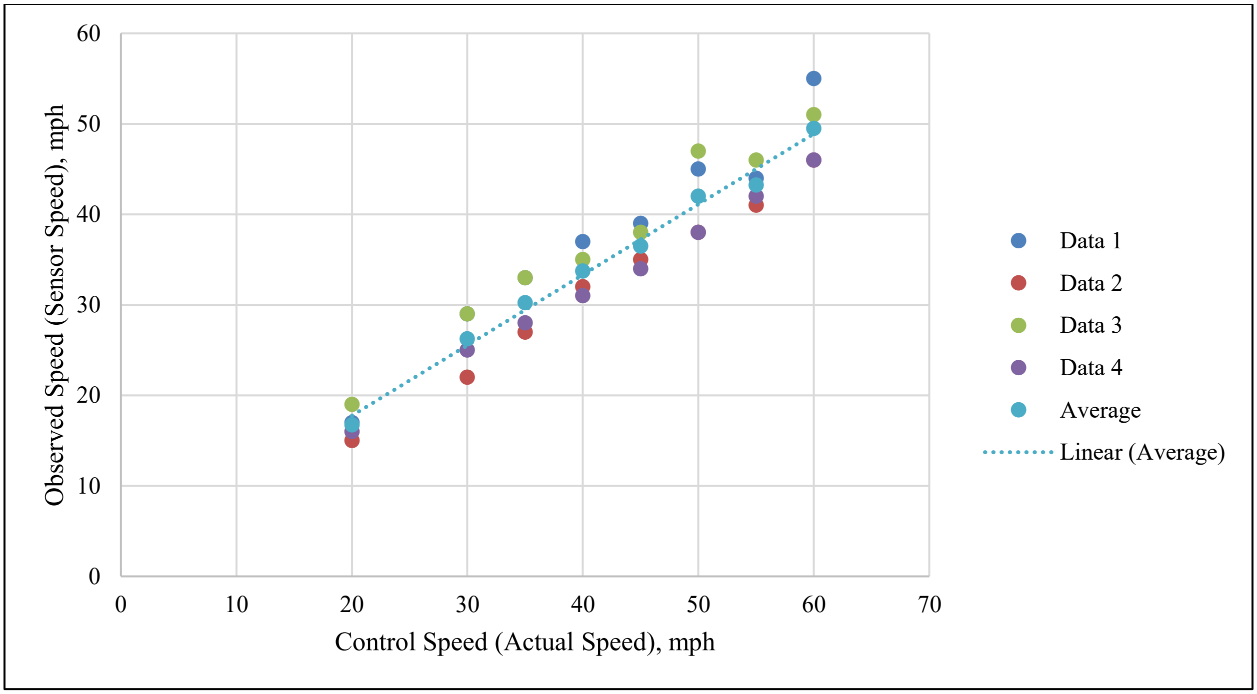

Figure 3.5: Linear regression of calibration data for traffic sensor 101

Table 3.4: Calibration Equations for Sensors

Sensor ID	Adjustment Equation**
101	y=0.7786x+2.1786
102	y=1.4604x-11.467
103	y=0.7183x+3.0464
104	n/a*
105	y=0.6523x+2.486
106	y=0.8313x+.0006
107	y=1.4241x-11.508
108	y=0.7387+2.6598
216	y=0.9337x-1.1303
379	y=0.7613x+2.5902
687	n/a*
748	y=0.9274x-1.4305
774	y=0.852x-0.834
816	y=0.7971x+0.7769
305	y=0.9811x-2.0514
317	y=1.2979x-8.067
318	y=1.03732x-3.5645
325	y=1.1856x-6.1153

* n/a = Inactive sensor
** x = speed recorded by the sensor; y = actual speed of the vehicle

3.2.1.3 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.

3.2.2 GPS Tracker and Handheld GPS

During each data collection period, two iTrail GPS trackers Figure 3.6 were placed on the light bar of the paver to record the trajectory of the paver during the nighttime paving operation. 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 Tackers were placed on the paver before each data collection period while it was parked in the yard, and then removed after the data collection period to download the data for analysis. Figure 3.6 also shows a hand-held GPS device used in the data collection process. This device 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. However, a 5 to 10 ft. deviation in accuracy was reported in several records. The researchers corrected the location using Google maps after sensor placement on each day.

Figure 3.6: Handheld GPS device (left), and GPS tracker and casing for GPS tracker (right)

Figure 3.7 shows the GPS sensor placement on the paver. The 1.5”x1.5” devices were protected using a casing with magnetic attachment that attached to the metal light bar on the paver. Attachment to the light bar ensured that the sensors would not interfere with or get damaged from the paver operations, and that there would be a continuous clear signal to the tracking satellites. 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 3.7: GPS sensor installation (left), and location on the paver light bar (right)

4.0 METHODOLOGY

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

4.1 DATA ACQUISITION

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

4.1.1 Flashing Blue Lights

As previously described, traffic sensors were placed on the road surface and GPS trackers were placed on the paver. The control treatment was the flashing blue lights on the paver turned off and the alternate treatment was the flashing blue lights turned on (see Figure 4.1). The blue lights were flashing; the left photo in Figure 4.1 shows the blue lights when they were off, and the right photo shows the blue lights on. Both of the individual blue lights on the paver flash simultaneously, i.e., both on at the same time and both off at the same time. A close-up view of one of the blue lights installed on the light bar of the paving equipment is displayed in Figure 4.2.

Figure 4.1: Paver with flashing blue lights off (left) and blue lights on (right)

Figure 4.2: Blue light installed on paving equipment

4.1.2 Traffic Sensor Placement

4.1.2.1 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 at least one lane closure, except for the Hassalo project (Case Study 1) which involved a double lane closure (B and C lanes closed). 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 4.3 shows a simplistic representation of the sensor placement plan in a generic work zone configuration. Two sensors were placed in each open lane 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 varies from 1 to 2 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 every 0.2 to 0.3 mile intervals along the activity area. The number of sensors placed each day varied from 6 to 10 based on the length of paving planned on that day.

Contrary to Figure 4.3, sensors were not placed exactly along the centerline of a lane; rather they were shifted slightly off-center of the travel lane, farther away from the work zone. Placing the sensors in this manner was designed to take into account the driving behavior through a work zone where drivers tend to position their driving path slightly away from the line of cones (Gambatese & Jafarnejad, 2017).

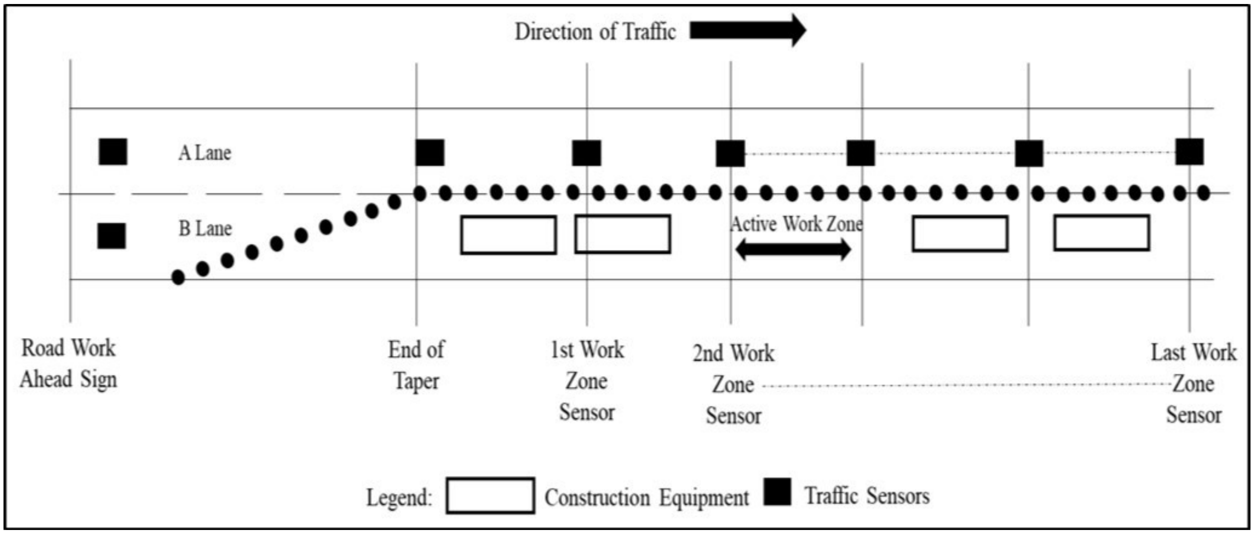

Figure 4.3: Typical sensor placement plan in work zone

4.1.3 Data Downloading and Storing

Using the HDM software for the traffic sensors and the iTrail software for the GPS trackers, raw, sequential, timed-stamped data was save and stored on a local computer and then uploaded to password protected cloud storage (OSU BOX). Figure 4.1 is an example of data recorded from a traffic sensor. The column headings are as follows:

- DateTime = date and time of data reading
- AdviceCode = Reliability code assigned to the data reading (possible values: 2, 4, and 128)
- Speed = vehicle speed (mph)
- Length = vehicle length (ft)
- StopTime = Time to record one data point (not applicable for spot speed measurement)
- RoadTemperature = temperature of the roadway (not used in the analysis)
- OCCFactor = Preassigned occupancy factor (not used in the analysis)
- Gap = time behind preceding vehicle (sec)
- Headway = distance from preceding vehicle (ft)

	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 4.4: Raw data format from HDM software

4.2 DATA FILTERING

Both sets of data (traffic and GPS location) recorded the date and time. The traffic sensor also recorded the vehicle speed (mph), approximate length of the vehicle (ft.), and gap (sec) and headway (ft.) 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 4.4 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 4.4 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 the Hassalo project (Case Study 1), data was selected specifically between the period from 23:00 to 04:00, a window of 5 hours. For both Grants Pass case studies, 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. This filtering step was taken to introduce more uniformity in terms of the time the data was collected across those data collection days being compared.

As this research study solely focused on evaluating how individual drivers react to two treatments (blue lights off and blue lights on) mounted on the light bar of a paver, it was important to remove every other 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. Therefore, vehicles with less than a 4 second headway were identified as non-free flow vehicles and their speeds were removed from the data set (Knodler Jr. et al. 2008; Athol, 1965). 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 researchers found that filtering beyond 4 seconds in this application 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.

4.3 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 4.5 is portion of an example of hourly distribution statistics produced for one of the traffic sensors on the first day of Case Study 1. The values in the table are provided for passenger cars (PC), heavy vehicles (HV), and both passenger cars and heavy vehicles combined (Total).

Speed Range	22:00-23:00			23:00-00:00			00:00-01:00		
	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%	0.4%	0.0%	0.3%	0.0%	0.0%	0.0%
15-19	0.0%	4.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	3.3%	0.0%	2.8%	0.0%	0.0%	0.0%	0.0%	1.3%	0.4%
25-29	20.8%	20.0%	20.7%	0.4%	0.0%	0.3%	1.7%	3.9%	2.3%
30-34	22.5%	28.0%	23.4%	3.4%	11.0%	5.2%	4.4%	3.9%	4.3%
35-39	22.5%	8.0%	20.0%	10.2%	16.4%	11.7%	8.3%	11.7%	9.3%
40-44	15.0%	12.0%	14.5%	22.0%	26.0%	23.0%	25.0%	29.9%	26.5%
45-49	10.0%	8.0%	9.7%	29.7%	12.3%	25.6%	25.6%	29.9%	26.8%
50-54	0.8%	4.0%	1.4%	16.5%	19.2%	17.2%	19.4%	10.4%	16.7%
55-59	2.5%	12.0%	4.1%	12.3%	9.6%	11.7%	12.8%	3.9%	10.1%
60-64	2.5%	0.0%	2.1%	3.8%	0.0%	2.9%	1.1%	1.3%	1.2%
65-69	0.0%	0.0%	0.0%	0.8%	4.1%	1.6%	0.6%	0.0%	0.4%
70-74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.6%	0.8%
75 and above	0.0%	4.0%	0.7%	0.4%	1.4%	0.6%	1.1%	1.3%	1.2%
Total	120	25	145	236	73	309	180	77	257
Average	36.9	39.8	37.4	47.9	46.4	47.5	47.9	45.7	47.2
Std Dev	8.7	13.5	9.7	7.6	10.4	8.3	8.2	9.2	8.6
85th Percentile	45.9	54.1	47.7	55.1	54.2	55.1	55.1	52.0	54.1
Min	22	19	19	11	31	11	28	25	25
Max	64	83	83	79	101	101	92	86	92
Range	42	63	63	67	70	90	64	61	67

Figure 4.5: Speed distribution and descriptive statistics sample

Vehicle volume in each speed range is shown as a percentage of the total volume during that hour. Descriptive statistics such as the mean speed, standard deviation, minimum speed, maximum speed, and 85th percentile speed were calculated using the dataset as shown in Figure 4.5. Average speed is a common measure of central tendency that traffic engineers consider when evaluating operating speeds of a segment of roadway. Measures of variation are also important when assessing operating conditions. In an unobstructed condition (e.g., no work zone or lane drop present), the 85th percentile speed represents the speed at which 85% of the traffic is traveling at or below. It is common for the 85th percentile speed on a roadway to be 5-7 miles per hour above the regulatory speed limit.

4.4 STATISTICAL ANALYSIS

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

To isolate the influence of the driver behavior with the blue 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's 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 4.6.

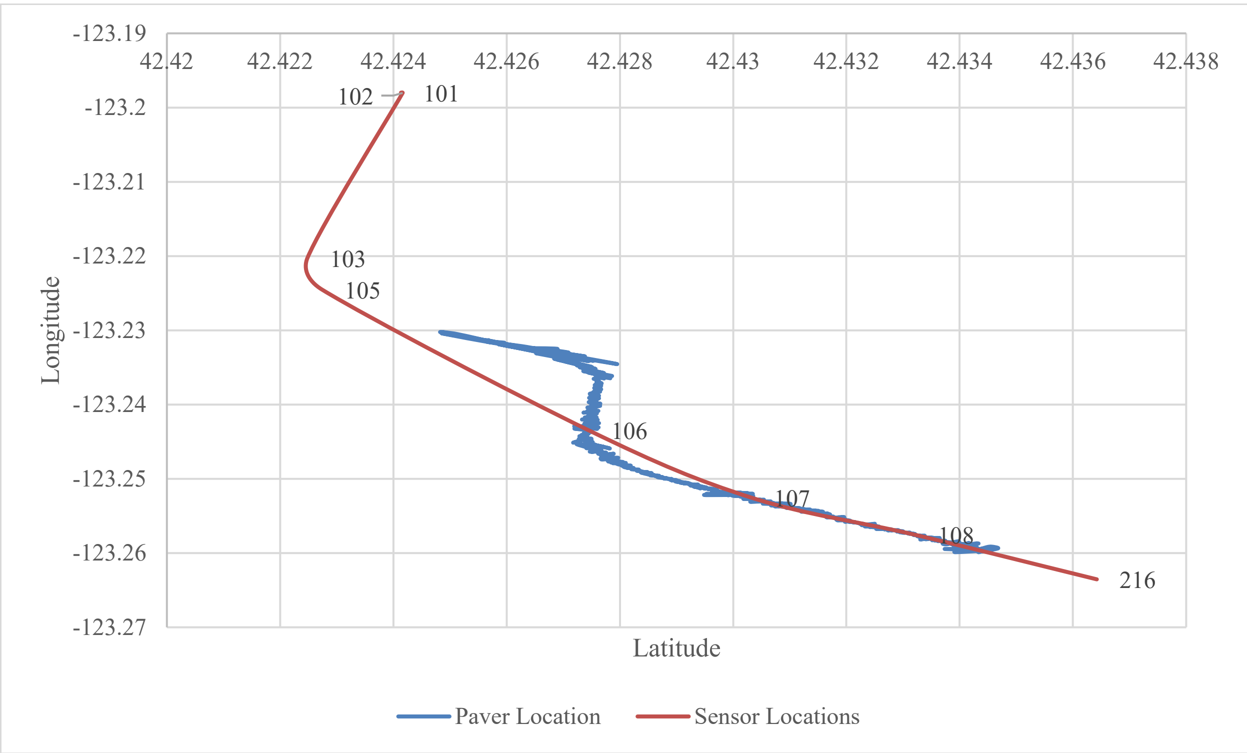

Figure 4.6: Sensor and paver locations

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 both 1,000 ft. upstream and 1,000 ft. downstream of the sensor. This operation was repeated for 250 ft. and 500 ft. intervals.

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 blue lights were on and when the blue lights were off.

5.0 RESULTS, ANALYSIS, AND DISCUSSION

5.1 SPEED STUDY

This section of the report is intended to provide 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. Note: To clearly convey the data given the large amount of data collected, multiple figures/tables are provided below. For example, vehicle volumes for Days 1 and 2 are shown in one figure and volumes for Days 3 and 4 on the same case study are shown in a separate figure.

5.1.1 Case Study 1: Hassalo, Portland

In this case study, data was collected from 23:00 until 04:00 the next morning on each night of testing. Figure 5.1 shows the number of vehicles passing through the work zone at different locations in Case Study 1 for the first day of testing when the blue lights were on and the second day when the blue lights were off. The data were recorded by different sensors in the middle of the work zone. There is some difference in the number of passing vehicles on these days. In general, it can be seen that Day 1 (blue lights on) had a greater number of passenger cars (vehicles < 25 feet in length) and Day 2 (blue lights off) had a greater number of trucks (vehicles > 25 feet in length). 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 number of vehicles may also occur when construction vehicles (e.g., asphalt trucks) enter the active work area and do not travel across some sensors. Also, if there is an entrance/exit in the middle of the active work area, some vehicles may enter/exit the roadway and not travel over all sensors.

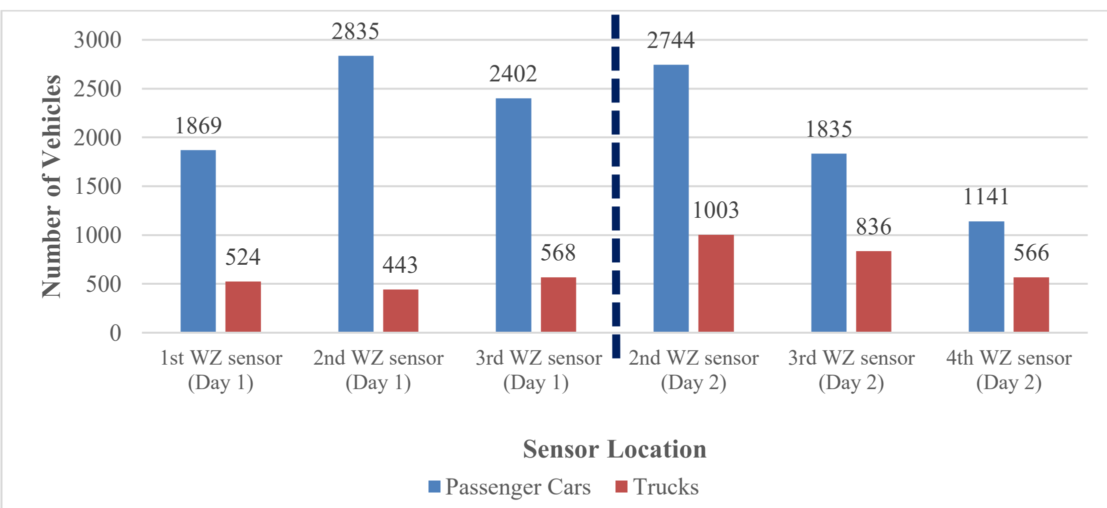

Figure 5.1: Traffic volumes for different vehicle types recorded by active WZ sensors for day 1 (blue lights on) and day 2 (blue lights off) (Case Study 1)

Figure 5.2 shows how the number of passenger cars and the number of trucks changed in the work zone over the course of each night of testing for Day 3 and Day 4. On Day 3 of testing, the blue lights were off and on Day 4 the blue lights were on. The data was collected from 23:00 to 04:00. There is variation in the volumes recorded by the different sensors. On Day 4, the lowest number of passenger cars was 743 as recorded by the 1st work zone sensor, and the highest number of passenger cars was 2,753 as recorded by the 2nd work zone sensor. As seen in the same figure, the lowest number of trucks was 365 as recorded by the 1st work zone sensor, and the highest number of trucks was 730 as record by the 4th work zone sensor. Compared with Day 3, the greatest and the least numbers of passenger cars and trucks were recorded by different sensors on Day 4. The variation in volumes between sensors on the same day may be due to several reasons as mentioned in the previous paragraph. The work zone placement plan followed the same layout for each night's work: roadwork ahead sign, progressive end of taper with lane drop, and single lane through the active work area. The number of sensors placed on the roadway was determined based on the planned length of paving for a particular night. Paver location throughout the work zone during the data collection period further dictated the sensors relevant to the study by being impacted by the location of paver. As real-time paving operations periodically encompass slight changes in plans, a wider safety net (additional sensors) was cast and as a result, for all recorded days, no data was missed.

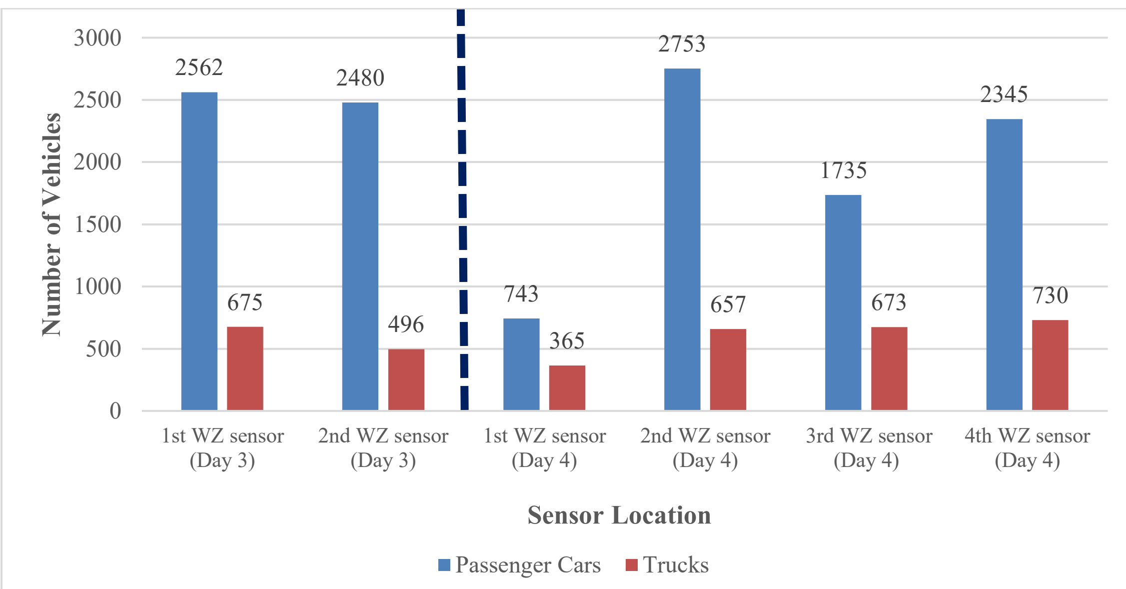

Figure 5.2: Traffic volumes for different vehicle types recorded by active WZ sensors for day 3 (blue lights off) and day 4 (blue lights on) (Case Study 1)

The change in the 85th percentile vehicle speed for different locations in the work zone on different days is shown in Figure 5.3. The figure shows the 85th percentile speed of the vehicles recorded at the Road Work Ahead (RWA) sign, at the end of the taper, and at all of the sensors locations in the work zone from 23:00 to 04:00 on the four days of testing.

The dashed line in the figure shows that the speed limit was 55 mph at the RWA sign and the speed limit in the work zone was temporarily reduced to 40 mph between the RWA sign and end of taper. Large drops in speed occurred on Days 2 and 3, but the 85th percentile speed increased on Days 1 and 4. As seen in the figure, vehicle speed changes from one location to another. The lowest 85th percentile speed of the passing vehicles was 37.2 mph as recorded by the 2nd work zone sensor on Day 1 (blue lights on), and the highest 85th percentile speed of the passing vehicles was 93.9 mph recorded by the A-lane sensor at the RWA sign. The largest change in speed between the end of taper and within the active work area, approximately 32 mph, occurred on Day 4. The reduction in speed is greatest at the 2nd work zone sensor, after which the speed increases gradually. In general, vehicle speed in the active work zone area is higher than the temporary speed limit (40 mph) except at the 1st and 2nd wok zone locations. It should be remembered that the construction equipment moves down the roadway. As a result, and given that previous research shows that vehicle speeds typically are lower adjacent the large equipment (e.g., paver and grinder), the 85th percentile speeds at the 1st work zone sensor are impacted by the equipment at a different time than the speeds at the downstream sensors. Vehicle speed at different times during the work period are discussed below.

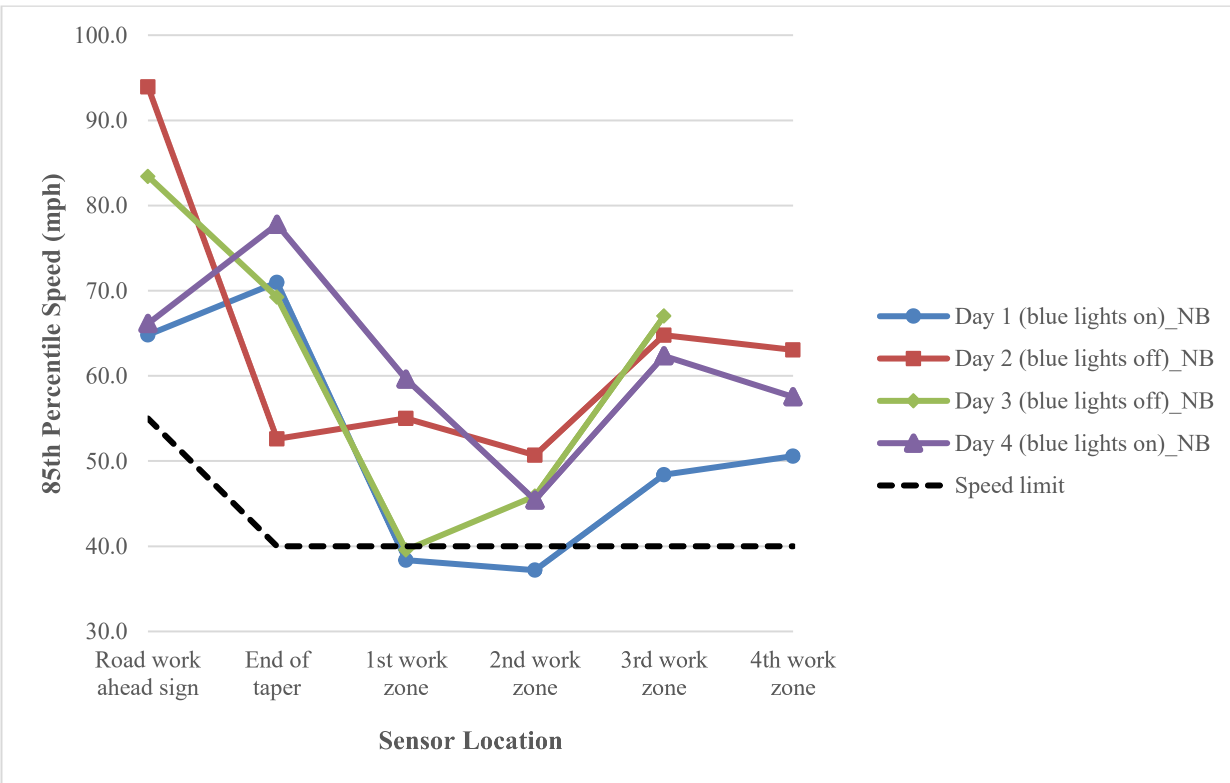

Figure 5.3: Vehicle speed (85th percentile) at different locations for all days on I-5 Hassalo (Case Study 1)

Figure 5.4 shows the variation in 85th percentile speed for Day 1 when the blue lights were on and for Day 2 when the blue lights were off. As seen in the figure, when the blue lights were off, the 85th percentile speed was greater as compared with when the blue lights were on. Assuming all other variables were controlled, this result indicates that the blue lights affected the behavior of the drivers such that the drivers reduced their speed in work zone. In general, vehicle speeds on all days of testing tended to increase gradually at later times in the testing period.

It should be noted that the 1st WZ sensor on this case study was typically located at or near the start of paving for the night. At this location, the construction equipment is typically staged in preparation for the paving at the beginning of the work shift. The paver often remains at this location for a longer period of time while the workers and equipment are mobilized to the site, the grinder progresses downstream, and the paving joint is prepared. Therefore, given that vehicle speeds are typically lower adjacent equipment and the traffic volumes are greater earlier in the work shift, the speeds at this location were found to typically be lower than at other locations and at later times during the paving operation.

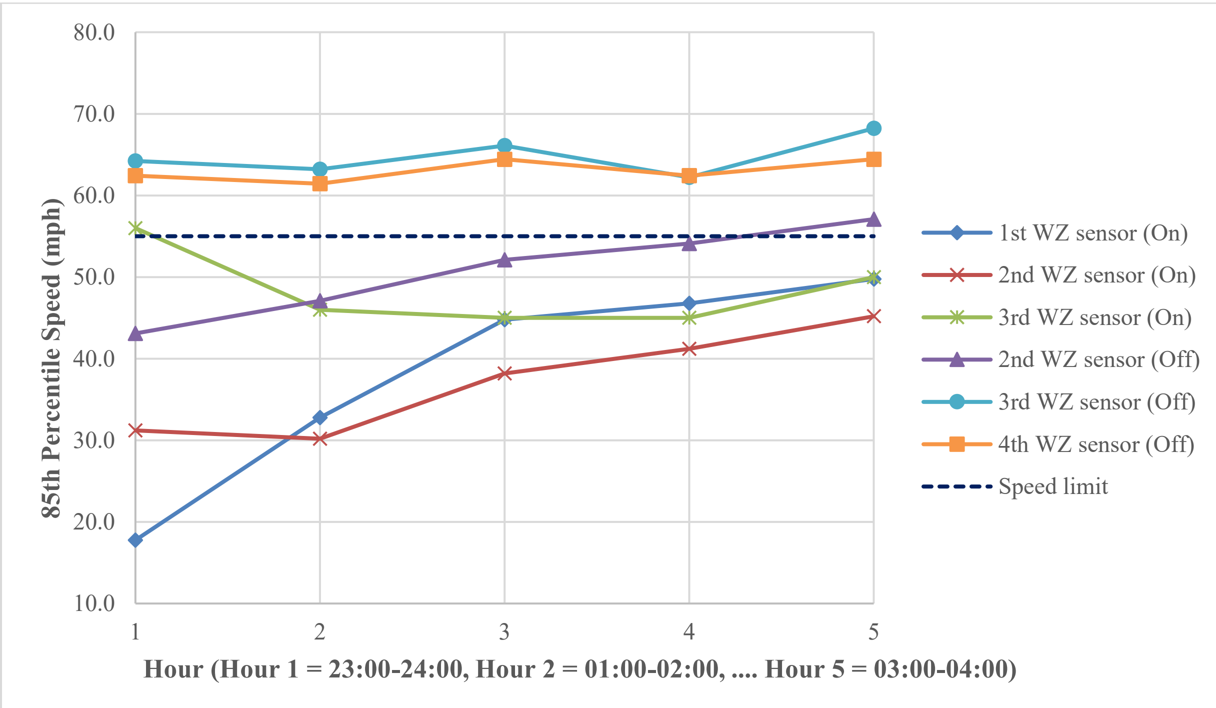

Figure 5.4: Hourly vehicle speed (85% percentile) at active WZ sensors for day 1 (blue lights on) and day 2 (blue lights off) (Case Study 1)

Similarly, Figure 5.5 explains the change in 85th percentile speed for the vehicles during five hours of data collection on Days 3 and 4. As with all of the case studies, the distance between the 1st WZ sensor in the active work area and the end of the taper was approximately the same on all data collection days (0.3 - 0.4 miles). There were two active work zone sensors when the blue lights were off (Day 3) and four active work zone sensors when the blue lights were on (Day 4). The number of active work zone sensors from one day to the next may differ based on the length of paving which the contractor completed on each day (e.g., a fewer number of sensors when the length of paving was shorter). An imbalance in the number of active work zone sensors may contribute to the difference in speeds for these two days where some sensors did not show a reduction in speed when the blue lights were on. Lastly, as described above for Figure 5.4, the speeds at the 1st WZ sensor were typically found to be lower than at other sensors, perhaps due to the staging of the equipment, length of time the equipment stays at this location, and the volume of traffic when the equipment is at this location.

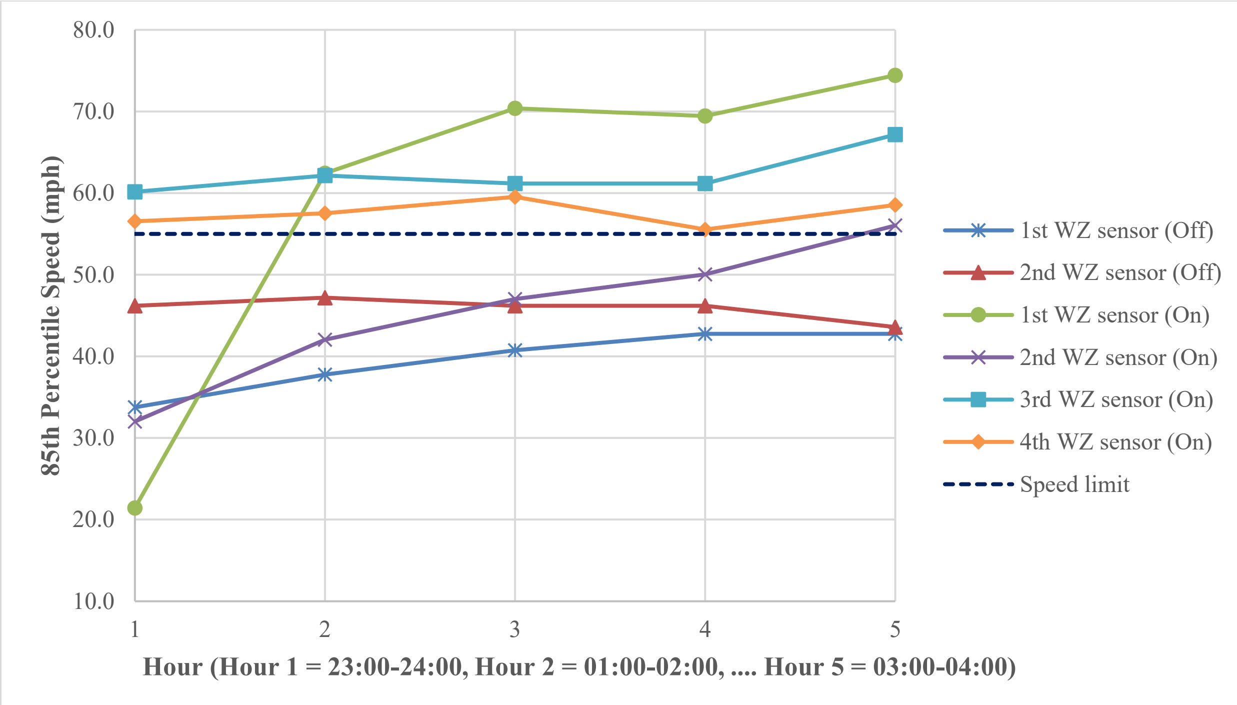

Figure 5.5: Hourly vehicle speed (85% percentile) at active WZ sensors for day 3 (blue lights off) and day 4 (blue lights on) (Case Study #1)

5.1.2 Case Study 2: Grants Pass I

In this case study, data was collected from 22:00 until 04:00 the next morning on each night of testing. Figure 5.6 shows the number of vehicles passing through the work zone at different locations in Case Study 2 for two days of testing when the blue lights were on and then off. The sensors were placed in the southbound lanes on Day 1 and in the northbound lanes on Day 2. The data were recorded by different active sensors in the middle of the active work area. There were three active sensors when the blue lights were off (Day 1) and three active sensors when the blue lights were on (Day 2). There is some difference in the number of passing vehicles on these days. In general, it can be seen that Day 1 (blue lights off) had the greatest number of passenger cars (844 vehicles) and Day 2 (blue lights on) had the greatest number of trucks (328 vehicles). However, based on the work zone layout, multiple entry and exit ramps were superimposed in the plan to account for variability in consecutive volumes. In addition, the accuracy of the sensor readings, and subsequent filtering of the data to account for inaccurate/error readings, had an impact on the differences in recorded traffic volumes.

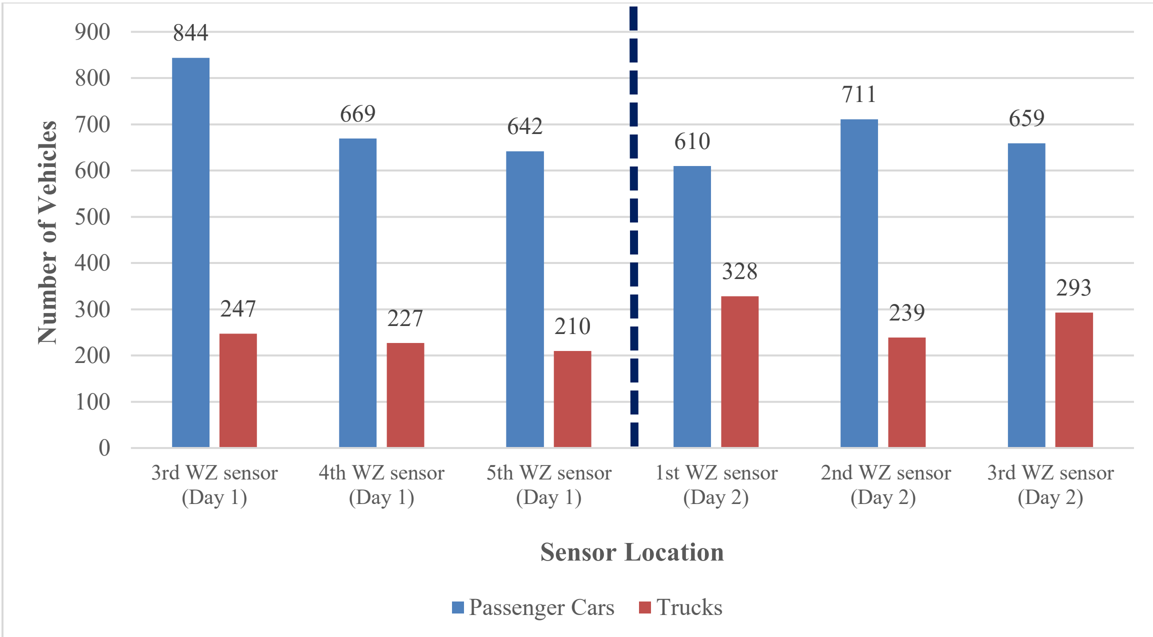

Figure 5.6: Traffic volumes for different vehicle types recorded by active WZ sensors for day 1 (blue lights off) and day 2 (blue lights on) (Case Study 2)

Similarly, Figure 5.7 shows how the number of passenger cars and trucks changed in the work zone over the course of each night of testing for Day 3 and Day 4. The blue lights on Day 3 of testing were off and on Day 4 the blue lights were on. The sensors were placed in the northbound lanes on both days. The data collection took place between 22:00 and 04:00 the next morning (six hours of data collection). There is variation in the volumes recorded by the different sensors. The lowest number of passenger cars was 414 as recorded by the 6th work zone sensor on Day 3 (blue lights off), and the highest number of passenger cars was 786 as record by the 4th work zone sensor on Day 4 (blue lights on). As seen in the same figure, the lowest number of trucks was 298 as recorded by the 6th work zone sensor on Day 3 (blue lights off), and the highest number of trucks was 419 as record by the 4th work zone sensor on Day 3. Day 3 had the greatest and lowest number of passenger cars and trucks, as recorded by the 6th work zone sensor in the work zone. As explained above, sensor accuracy and the number of entry and exit ramps have an impact on the total number of vehicles recorded by the sensors and used in the data analysis.

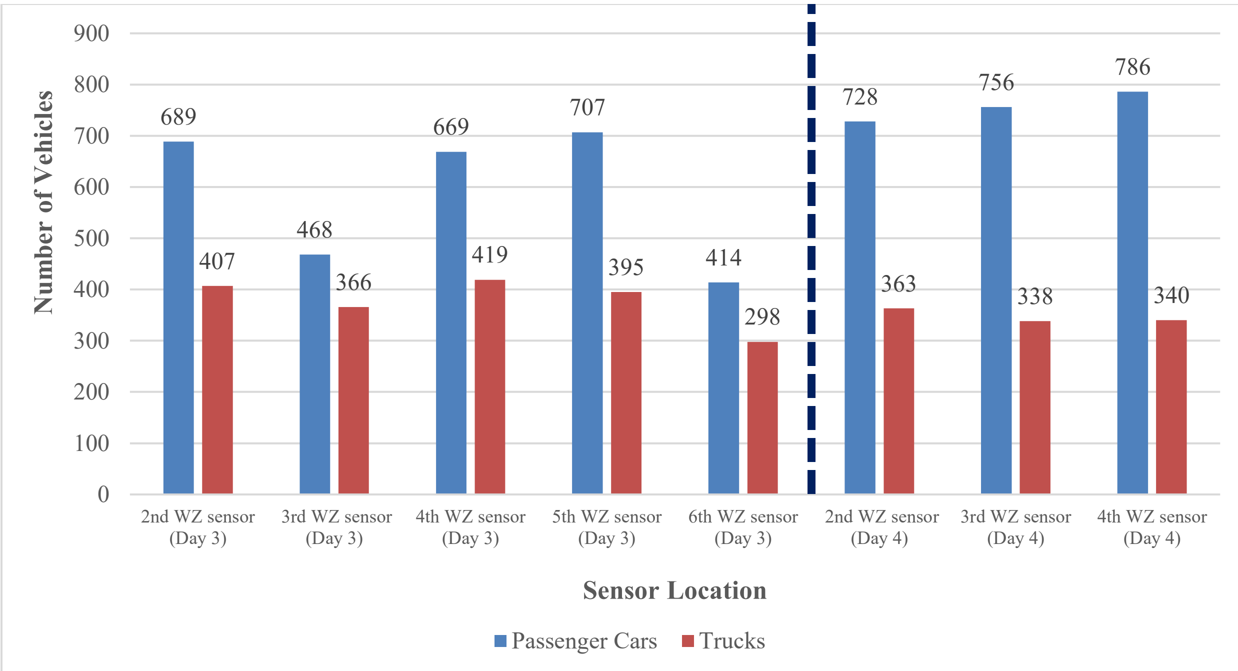

Figure 5.7: Traffic volumes for different vehicle types recorded by active WZ sensors for day 3 (blue lights off) and day 4 (blue lights on) (Case Study 2)

As shown in Figure 5.8, there is variation in the 85th percentile vehicle speed for vehicles recorded at different locations in this case study. 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 work zone from 22:00 through 04:00 on the four days of testing. The speed limit was 65 mph at the RWA sign and the temporarily reduced speed limit in the work zone was 40 mph. For Day 1, the sensors were placed in the southbound lanes, while on the other days the sensors were located in the northbound lanes. As can be seen in the figure, there is a change in speed from one location to another in the northbound lanes on Days 2 and 3. The lowest 85th percentile speed of the passing vehicles was 44.9 mph as recorded by the 1st work zone sensor when the blue lights were on (Day 4), and the highest 85th percentile speed of the passing vehicles was 93.1 mph for the same day as recorded by the A-lane sensor at the RWA sign. There is a reduction in the 85th percentile speed at different locations in the work zone. The speed increased gradually for Day 2 and Day 3 after the 3rd work zone sensor. In general, the 85th percentile speed of the vehicles in the work zone was higher than the work zone speed limit (40 mph).

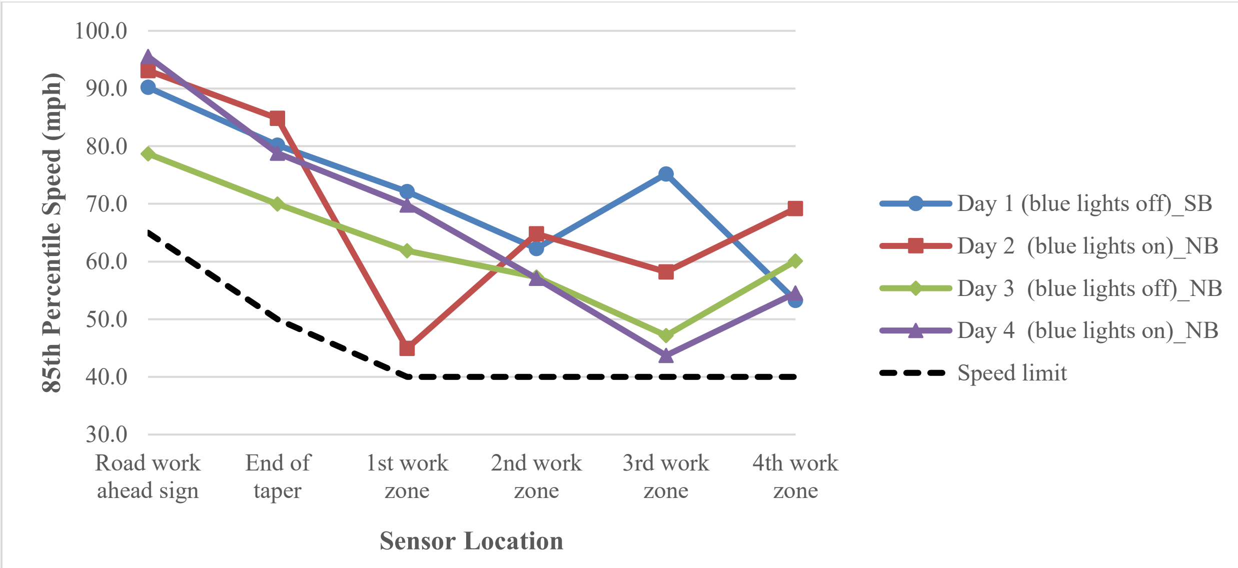

Figure 5.8: Vehicle speed (85th percentile) at different locations for all 4 days (Case Study 2)

Figure 5.9 shows the change in the 85th percentile vehicle speed over the course of the work shift for Day 1 when the blue lights were off and for Day 2 when the blue lights were on. There were three active WZ sensors on each day. With regard to Day 2 (blue lights on), the 1st work zone sensor shows a clear reduction in speed in the work zone. Generally, the 85th percentile speed in the work zone when the blue lights were off (Day 1) was higher than the 85th percentile speed when the blue lights were on (Day 2), except for the 3rd work zone sensor (blue lights on).

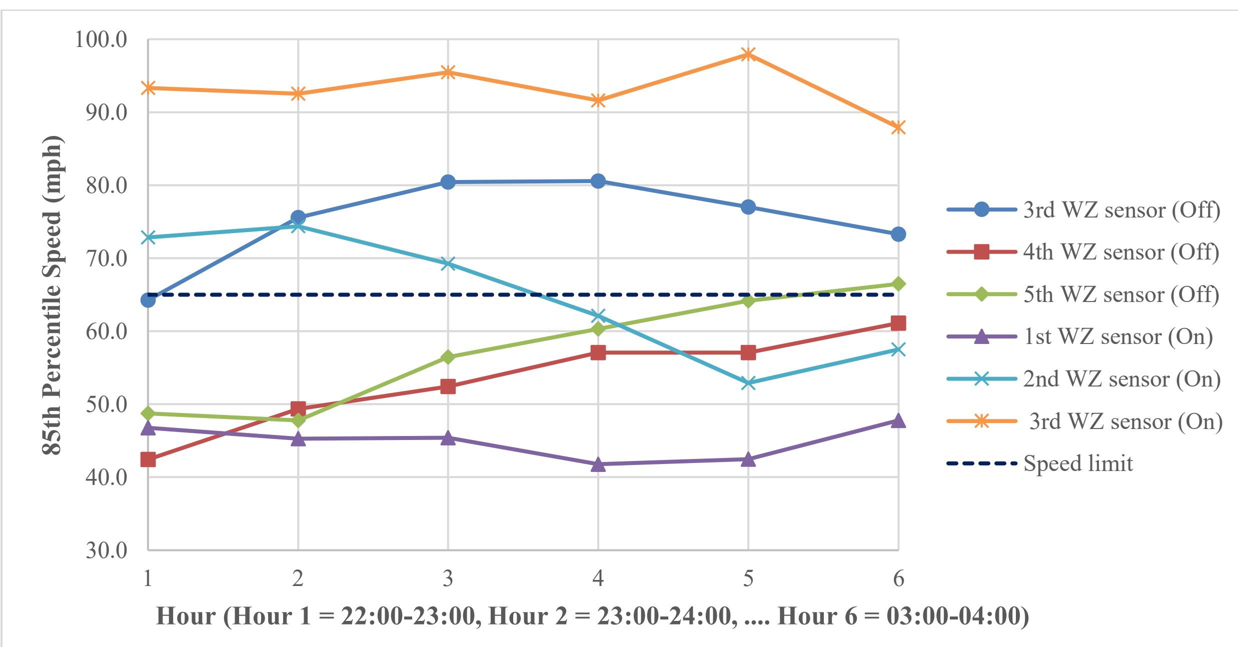

Figure 5.9: Hourly vehicle speed (85% percentile) at active WZ sensors for day 1 (blue lights off) and day 2 (blue lights on) (Case Study 2)

As shown in Figure 5.10, there were three active WZ sensors when the blue lights were off (Day 3) and five sensors when the blue lights were on (Day 4). Based on visual inspection of the figure, the variation in the 85th percentile vehicle speed does not follow a specific trend; some sensors show a reduction in speed later in the work shift when the blue light was on and other sensors did not show any reduction.

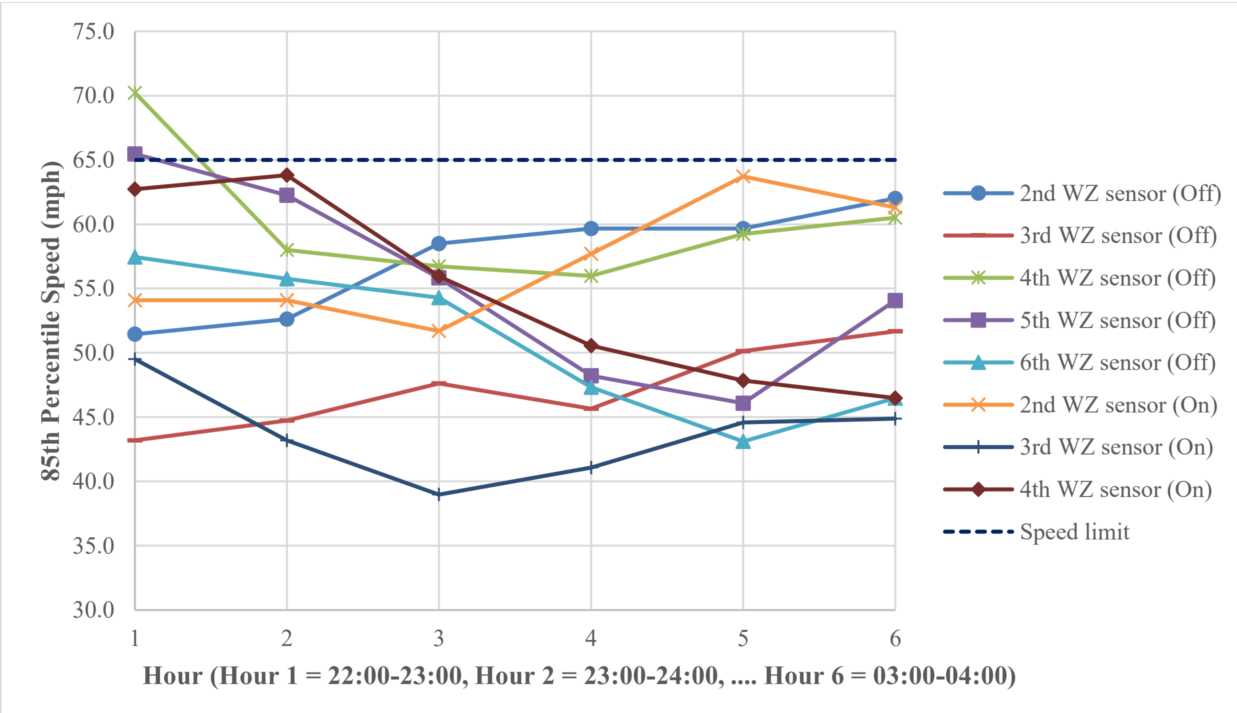

Figure 5.10: Hourly vehicle speed (85% percentile) at active WZ sensors for day 3 (blue lights off) and day 4 (blue lights on) (Case Study 2)

5.1.3 Case Study 3: Grants Pass II

Similar to Case Study 2, data was collected from 22:00 until 04:00 the next morning on each night of testing for Case Study 3. Figure 5.11 presents the number of vehicles passing through the work zone during Case Study 3 for two days of testing when the blue lights were off (Day 1) and when the blue lights were on (Day 2). The data were recorded by different active sensors in the middle of the work zone. There were three active sensors on Day 1 when the blue lights were off and six active sensors on Day 2 when the blue lights were off. There is a difference in the number of passing vehicles on these two days. It can be noticed that Day 2 (blue lights on) had the greatest number of passenger cars (952 vehicles) as recorded by the 6th work zone sensor. Also, Day 1 (blue lights off) had the greatest number of trucks (448 vehicles) as recorded by the 2nd work zone sensor.

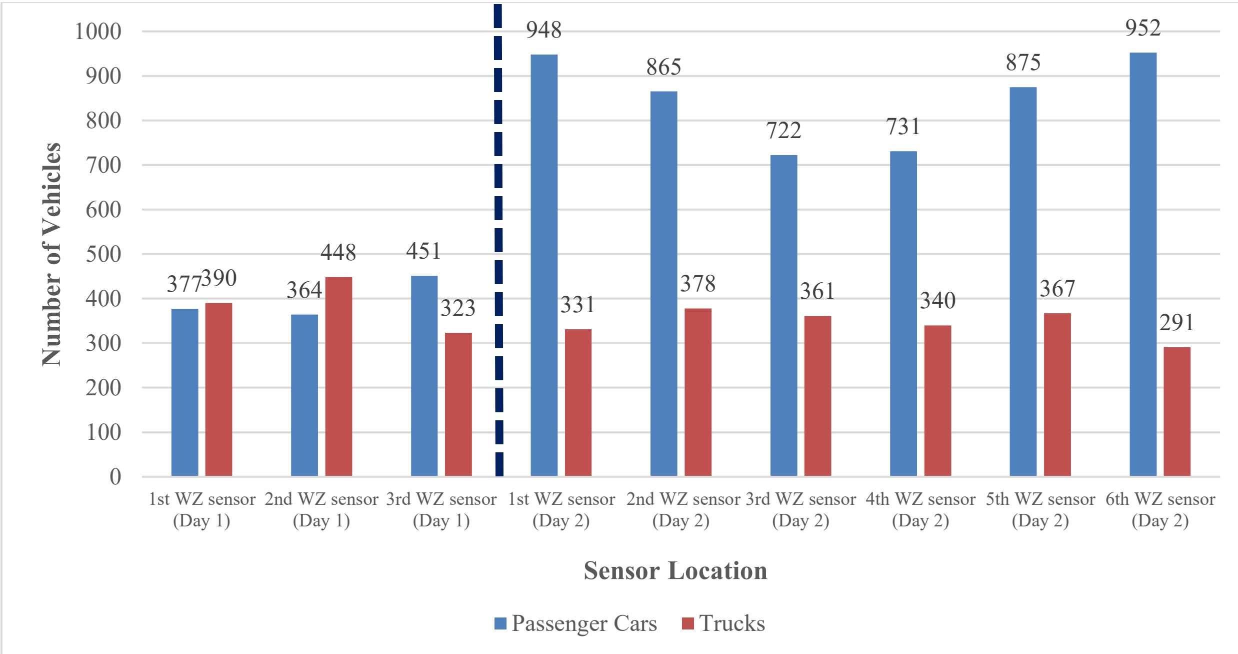

Figure 5.11: Traffic volumes for different vehicle types recorded by active WZ sensors for day1 (blue lights off) and day 2 (blue lights on) (Case Study 3)

Figure 5.12 shows how the number of passing vehicles changed in the work zone over the course of Days 3 and 4 of testing. The blue lights on Day 3 were off and on Day 4 the blue lights were on. 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. The fewest number of passenger cars was 642 as recorded by the 1st sensor in the work zone on Day 4 (blue lights on), and the greatest number of passenger cars was 1,128 as record by the 4th work zone sensor on Day 3 (blue lights off). As seen in the same figure, the fewest number of trucks was 319 as recorded by the 5th work zone sensor on Day 4, and the greatest number of trucks was 417 as record by the 3rd work zone sensor on Day 3. The greatest and fewest number of passenger cars and trucks occurred on Day 3, as recorded by different sensors.

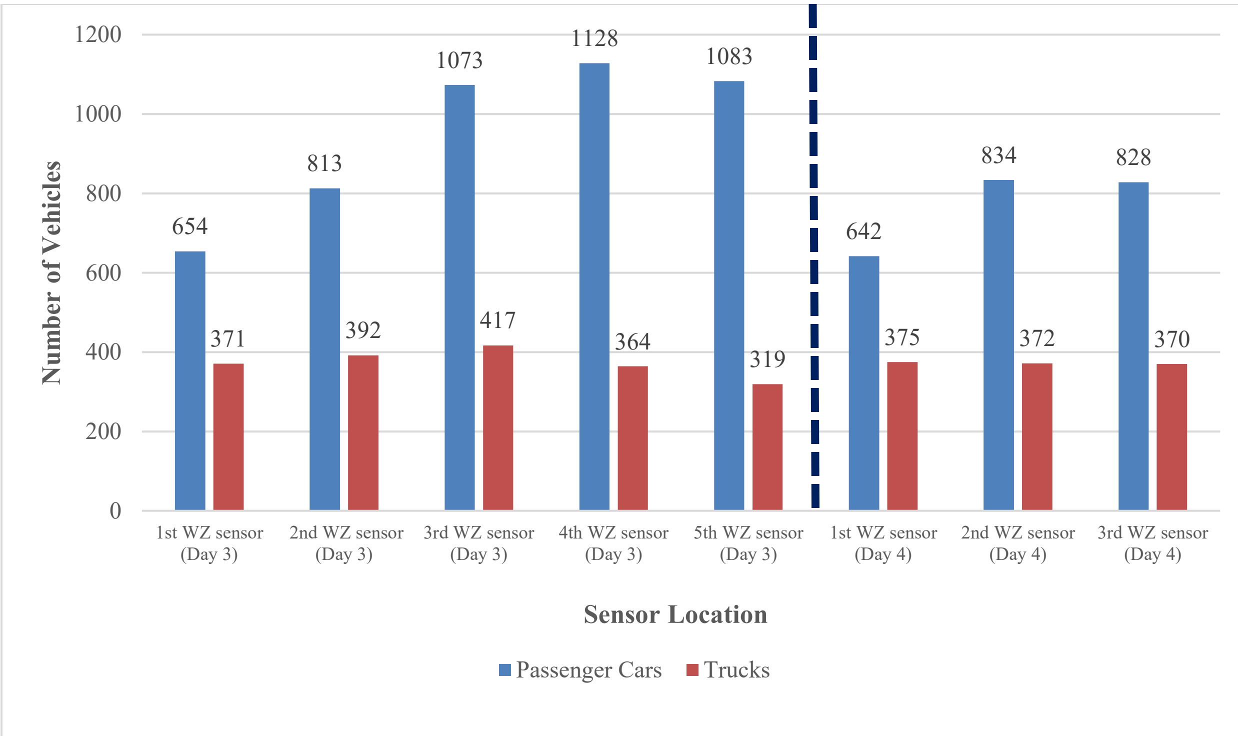

Figure 5.12: Traffic volumes for different vehicle types recorded by active WZ sensors for day 3 (blue lights off) and day 4 (blue lights on) (Case Study 3)

The 85th percentile vehicle speed for different locations in the work zone on different days is shown in Figure 5.13. 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 sensors were placed in the southbound lanes on Day 1 and in the northbound lanes on Days 2, 3, and 4. The speed limit was 65 mph at the RWA sign and the temporarily reduced speed limit in the work zone was 40 mph. As seen in the figure, there is variation in the speed between the different locations in the northbound lanes on Days 2 and 3. The lowest 85th percentile speed of the passing vehicles was 38.4 mph as recorded by the 1st work zone sensor, and the highest 85th percentile speed of the passing vehicles was 105.7 mph recorded by the A-lane sensor at the RWA sign. The reduction in speed is clear at the 1st work zone sensor when the blue lights were on (Day 2). After the 3rd work zone sensor, the speed increases gradually on all days. In general, the 85th percentile speed in the work zone is higher than the temporary speed limit (40 mph) except at the 1st work zone sensor location for Day 2.

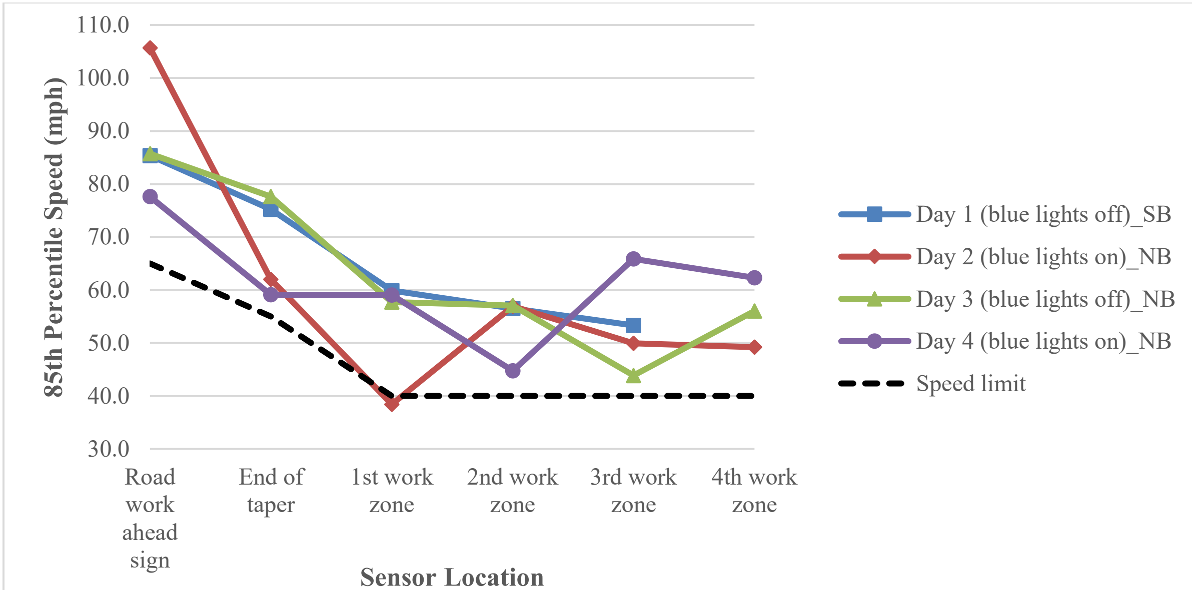

Figure 5.13: Vehicle speed (85th percentile) at different locations for all four days (Case Study 3)

For the third case study, the variation in the 85th percentile vehicle speed is clear in Figure 5.14. There were six active WZ sensors when the blue lights were turned on (Day 2), and three of the sensors (1st sensor, 3rd sensor, 4th sensor) show a reduction in speed in the work zone as compared with other sensors when the blue lights were off (Day 1). In general, there was variation in the 85th percentile speed on both days. It is also interesting to note that for those days when the blue lights were off, the 85th percentile speed was typically lower at the 1st WZ sensor location.

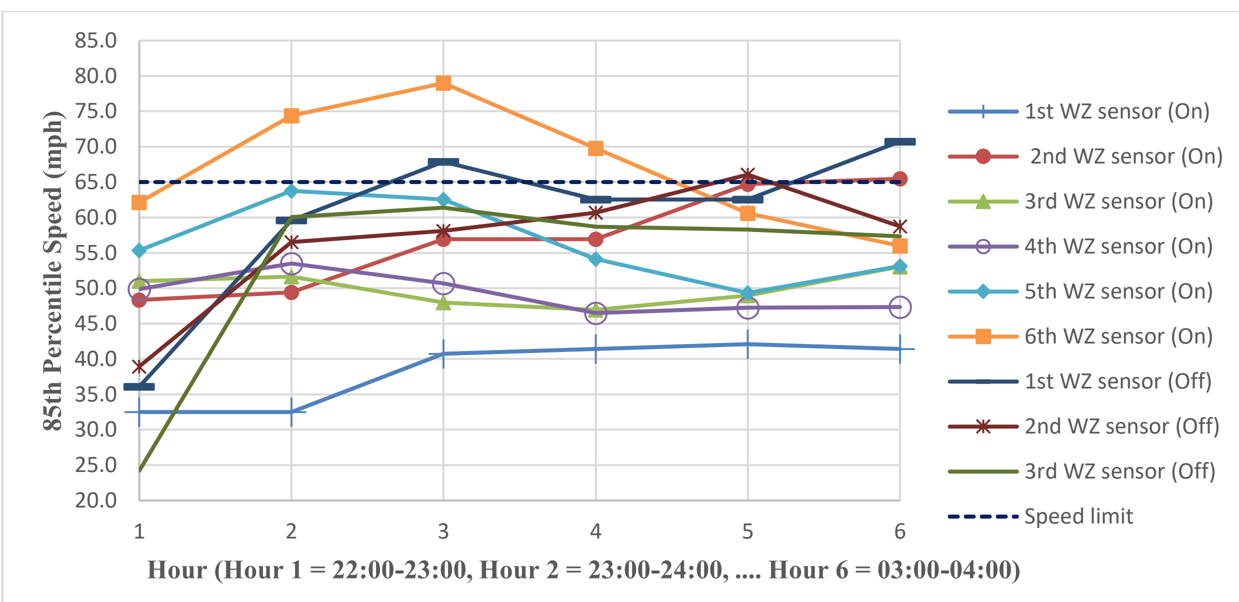

Figure 5.14: Hourly vehicle speed (85% percentile) at active WZ sensors for day 1 (blue lights off) and day 2 (blue lights on) (Case Study 3)

As seen in Figure 5.15, there were five active WZ sensors when the blue lights were off (Day 3) and three active WZ sensors when the blue lights were on (Day 4). The range of speed in the work zone for six hours of data collection was between 42.2 mph and 68 mph. Based on visual inspection of the figure, there is no specific pattern for the speed variation in the work zone where some sensors showed reduction in 85th percentile speed when the blue lights were on (Day 4) and other sensors did not show any reduction in speed. The 3rd WZ sensor with the blue lights off (Day 3) and the 2nd WZ sensor with the blue lights on (Day 4) consistently showed lower speeds than on all of the other days (both blue lights on and off). --

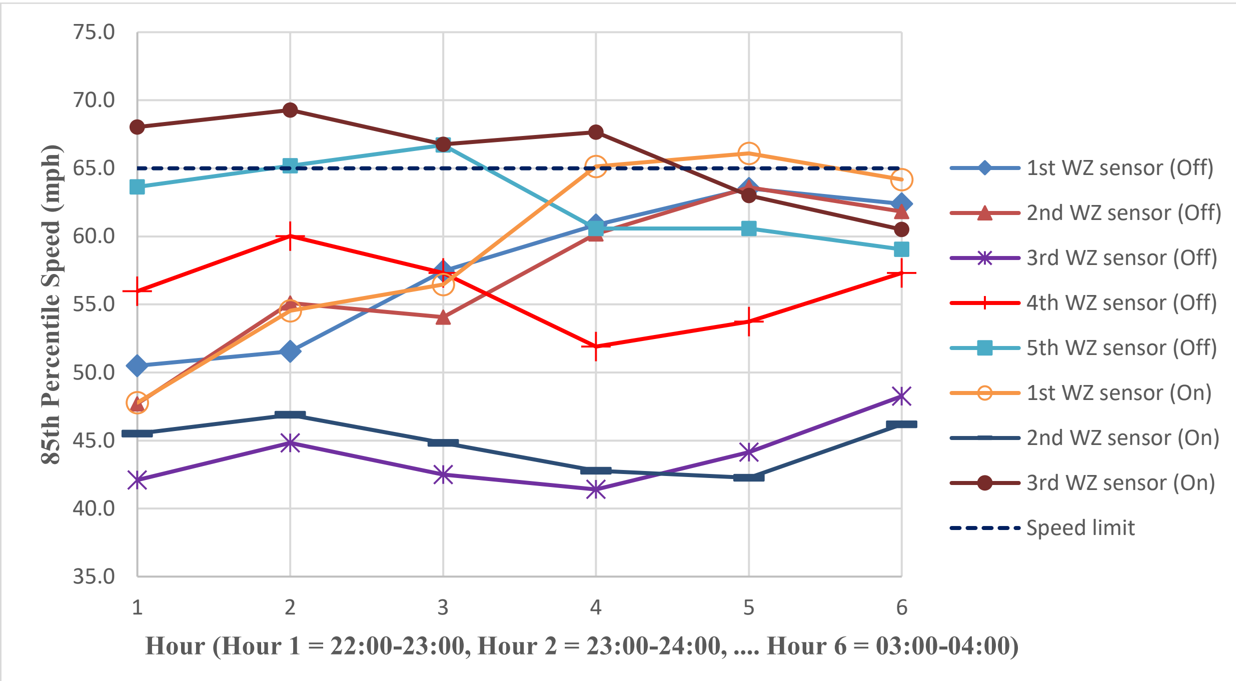

Figure 5.15: Hourly vehicle speed (85% percentile) at active WZ sensors for day 3 (blue lights off) and day 4 (blue lights on) (Case Study 3)

5.2 DESCRIPTIVE STATISTICS

Descriptive statistics of the data collected, especially vehicle speed on 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. These two locations were selected to provide a sample of the data prior to the work zone and within 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. The additional descriptive statistics are available upon request as indicated in the Appendix.

5.2.1 Case Study 1: Hassalo, Portland

Figure 5.16 presents a summary of the vehicle speeds recorded for all vehicles (passenger cars and trucks) at the RWA sign location on Day 4 when the blue lights were turned on. The values in the table are provided for passenger cars (PC), heavy vehicles (HV), and both passenger cars and heavy vehicles combined (Total). In this table, data is recorded from one sensor placed near the RWA sign in the A (fast) lane. The average speed over the entire recording time during the test period was 60 mph. Average speed varies from 57.6 mph during the period from 23:00-00:00 to 61.0 mph during the period from 03:00-04:00. The posted speed limit was 65 mph at the RWA sign. The 85th percentile speed for the entire recoding time was 66.1 mph. The 85th percentile speed value ranged from 67.1 mph to 63.3 mph throughout the test period.

		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
<10	0.4%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.4%	0.0%	0.3%	0.0%	0.0%	0.0%	0.8%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.4%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.4%	0.0%	0.3%	0.6%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.0%	0.6%
30-34	0.0%	0.0%	0.0%	0.6%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
35-39	0.8%	3.3%	1.0%	0.6%	5.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
40-44	0.4%	3.3%	0.7%	0.0%	5.0%	0.5%	0.8%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	3.8%	0.6%
45-49	5.7%	16.7%	6.8%	2.9%	0.0%	2.6%	1.6%	5.6%	2.1%	4.8%	4.3%	4.7%	0.0%	3.8%	0.6%
50-54	21.1%	43.3%	23.4%	16.4%	35.0%	18.3%	18.0%	44.4%	21.4%	14.3%	21.7%	15.6%	14.6%	11.5%	14.1%
55-59	29.4%	16.7%	28.1%	25.1%	35.0%	26.2%	20.5%	5.6%	18.6%	25.7%	26.1%	25.8%	18.2%	42.3%	22.1%
60-64	30.2%	0.0%	27.1%	30.4%	10.0%	28.3%	35.2%	22.2%	33.6%	33.3%	26.1%	32.0%	41.6%	30.8%	39.9%
65-69	6.8%	3.3%	6.4%	12.9%	5.0%	12.0%	12.3%	5.6%	11.4%	10.5%	13.0%	10.9%	12.4%	3.8%	11.0%
70-74	1.1%	3.3%	1.4%	5.3%	0.0%	4.7%	6.6%	5.6%	6.4%	7.6%	0.0%	6.3%	7.3%	0.0%	6.1%
75 and above	3.0%	10.0%	3.7%	5.3%	5.0%	5.2%	4.1%	11.1%	5.0%	3.8%	8.7%	4.7%	5.1%	3.8%	4.9%
Total	265	30	295	171	20	191	122	18	140	105	23	128	137	26	163
Average	57.8	56.0	57.6	60.5	55.7	60.0	60.8	60.0	60.7	60.6	61.7	60.8	61.6	58.2	61.0
Std Dev	8.6	11.7	8.9	8.0	9.8	8.3	8.9	12.6	9.4	7.3	13.5	8.7	7.4	7.1	7.4
85th Percentile	63.1	66.1	63.3	67.9	61.6	67.1	67.1	70.3	67.1	67.1	66.2	67.1	67.0	62.1	66.1
Min	7	39	7	29	38	29	12	46	12	45	48	45	29	44	29
Max	91	94	94	93	88	93	93	100	100	89	106	106	94	84	94
Range	84	55	87	64	50	64	81	54	88	44	58	61	65	40	65

Figure 5.16: Hourly summary of vehicle speed, day 4 (blue lights on) at RWZ sign (Case Study 1)

Similarly, Figure 5.17 presents a summary of the vehicle speeds over the same period recorded in the work zone, specifically at the 3rd work zone sensor. As seen in the table, the average speed varied between 54.1 mph and 59.6 mph. The average speed for the entire recoding time was 55.1 mph. The posted regulatory speed limit in the work zone was reduced to 40 mph. The average speed reduced from 60.0 mph at the RWA sign to 55.1 mph in the middle of the work zone. However, the average speed in the work zone was still higher than the regulatory speed limit in the work zone. The average of the 85th percentile speeds was 66.1 mph for the entire recoding time. This value ranged from 63.3 mph to 67.1 mph throughout the test period.

		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
<10	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	1.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.2%	0.0%	0.2%	0.2%	0.0%	0.2%	0.3%	0.0%	0.2%	0.0%	0.7%	0.2%	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%	1.1%	1.4%	1.2%	0.0%	0.6%	0.2%
25-29	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.2%	2.3%	2.2%	2.2%	0.0%	0.0%	0.0%
30-34	0.5%	0.0%	0.4%	0.2%	0.0%	0.2%	2.6%	1.4%	2.3%	2.7%	2.2%	2.5%	0.4%	0.0%	0.2%
35-39	0.9%	0.0%	0.8%	1.2%	1.6%	1.3%	2.9%	3.4%	3.1%	3.4%	5.8%	4.2%	0.4%	0.0%	0.2%
40-44	2.8%	1.0%	2.5%	4.4%	2.4%	4.0%	4.4%	6.9%	5.1%	9.5%	10.9%	10.0%	1.8%	2.5%	2.1%
45-49	14.6%	11.0%	13.9%	18.5%	20.5%	19.0%	13.1%	16.6%	14.1%	18.6%	15.2%	17.4%	6.2%	6.7%	6.4%
50-54	35.9%	37.0%	36.1%	31.4%	23.6%	29.6%	25.7%	31.0%	27.3%	17.0%	29.7%	21.4%	16.7%	19.0%	17.6%
55-59	30.5%	25.0%	29.5%	24.1%	24.4%	24.2%	28.0%	26.2%	27.5%	25.0%	19.6%	23.1%	23.3%	26.4%	24.4%
60-64	12.0%	13.0%	12.2%	12.2%	9.4%	11.6%	14.9%	9.7%	13.3%	12.9%	5.1%	10.2%	20.0%	27.6%	22.8%
65-69	1.4%	4.0%	1.9%	4.4%	8.7%	5.4%	4.4%	0.7%	3.3%	4.5%	4.3%	4.5%	20.7%	11.0%	17.1%
70-74	0.7%	1.0%	0.8%	1.4%	0.0%	1.1%	2.6%	1.4%	2.3%	2.3%	2.2%	2.2%	8.4%	4.3%	6.8%
75 and above	0.5%	7.0%	1.7%	1.9%	9.4%	3.6%	1.2%	2.1%	1.4%	0.8%	0.7%	0.7%	2.2%	1.8%	2.1%
Total	426	100	526	427	127	554	343	145	488	264	138	402	275	163	438
Average	54.0	57.1	54.6	54.4	58.2	55.3	54.4	53.3	54.1	52.2	50.7	51.7	60.2	58.6	59.6
Std Dev	6.4	12.0	7.8	7.7	14.1	9.7	8.6	8.7	8.6	9.8	10.0	9.9	8.1	8.5	8.3
85th Percentile	59.2	63.2	60.2	61.2	65.2	62.2	62.2	59.2	61.2	61.2	59.2	61.2	68.2	65.2	67.2
Min	18	12	12	17	37	17	17	29	17	23	17	17	32	21	21
Max	89	111	111	93	109	109	86	104	104	83	75	83	83	104	104
Range	71	99	99	76	72	92	69	75	87	60	58	66	51	83	83

Figure 5.17: Hourly summary of vehicle speed, day 4 (blue lights on) at 3rd work zone sensor (Case Study 1)

5.2.2 Case Study 2: Grants Pass I

Figure 5.18 shows a summary of the vehicle speeds recorded for all passenger cars and trucks at the RWA sign location on Day 4 when the blue lights were turned on. Data is recorded from one sensor placed near the RWA sign in the B (slow) lane. The mean speed for the entire recording time was 56.3 mph. The mean speed varied from 55.7 mph during the period from 01:00 to 02:00 to 56.8 mph from 22:00-23:00 and from 00:00-01:00. The posted speed limit on this segment of highway was 65 mph. The 85th percentile speed for the entire recoding time was 64.5 mph. The range for this value was from 62.4 mph to 65.8 mph throughout the test period.

		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%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	0.0%	0.0%	0.0%	1.0%	0.0%	0.6%	0.0%	0.0%	0.0%	1.8%	0.0%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	0.0%	1.1%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.0%	0.7%
35-39	0.0%	1.1%	0.5%	1.0%	0.0%	0.6%	2.3%	0.0%	1.2%	1.8%	1.6%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
40-44	4.0%	6.7%	5.1%	4.2%	6.9%	5.4%	5.7%	1.2%	3.6%	1.8%	3.1%	2.5%	2.3%	6.8%	5.1%	6.1%	7.9%	7.2%
45-49	13.6%	20.0%	16.3%	9.4%	9.7%	9.5%	6.9%	23.5%	14.9%	10.9%	18.8%	15.1%	20.9%	9.5%	13.7%	16.3%	18.0%	17.4%
50-54	18.4%	22.2%	20.0%	16.7%	34.7%	24.4%	20.7%	28.4%	24.4%	21.8%	32.8%	27.7%	18.6%	36.5%	29.9%	24.5%	27.0%	26.1%
55-59	33.6%	23.3%	29.3%	38.5%	27.8%	33.9%	23.0%	25.9%	24.4%	29.1%	28.1%	28.6%	27.9%	27.0%	27.4%	20.4%	24.7%	23.2%
60-64	15.2%	7.8%	12.1%	17.7%	8.3%	13.7%	18.4%	12.3%	15.5%	16.4%	10.9%	13.4%	11.6%	9.5%	10.3%	10.2%	10.1%	10.1%
65-69	10.4%	6.7%	8.8%	9.4%	5.6%	7.7%	12.6%	4.9%	8.9%	5.5%	3.1%	4.2%	14.0%	6.8%	9.4%	4.1%	4.5%	4.3%
70-74	3.2%	5.6%	4.2%	1.0%	4.2%	2.4%	6.9%	2.5%	4.8%	9.1%	1.6%	5.0%	4.7%	1.4%	2.6%	10.2%	6.7%	8.0%
75 and above	1.6%	5.6%	3.3%	1.0%	2.8%	1.8%	3.4%	1.2%	2.4%	1.8%	0.0%	0.8%	0.0%	2.7%	1.7%	6.1%	1.1%	2.9%
Total	125	90	215	96	72	168	87	81	168	55	64	119	43	74	117	49	89	138
Average	57.3	56.1	56.8	56.8	56.0	56.4	58.5	55.1	56.8	57.4	54.3	55.7	56.7	55.8	56.1	57.1	55.4	56.0
Std Dev	7.7	9.4	8.5	7.4	8.0	7.7	8.9	6.7	8.1	8.9	6.4	7.8	7.4	7.6	7.5	10.3	8.2	9.0
85th Percentile	65.2	66.1	65.4	64.1	64.3	64.2	68.0	61.3	65.6	65.5	60.5	62.4	66.1	62.6	63.3	71.1	64.1	65.8
Min	41	34	34	29	40	29	36	45	36	30	39	30	45	42	42	35	42	35
Max	82	81	82	76	82	82	76	80	80	79	75	79	72	80	80	81	82	82
Range	41	47	49	47	42	53	40	36	45	49	36	49	27	38	38	47	40	47

Figure 5.18: Hourly summary of vehicle speed, day 4 (blue lights on) at RWA sign (Case Study 2)

In the same way, Figure 5.19 summarizes the vehicle speeds over the same period recorded in the work zone, specifically at the 2nd sensor in the work zone. As seen in the table, the average speed varied between 43.9 mph and 54.2 mph. The average speed for the entire recoding time was 48.5 mph. The posted regulatory speed limit in the work zone was reduced to 40 mph. The average speed reduced from 56.3 mph at the RWA sign to 48.5 mph in the middle of the work zone. However, the average speed in the work zone was still slightly higher than the speed limit in the work zone. The average of the 85th percentile speeds was 57.1 mph for the entire recoding time. This value ranged from 51.7 mph to 64.7 mph throughout the test period.

		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%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.5%	1.9%	0.8%	0.0%	0.0%	0.0%	0.8%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	1.6%	1.9%	1.6%	0.0%	2.1%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	1.6%	3.8%	2.1%	0.6%	2.1%	0.9%	0.0%	0.0%	0.0%	1.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	3.1%	3.8%	3.3%	2.4%	4.2%	2.8%	1.7%	6.2%	3.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	6.8%	13.5%	8.2%	6.5%	12.5%	7.8%	12.6%	12.3%	12.5%	4.1%	7.3%	5.2%	0.0%	1.7%	0.8%	0.0%	0.0%	0.0%
35-39	20.9%	26.9%	22.2%	8.9%	14.6%	10.1%	11.8%	18.5%	14.1%	10.2%	12.7%	11.1%	2.7%	1.7%	2.3%	3.8%	2.4%	3.1%
40-44	23.0%	17.3%	21.8%	13.6%	20.8%	15.2%	21.8%	29.2%	24.5%	15.3%	21.8%	17.6%	8.2%	26.7%	16.5%	12.8%	16.9%	14.9%
45-49	17.3%	15.4%	16.9%	26.6%	27.1%	26.7%	26.1%	23.1%	25.0%	26.5%	27.3%	26.8%	19.2%	21.7%	20.3%	16.7%	31.3%	24.2%
50-54	11.5%	1.9%	9.5%	26.0%	12.5%	23.0%	16.0%	6.2%	12.5%	17.3%	16.4%	17.0%	16.4%	23.3%	19.5%	25.6%	20.5%	23.0%
55-59	6.3%	7.7%	6.6%	8.9%	4.2%	7.8%	5.9%	0.0%	3.8%	8.2%	9.1%	8.5%	21.9%	10.0%	16.5%	15.4%	16.9%	16.1%
60-64	2.6%	1.9%	2.5%	5.3%	0.0%	4.1%	0.8%	1.5%	1.1%	9.2%	0.0%	5.9%	19.2%	5.0%	12.8%	15.4%	6.0%	10.6%
65-69	1.6%	1.9%	1.6%	1.2%	0.0%	0.9%	2.5%	1.5%	2.2%	4.1%	3.6%	3.9%	1.4%	1.7%	1.5%	5.1%	2.4%	3.7%
70-74	0.5%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.0%	0.0%	0.7%	6.8%	3.3%	5.3%	1.3%	2.4%	1.9%
75 and above	2.6%	1.9%	2.5%	0.0%	0.0%	0.0%	0.0%	1.5%	0.5%	3.1%	1.8%	2.6%	4.1%	5.0%	4.5%	3.8%	1.2%	2.5%
Total	191	52	243	169	48	217	119	65	184	98	55	153	73	60	133	78	83	161
Average	44.7	41.8	44.1	47.3	42.3	46.2	44.7	42.5	43.9	50.8	47.5	49.6	56.1	51.8	54.2	54.4	51.3	52.8
Std Dev	11.4	13.9	12.0	8.5	8.7	8.8	8.7	8.9	8.8	12.5	11.4	12.2	10.1	11.3	10.8	9.5	7.8	8.8
85th Percentile	54.1	52.7	54.1	55.3	52.1	54.1	52.9	48.1	51.7	61.1	54.4	57.7	64.4	59.5	63.7	62.5	57.8	61.3
Min	13	14	13	24	19	19	11	25	11	23	30	23	37	35	35	38	38	38
Max	96	105	105	69	58	69	69	77	77	107	108	108	85	95	95	90	76	90
Range	83	90	91	44	38	49	58	52	66	84	78	85	48	60	60	52	37	52

Figure 5.19: Hourly summary of vehicle speed, day 4 (blue lights on) at 2nd sensor in the work zone (Case Study 2)

5.2.3 Case Study 3: Grants Pass II

Figure 5.20 shows a summary of the vehicle speeds recorded for all passenger cars and trucks at the RWA sign location on Day 4 when the blue lights were turned on. In this table, data is shown for one sensor placed near the RWA sign in the B (slow) lane. The mean speed for the entire recording time during the test period was 60.5 mph. Mean speed varied from 51.7 mph during the period from 22:00 to 23:00 to 63.8 mph from 00:00-01:00. The posted speed limit was 65 mph. The 85th percentile speed for the entire recoding time was 70 mph. This value ranged from 66.3 mph to 72.5 mph throughout the test period.

		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%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.9%	0.0%	0.7%	0.5%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	2.8%	2.7%	2.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	4.6%	2.7%	4.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	8.3%	2.7%	6.9%	0.5%	0.0%	0.3%	0.0%	0.0%	0.0%	0.7%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	10.2%	5.4%	9.0%	0.5%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
35-39	0.0%	5.4%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
40-44	3.7%	5.4%	4.1%	0.5%	0.9%	0.7%	1.0%	0.0%	0.7%	0.7%	0.0%	0.5%	0.0%	0.0%	0.0%	2.0%	0.0%	0.8%
45-49	5.6%	8.1%	6.2%	2.6%	1.8%	2.3%	0.5%	3.2%	1.4%	2.2%	6.6%	3.8%	2.4%	6.3%	4.2%	4.1%	4.8%	4.5%
50-54	11.1%	8.1%	10.3%	8.9%	19.1%	12.6%	8.3%	22.3%	12.9%	13.4%	17.1%	14.8%	10.6%	20.0%	15.2%	8.2%	25.3%	18.9%
55-59	10.2%	32.4%	15.9%	12.0%	22.7%	15.9%	12.0%	27.7%	17.1%	15.7%	23.7%	18.6%	18.8%	31.3%	24.8%	10.2%	28.9%	22.0%
60-64	20.4%	13.5%	18.6%	34.9%	28.2%	32.5%	27.1%	25.5%	26.6%	27.6%	27.6%	27.6%	24.7%	26.3%	25.5%	24.5%	24.1%	24.2%
65-69	14.8%	5.4%	12.4%	20.8%	17.3%	19.5%	24.5%	10.6%	19.9%	20.9%	7.9%	16.2%	27.1%	11.3%	19.4%	34.7%	10.8%	19.7%
70-74	5.6%	5.4%	5.5%	11.5%	5.5%	9.3%	17.2%	3.2%	12.6%	8.2%	9.2%	8.6%	10.6%	1.3%	6.1%	14.3%	4.8%	8.3%
75 and above	1.9%	2.7%	2.1%	7.3%	4.5%	6.3%	9.4%	7.4%	8.7%	9.7%	7.9%	9.0%	5.9%	3.8%	4.8%	2.0%	1.2%	1.5%
Total	108	37	145	192	110	302	192	94	286	134	76	210	85	80	165	49	83	132
Average	51.4	52.8	51.7	63.4	61.4	62.7	65.3	60.6	63.8	62.8	61.2	62.2	63.3	59.5	61.5	63.8	59.3	61.0
Std Dev	16.9	14.1	16.2	8.9	7.5	8.4	7.9	8.0	8.2	9.4	8.2	9.0	7.2	6.6	7.1	7.6	7.0	7.6
85th Percentile	67.1	64.6	66.3	70.2	68.6	70.2	73.2	67.1	72.5	72.0	70.2	71.7	70.2	65.9	68.6	70.2	66.4	68.6
Min	14	15	14	11	44	11	42	46	42	21	46	21	46	46	46	43	46	43
Max	81	80	81	90	90	90	89	87	89	86	83	86	81	80	81	83	89	89
Range	67	65	67	79	46	79	47	41	47	65	37	65	35	34	35	40	43	46

Figure 5.20: Hourly summary of vehicle speed, day 4 (blue lights on) at RWA sign (Case Study 3)

Similarly, Figure 5.21 shows the vehicle speeds over the same period recorded in the work zone, specifically at the 2nd work zone sensor. As seen in the table, the average speed over the different hourly periods varied between 36 mph and 40.6 mph. The average speed for the entire recoding time was 38.6 mph. The posted regulatory speed limit in the work zone was reduced to 40 mph. The average speed reduced from 60.5 mph at the RWA sign to 38.6 mph at the 2nd sensor in the work zone. In general, the average speed in the work zone was slightly lower than the speed limit in the work zone. The average of the 85th percentile speed was 45 mph for the entire recoding time. This value ranged from 42.3 mph to 46.9 mph throughout the test period.

		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%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.7%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.0%	0.6%	0.0%	0.0%	0.0%
15-19	2.1%	0.0%	1.6%	0.0%	0.0%	0.0%	0.6%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	0.0%	0.0%	1.3%	0.0%	1.0%	0.0%	3.0%	0.9%	0.7%	0.0%	0.5%	2.9%	5.9%	3.9%	0.0%	0.0%	0.0%
25-29	1.4%	7.7%	2.7%	1.3%	4.4%	2.2%	7.5%	4.5%	6.6%	12.1%	10.2%	11.6%	14.4%	19.6%	16.1%	1.6%	10.4%	6.2%
30-34	22.4%	17.9%	21.4%	13.3%	20.0%	15.2%	12.5%	18.2%	14.2%	27.1%	20.3%	25.1%	27.9%	19.6%	25.2%	22.6%	23.9%	23.3%
35-39	30.1%	23.1%	28.6%	32.9%	30.0%	32.1%	30.6%	37.9%	32.7%	29.3%	35.6%	31.2%	26.0%	37.3%	29.7%	29.0%	26.9%	27.9%
40-44	30.1%	28.2%	29.7%	32.4%	23.3%	29.8%	33.1%	24.2%	30.5%	21.4%	27.1%	23.1%	17.3%	7.8%	14.2%	25.8%	22.4%	24.0%
45-49	10.5%	12.8%	11.0%	12.0%	8.9%	11.1%	8.8%	4.5%	7.5%	7.9%	3.4%	6.5%	6.7%	3.9%	5.8%	8.1%	11.9%	10.1%
50-54	2.8%	5.1%	3.3%	5.3%	4.4%	5.1%	5.0%	3.0%	4.4%	1.4%	0.0%	1.0%	3.8%	0.0%	2.6%	9.7%	3.0%	6.2%
55-59	0.0%	0.0%	0.0%	0.4%	2.2%	1.0%	1.3%	3.0%	1.8%	0.0%	1.7%	0.5%	1.0%	2.0%	1.3%	1.6%	0.0%	0.8%
60-64	0.0%	0.0%	0.0%	0.4%	4.4%	1.6%	0.6%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	2.0%	0.6%	0.0%	0.0%	0.0%
65-69	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.0%	0.8%
70-74	0.0%	2.6%	0.5%	0.0%	2.2%	0.6%	0.0%	1.5%	0.4%	0.0%	1.7%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
75 and above	0.0%	2.6%	0.5%	0.4%	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.5%	0.8%
Total	143	39	182	225	90	315	160	66	226	140	59	199	104	51	155	62	67	129
Average	38.4	41.1	39.0	40.4	41.1	40.6	39.5	39.1	39.4	36.8	37.8	37.1	36.6	34.7	36.0	40.4	38.6	39.5
Std Dev	6.5	10.4	7.5	6.5	9.2	7.4	6.7	7.4	6.9	5.8	7.4	6.3	6.9	7.9	7.3	7.5	7.8	7.7
85th Percentile	44.8	48.7	45.5	46.9	46.9	46.9	45.5	44.6	44.8	42.4	43.2	42.8	43.4	39.9	42.3	49.1	45.5	46.2
Min	11	27	11	22	26	22	19	24	19	22	26	22	20	15	15	29	28	28
Max	52	77	77	77	74	77	63	71	71	52	75	75	56	62	62	65	79	79
Range	42	50	66	55	49	55	44	47	52	31	49	53	36	47	47	36	51	51

Figure 5.21: Hourly summary of vehicle speed, day 4 (blue lights on) at the 2nd sensor in the work zone (Case Study 3)

5.3 STATISTICAL ANALYSIS

A variety of statistical tests were performed on the datasets to determine whether the flashing blue 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 (blue lights off) and treatment (blue lights on). With the goal of explaining the drivers' behavior in terms of speed reduction, the 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 entered the active work zone and first saw the paver.

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, direction of travel (northbound or southbound), 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 blue lights were off (control) and those days with the blue lights turned on (treatment).

It should be noted that making the comparisons based on the speed differential (the difference in speed between the RWA sign and when the driver initially sees the paver), rather than the actual speed in the active work area, provides several benefits. It enables controlling the confounding variables associated with the dynamic construction operations and increases the level of confidence in the results.

5.3.1 Data Structuring

During the course of the work shift, the paver moves along the roadway. Therefore, analyses needed to take into consideration the location of the paver relative to the sensors. 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 the 0.5 miles apart, 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. 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 a portion of the 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 blue 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 blue lights on the top of the paver. That is, in this case, the sensor records the vehicle speeds as the driver approaches and reacts to the blue lights. When the paver is adjacent the location of the sensor, the driver passing over the sensor has seen the blue lights on the paver and already reacted to it. Lastly, when the sensor is downstream of the paver, the speeds recorded by the sensor represent driver behavior after seeing the blue lights and after passing the paver (i.e., the vehicle is downstream of the paver). Therefore, three likely reactions of the driver based on location could be recorded in this dataset, namely: (1) preparing to react to the blue lights as the driver can see the lights and is approaching the paver; (2) saw the blue lights and is reacting to the lights (is adjacent the paver); and (3) travelled passed the paver and reacted to the blue 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 Figure 5.22 and Figure 5.23 illustrate the datasets for 250 ft. intervals and 500 ft. intervals, respectively. Each dataset was developed separately for all case studies, and included control data (blue lights off) and treatment data (blue 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.

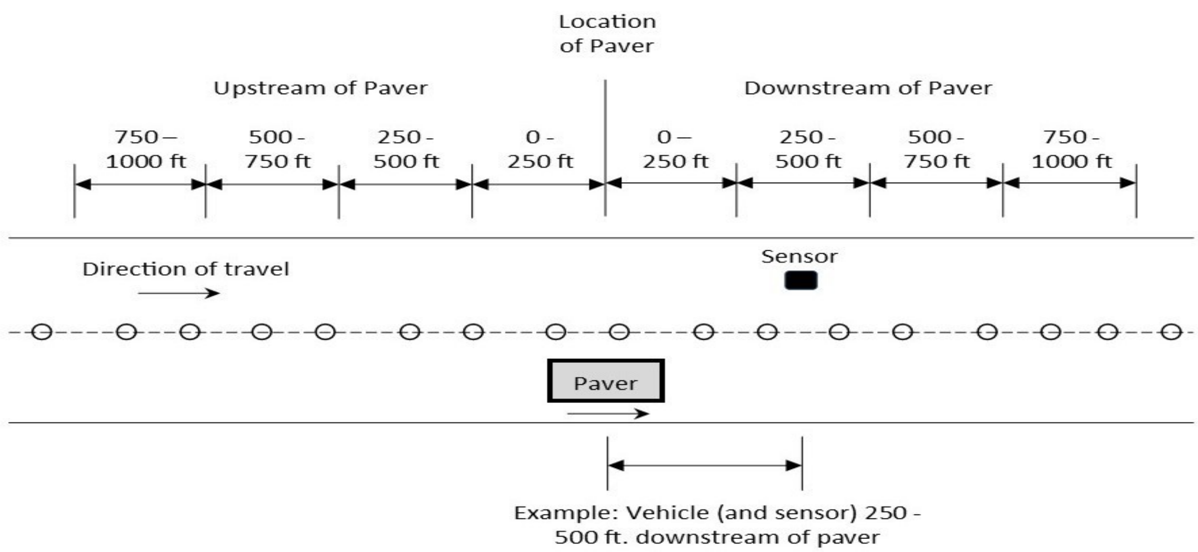

Figure 5.22: Data intervals for analysis – 250 ft. intervals dataset

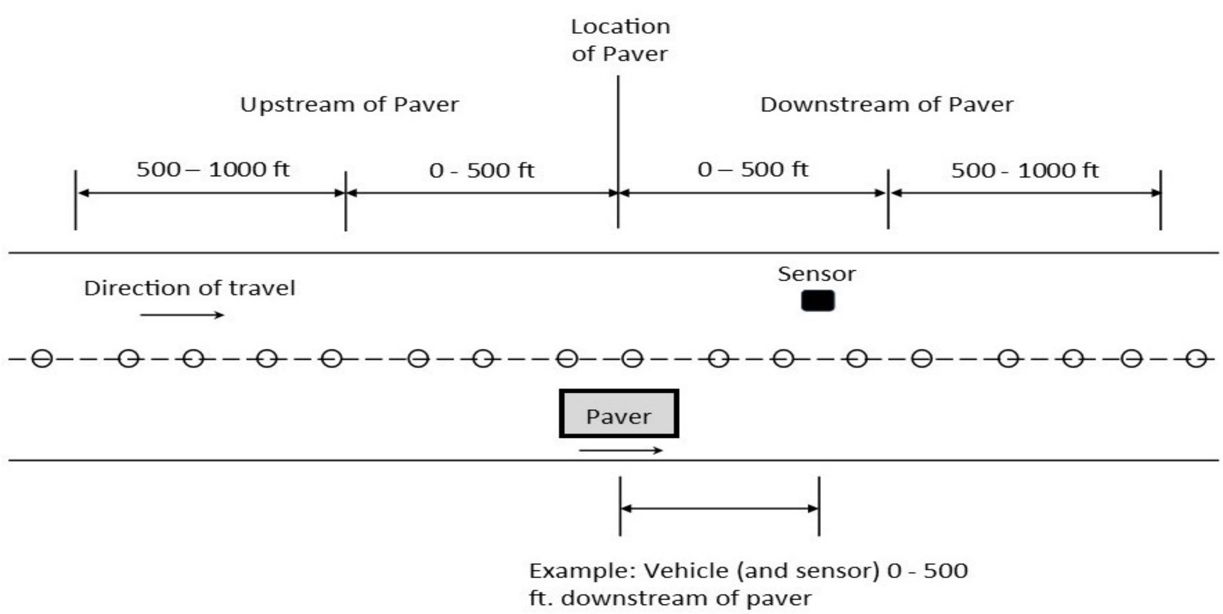

Figure 5.23: Data intervals for analysis – 500 ft. intervals dataset

5.3.2 Case Study 1: Hassalo, Portland

5.3.2.1 Normality Test

As a first step, the data was evaluated for normality. The sensors that were placed in both lanes at the RWA sign were considered to capture normality the most as opposed to the sensors located inside the active work area. For this reason, normality tests were performed on the two RWA sensors. One sample Kolmogorov-Smirnov tests, Anderson-

Darling tests, and Jarque-Bera tests were performed and the results are presented in Table 5.. For the dataset obtained from the Hassalo project (Case Study 1), the normality tests on the adjusted speeds were not consistent in the results. The first two statistical tests did not reveal normality in the dataset. However, the Jarque-Bera test revealed normality. To further analyze this issue, a normality superimposed histogram was plotted (Figure 5.) and the cumulative frequency distribution was analyzed. Visual observation indicated strong tendency to normalcy. Therefore, based on both a positive Jarque-Bera test result and visual observation, the researchers elected to proceed to further analyze the data as normally distributed speed data (Ghasemi & Zahediasl, 2012). Further assessment of the data indicated that, due to the presence of a significant number of outliers in the dataset (high values), the first two tests were not successful in identifying normality. However, in transportation engineering literature, speed distribution is commonly considered as normally distributed (Berry & Belmont, 1951; Jeong et al., 2012).

Table 5.1: Normality Test Summary (Case Study 1)

Test	p-Value	Normality
Kolmogorov-Smirnov test	0.0052	No
Anderson-Darling test	0.0003	No
Jarque-Bera test	0.2597	Yes

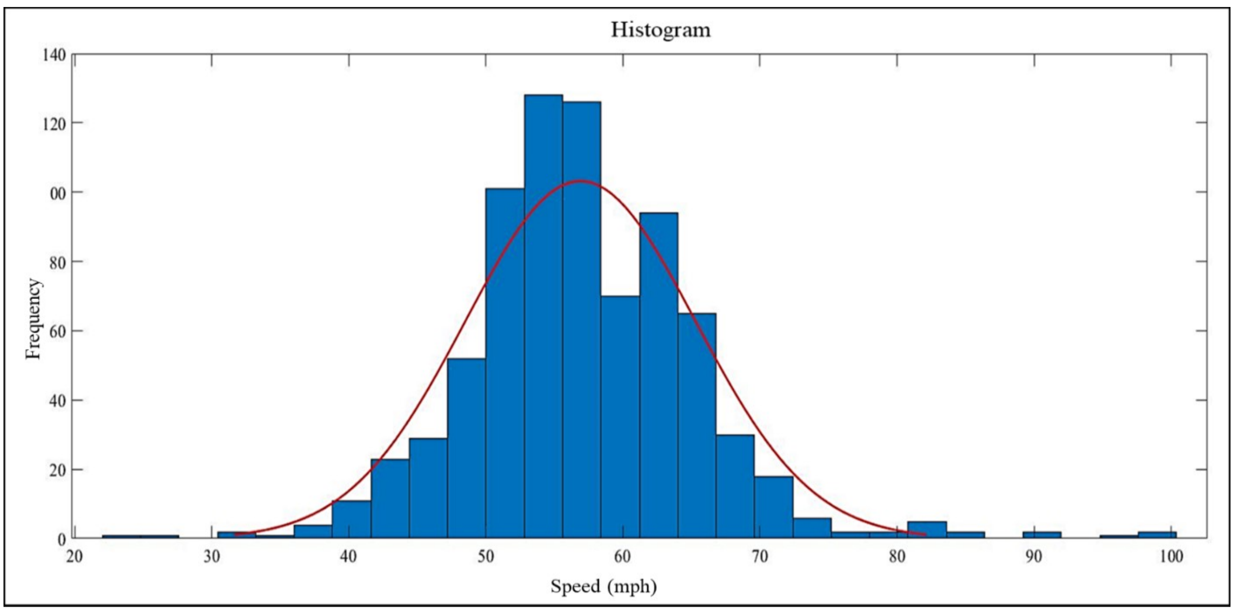

Figure 5.24: Histogram from sensor data at road work ahead sign (Case Study 1)

5.3.2.2 Two Sample t-Test for 250 ft. Interval

To identify statistical significance of the mean speed difference between control (blue lights off) and treatment (blue lights on) days, using the data structuring method described above, two datasets were created individually: one dataset for the control and the other dataset for the treatment. The number of data points in each dataset was not equal; therefore, two sample t-tests were performed. Table 5.2 shows the datasets compared in the analysis. Speed data of two blue lights on days and off days were merged together and compared as control (blue lights off) and treatment (blue lights on). This merging was done based on the assumption that regardless of the date and geometric properties of the roadway, driver behavior is likely to be similar when the drivers see a flashing blue light. A similar assumption was made for the control dataset. The impacts of the geometric properties were minimized manually by selecting control and treatment day work zones from a continuous stretch of road with no abrupt variation of geometric properties. This method provided relatively large datasets for reliable statistical comparison.

Table 5.2: Dataset Comparisons (Case Study 1)

Data Collection Day	Direction of Travel	Blue Lights On/Off	Datasets Compared
1	Northbound	On	Days 1 and 4 combined vs. Days 2 and 3 combined
2	Northbound	Off	
3	Northbound	Off	
4	Northbound	On	

Table 5.3 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 158 data points (N), meaning that 158 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 1,945 data points means that this number of vehicles was recorded by the sensor when the vehicles had already passed the paver and were 250 to 500 ft. downstream of the paver.

Table 5.3: t-Test Summary at 250 ft. Intervals (Case Study 1)

Category	Statistics	Distance Upstream of Paver (before passing paver)				Distance Downstream of Paver (already passed paver)			
		1,000 - 750 ft.	750 - 500 ft.	500 - 250 ft.	250 - 0 ft.	0 - 250 ft.	250 - 500 ft.	500 - 750 ft.	750 - 1,000 ft.
Blue Lights Off	N	158	510	640	326	642	1945	474	514
	Average speed	45.0	45.5	36.7	28.8	31.0	38.9	39.0	49.3
	Standard Deviation	18.5	11.2	13.4	10.5	8.9	11.8	11.0	12.2
	Minimum speed	11.8	1.8	3.2	1.2	10.4	5.1	17.2	8.4
	Maximum speed	81.2	87.1	89.2	69.4	81.4	101.2	84.2	87.2
	85^{th} percentile speed	64.2	56.2	51.2	39.0	39.2	51.9	50.4	61.2
Blue Lights On	N	235	579	658	1097	587	1568	1264	1764
	Average speed	40.0	32.6	39.2	30.5	32.1	24.6	35.3	33.4
	Standard Deviation	12.2	12.8	14.0	11.8	13.3	11.9	16.2	18.2
	Minimum speed	13.2	7.2	6.0	9.8	3.7	7.8	1.2	13.2
	Maximum speed	87.0	104.2	83.2	76.8	72.2	96.8	104.2	109.2
	85^{th} percentile speed	52.1	43.2	54.2	43.0	48.2	35.0	54.2	54.2
Comparison	Difference in mean speed (Off-On)	5.0	12.9	-2.6	-1.7	-1.1	14.3	3.6	16.0
	t-Stat	3.238	16.120	-3.361	-2.121	-1.673	35.709	4.505	18.723
	p-Value	0.001	0.000	0.001	0.034	0.095	0.000	0.000	0.000

From this table, it can be observed that while approaching the paver, and after passing by the paver, on days with the blue lights off the mean of the recorded speed values was higher than the mean speed on the days with the blue lights turned on for all intervals except 0-500 ft. upstream and 0-250 ft. downstream of the paver. These differences were statistically significant (p-value < 0.05). However, closer to the paver (0-500 ft. upstream and 0-250 ft. downstream), some differences indicate that on blue lights “on” days, speed was recorded to be higher. However, the higher value was found to be statistically significant (p-value < 0.05) in the 0-250 ft. and 250-500 ft. intervals only (Figure 5.25).

Based on the results, it appears that when a vehicle is 1,000 ft. upstream of the paver, the driver observes the paver with flashing blue lights on and slows down. But, once the driver comprehends that the blue lights are not on a law enforcement or emergency vehicle, the driver speeds up slightly until they pass the paver. Then, shortly after passing the paver, their behavior is normalized and a low average speed is recorded again. However, for the majority of the intervals, at 95% level of confidence, the reductions in mean speed associated with the blue lights turned on were found to be statistically significant.

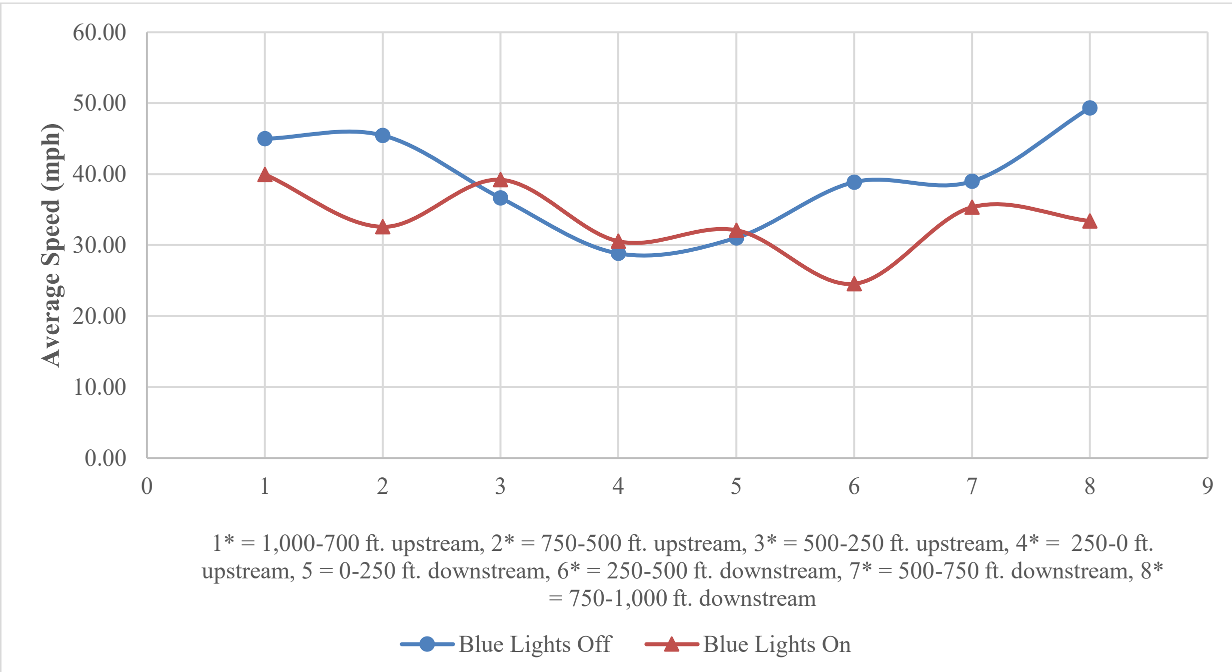

Figure 5.25: Speed distribution across the work zone at 250 ft. intervals (Case Study 1) (* p-value < 0.05)

5.3.2.3 Two Sample t-Test for 500 ft. Interval

As further investigation, the same two datasets were used to compare control and treatment based on 500 ft. intervals. The longer interval normalized that dataset and revealed the speed relationships shown in Figure 5.26. In the figure, it can be observed that the average speed recorded on days with the blue lights turned on is always lower than on days with the blue lights turned off except for the location closer to and upstream of the paver (500 to 0 ft. interval). At this location, the difference between the two average speeds is so small that no statistical difference could be observed. However, for the other location intervals, statistically significant reductions of speed were recorded on days with the blue lights turned on (Table 5.4).

Table 5.4: t-Test Summary at 500 ft. Intervals (Case Study 1)

Category	Statistics	Distance Upstream of Paver (before passing paver)		Distance Downstream of Paver (already passed paver)	
		1,000 - 500 ft.	500 - 0 ft.	0 - 500 ft.	500 – 1,000 ft.
	N	688	966	2587	988
Blue Lights Off	Average speed	45.4	34.0	36.9	44.4
	Standard Deviation	13.3	13.0	11.6	12.7
	Minimum speed	1.8	1.2	5.1	8.4
	Maximum speed	87.1	89.2	101.2	87.2
	85th percentile speed	51.2	39.0	50.4	61.2
Blue Lights On	N	814	1755	2155	3028
	Average speed	35.4	34.0	26.6	34.2
	Standard Deviation	12.3	13.1	12.8	17.4
	Minimum speed	7.2	6.0	2.4	2.4
	Maximum speed	104.2	83.2	96.8	109.2
	85th percentile speed	54.2	43.0	54.2	54.2
Comparison	Difference in mean speed (Off-On)	10.0	0.0	10.3	10.2
	t-Stat	14.944	0.006	29.136	16.935
	p-Value	0.000	0.995	0.000	0.000

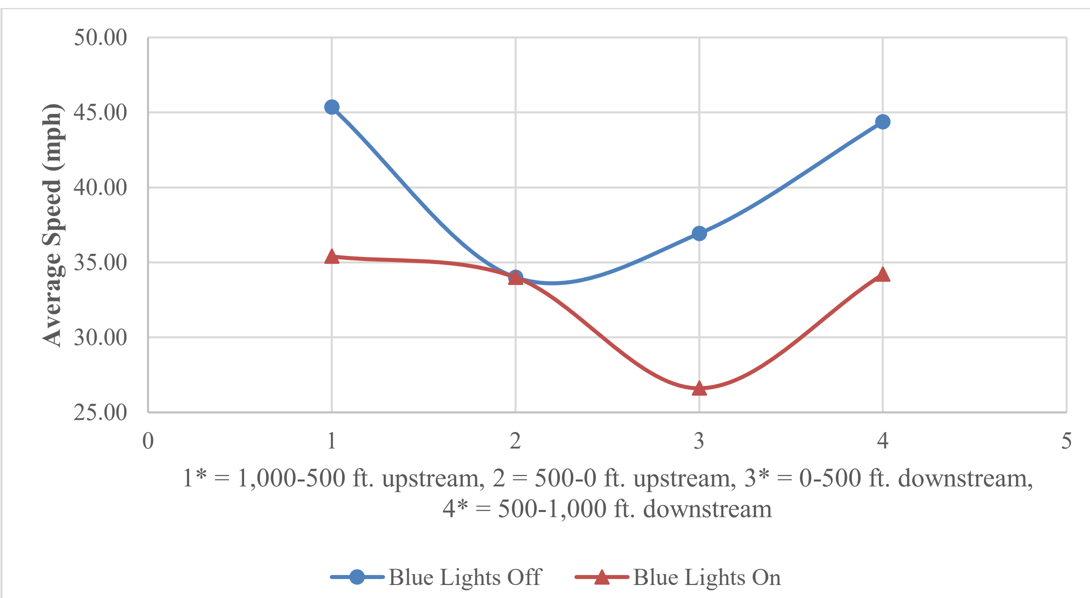

Figure 5.26: Speed distribution across the work zone at 500 ft. intervals (Case Study 1) (* p-value < 0.05)

5.3.2.4 Speed Reduction Analysis

This test was performed to evaluate whether there is a statistically significant difference in speed differential for the control and treatment, particularly between the RWA sign and the first exposure to the paver (at least 1,000 ft. upstream of the paver). In an ideal scenario, this test should be performed in pairs. However, due to the nature of the project location (merge and diverge action) and sensor types, individual vehicles could not be identified. To overcome this obstacle, data points of similar proximity to the paver were combined in one dataset but not repeated (one vehicle was only used once) and a t-Test was performed.

From the Table 5., it can be observed that the mean speed differential with the blue lights off was 29.7 mph. That is, with the blue lights off, the vehicles were travelling on average 29.7 mph slower when located 1,000 ft. upstream of the paver than when located at the RWA sign. Similarly, with the blue lights on, the differential was 32.6 mph. However, no statistically significant difference is observed in speed differential. While there is a difference in mean speed differential with the blue lights on and off, the difference is not statistically significant in this case.

Table 5.5: Speed Reduction Significance Test (Case Study 1)

Blue Light Status	Mean Speed Differential (mph)	N	p-Value	t-Value	Degrees of Freedom	Standard Deviation
Off	29.7	408	0.2092	1.2573	535	16.8
On	32.6	770				

5.3.3 Case Study 2: Grants Pass I

5.3.3.1 Normality Test

Similar normality-superimposed histograms were plotted for Case Study 2 located in Grants Pass. Figure 5.27 shows a sample histogram derived from the first sensor at the RWA sign in the A (fast) lane. From the plot shown in Figure 5.7, it can be observed that data is normally distributed. The distribution is shifted slightly towards the right due to the nature of the lane and location of the sensor relative to the active work area (the average speed is higher than in the work zone).

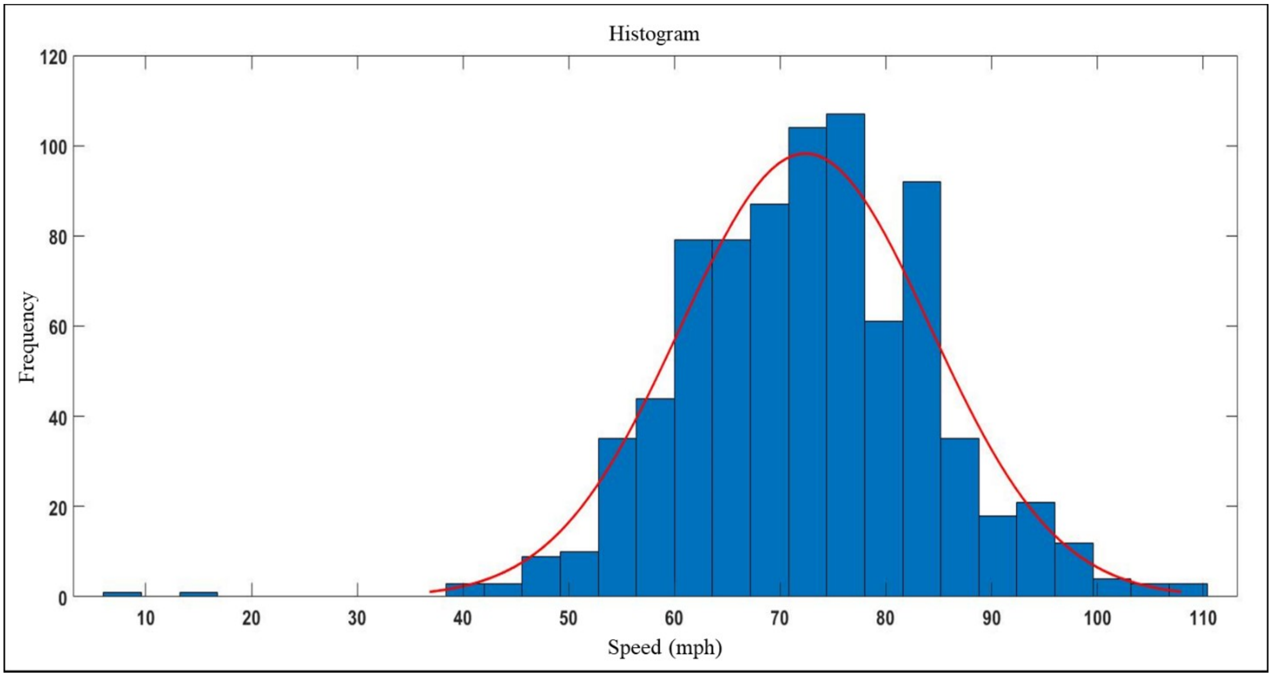

Figure 5.27: Histogram from sensor data at road work ahead sign (Case Study 2)

5.3.3.2 Two Sample t-Test for 250 ft. Interval

As mentioned in the similar section for Case Study 1, control and treatment datasets were merged for two flashing blue lights on days and two off days. It should be noted that for this case study, southbound and northbound speed data were merged based on the assumption that the drivers' reaction to flashing blue lights is independent of the direction of travel as data collection locations were placed on a similar roadway type and located in close proximity to each other. In addition, the nature of the paving operations was consistent from one day to the next. Table 5.6 presents the datasets compared.

Table 5.6: Dataset Comparisons (Case Study 2)

Data Collection Day	Direction of Travel	Blue Lights On/Off	Datasets Compared
1	Southbound	Off	Days 1 and 3 combined vs. Days 2 and 4 combined
2	Northbound	On	
3	Northbound	Off	
4	Northbound	On	

Case Study 2 showed consistent results from 750 ft. upstream to 750 ft. downstream of the paver. In this range, vehicle speeds for the control days were found to be higher than for the treatment days. Statistically significant differences were found for most of the intervals other than the 500 to 250 ft. range upstream of the paver (Table 5.7). However, the first and last two ranges (1,000 to 750 ft. upstream and downstream) showed opposite results (Figure 5.28). At a statistically significant level, days with the blue lights turned on showed higher average speed than days with the blue lights turned off. As presented previously, this roadway section has several tight horizontal curves. Based on the location of the paver on the roadway, at multiple locations the paver may not be visible to drivers while the vehicles are at longer distances upstream of the paver. Therefore, the analysis based on 250 ft. intervals is likely more accurate than the analysis based on the 500 ft. intervals.

Table 5.7: t-Test Summary at 250 ft. Intervals (Case Study 2)

Category	Statistics	Distance Upstream of Paver (before passing paver)				Distance Downstream of Paver (already passed paver)			
		1,000 - 750 ft.	750 - 500 ft.	500 - 250 ft.	250 - 0 ft.	0 - 250 ft.	250 - 500 ft.	500 - 750 ft.	750 - 1,000 ft.
Blue Lights Off	N	152	425	225	141	155	224	334	274
	Average speed	42.2	45.1	41.3	42.4	42.8	39.2	41.8	37.0
	Standard Deviation	7.9	13.5	8.8	11.5	10.9	12.4	9.4	7.8
	Minimum speed	23.2	11.6	13.2	16.1	17.0	10.8	15.5	11.9
	Maximum speed	86.9	91.9	78.1	77.3	93.1	108.3	90.2	75.6
	85th Percentile speed	47.7	58.0	49.4	51.5	51.9	47.1	49.1	43.2
Blue Lights On	N	42	193	156	108	72	181	107	142
	Average speed	44.0	41.2	40.6	36.0	39.3	37.7	37.0	42.8
	Standard Deviation	10.4	8.8	10.9	9.2	10.4	10.4	9.1	12.4
	Minimum speed	25.3	17.9	13.1	18.6	10.8	11.5	17.9	21.4
	Maximum speed	68.5	81.7	85.1	69.2	76.9	67.3	72.7	95.8
	85th Percentile speed	54.3	49.5	52.9	43.8	48.1	48.3	43.8	54.4
Comparison	Difference in mean speed (Off-On)	-1.8	3.9	0.6	6.3	3.6	1.5	4.7	-5.8
	t-Stat	-1.235	3.706	0.611	4.641	2.313	1.323	4.567	5.870
	p-Value	0.218	0.000	0.542	0.000	0.022	0.187	0.000	0.000

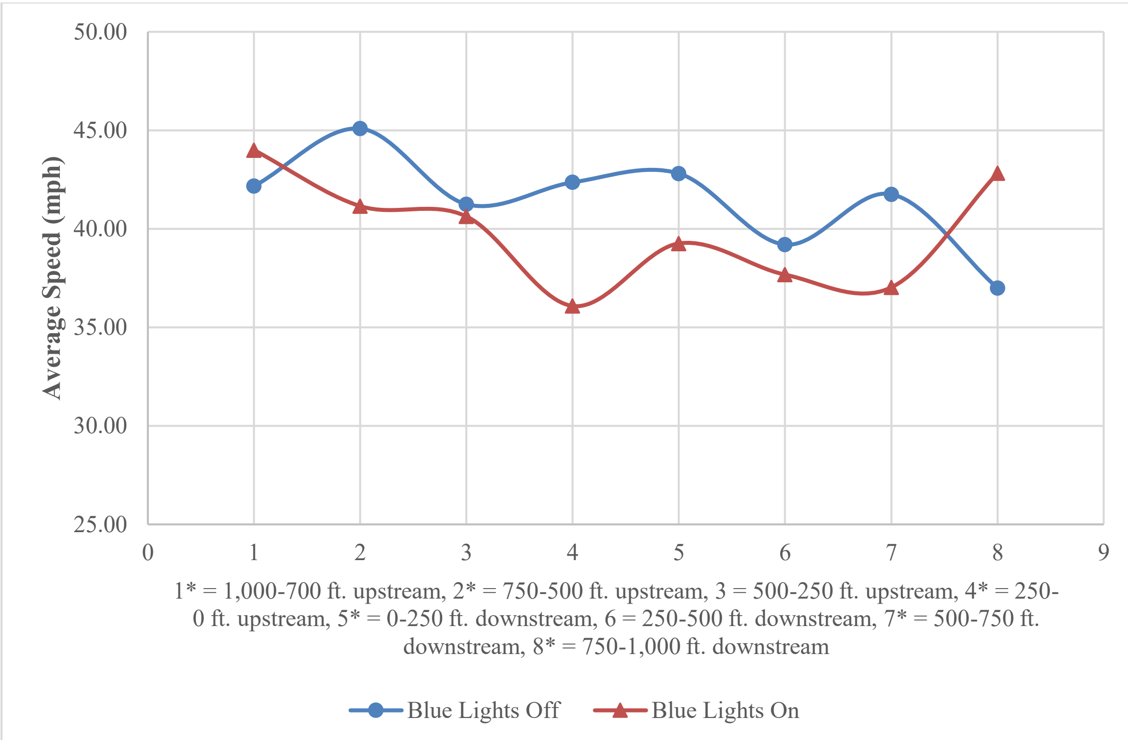

Figure 5.28: Speed distribution across the work zone at 250 ft. intervals (Case Study 2) (* p-value < 0.05)

5.3.3.3 Two Sample t-Test for 500 ft. Interval

To further normalize the effect of the interval, the same analysis was performed with similar assumptions on the dataset and with 500 ft. intervals. The analysis revealed that at all locations other than 500 to 1,000 ft. upstream of the paver, days with the blue lights turned on had statistically significant reductions in speed as seen in Table 5.8. For the last interval location, the difference was reversed; however, this difference was found to be statistically significant as well. After travelling passed the paver, on days with the blue lights turned on (treatment days), the drivers tended to speed up more (Figure 5.29).

Table 5.8: t-Test Summary at 500 ft. Intervals (Case Study 2)

Category	Statistics	Distance Upstream of Paver (before passing paver)		Distance Downstream of Paver (already passed paver)	
		1,000 - 500 ft.	500 - 0 ft.	0 - 500 ft.	500 - 1,000 ft.
Blue Lights Off	N	577	366	379	608
	Average speed	44.3	41.7	40.7	39.6
	Standard Deviation	12.3	9.9	11.9	9.0
	Minimum speed	11.6	13.2	10.8	11.9
	Maximum speed	91.9	78.1	108.3	90.2
	85th Percentile speed	49.4	51.5	49.1	43.2
Blue Lights On	N	235	264	253	249
	Average speed	41.7	38.8	38.1	40.3
	Standard Deviation	9.2	10.	10.4	11.4
	Minimum speed	17.9	13.1	10.8	17.9
	Maximum speed	81.7	85.1	76.9	95.8
	85th Percentile speed	52.9	43.8	43.8	54.4
Comparison	Difference in Mean Speed (Off-On)	2.7	3.0	2.6	-0.7
	t-Stat	0.611	4.641	4.567	-5.870
	p-Value	0.542	0.000	0.000	0.000

5.3.3.4 Headway Sensitivity Analysis

A sensitivity analysis using a 3 second headway rather than a 4 second headway was conducted for this case study. The Appendix contains the results of the sensitivity analysis. The analysis of statistical significance of mean speed difference with flashing blue lights off and on yielded the same results as when a 4 second headway was used.

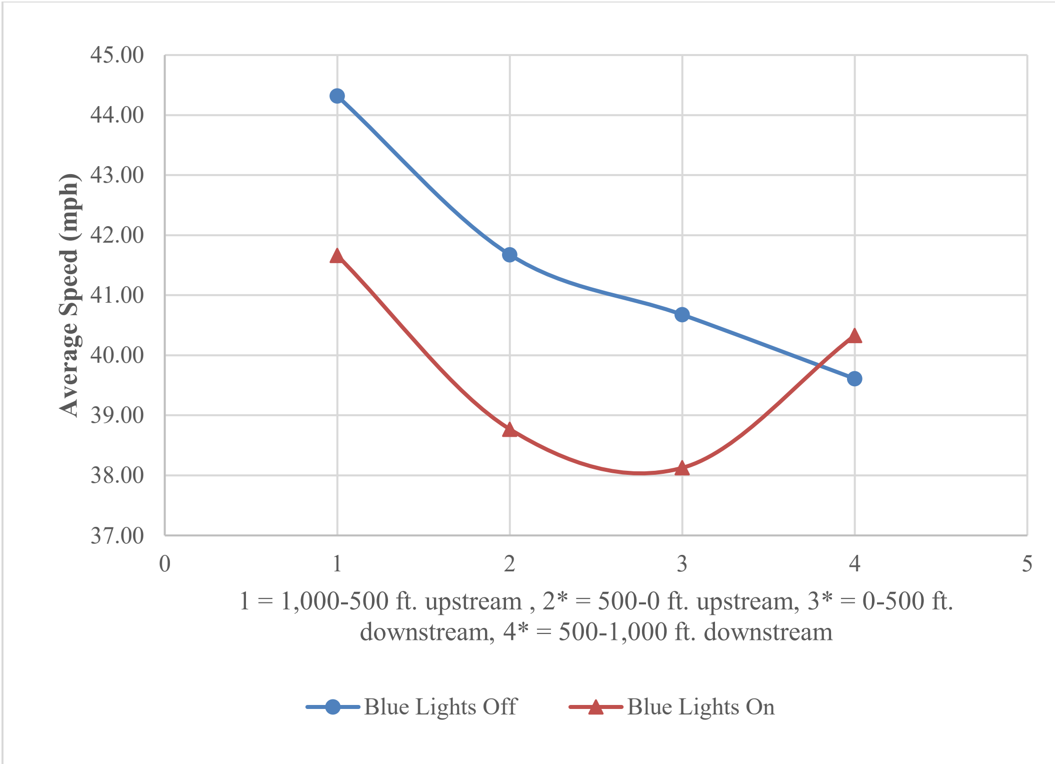

Figure 5.29: Speed distribution across the work zone at 500 ft. intervals (Case Study 2) (* p-Value < 0.05)

5.3.3.5 Speed Reduction Analysis

Similar to Case Study 1, a speed change analysis was performed for Case study 2 using a t-Test. This analysis was performed between speed data of the control and treatment datasets. Differential speed at certain locations referenced to the paver was tested for statistical significance. Table 5.8 summarizes the outcome of the test. From the p-Value, it can be inferred that at a level of confidence of 95%, speed reduction on days with the blue lights turned on was higher than on days with the blue lights turned off.

Table 5.9: Speed Reduction Significance Test (Case Study 2)

Blue Light Status	Mean Speed Differential (mph)	N	p-Value	t-Value	Degrees of Freedom	Standard Deviation
Off	17.1	988	0.000	7.603	3355	17.2
On	25.0	2369				

5.3.4 Case Study 3: Grants Pass II

5.3.4.1 Normality Test

Sensors placed in both lanes at the RWA sign location were tested for normality using a histogram. From the histogram and normal distribution superimposed on it, the assumption of normality was considered satisfied as shown in Figure 5.30.

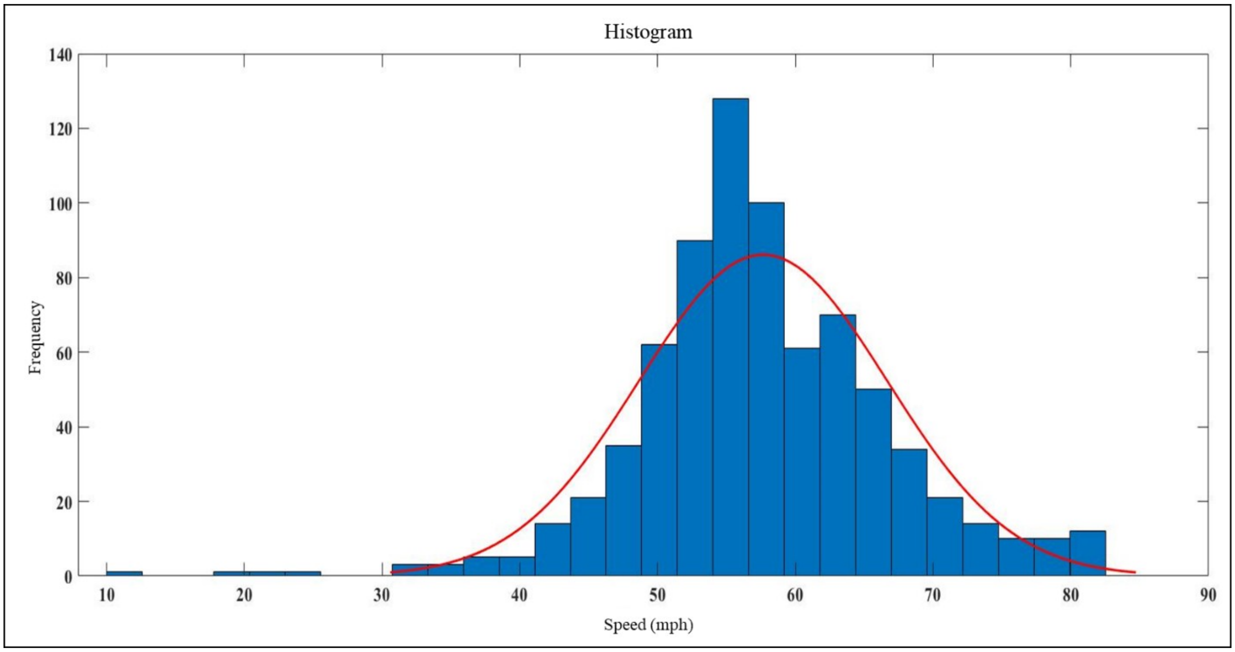

Figure 5.30: Histogram from sensor data at road work ahead sign (Case Study 3)

5.3.4.2 Two Sample t-Test for 250 ft. Interval

As explained for previous case studies, a similar data structure was obtained for the statistical analysis. Table 5.10 presents the datasets compared.

Table 5.10: Dataset Comparisons (Case Study 3)

Data Collection Day	Direction of Travel	Blue Lights On/Off	Datasets Compared
1	Southbound	Off	Days 1 and 3 combined vs. Days 2 and 4 combined
2	Northbound	On	
3	Northbound	Off	
4	Northbound	On	

In Case Study 3, days in which the blue lights were turned off showed a higher recorded average speed across all locations. The differences can be observed in Table 5.11. However, at 1,000 to 750 ft. both upstream and downstream, and 0-250 ft. upstream, even though the differences were higher, the differences were not found to be statistically significant. In the plot shown in Figure 5.31, it can be seen that at close proximity to the paver, drivers did not display highly different behavior in both cases. In addition, with the blue lights on, the rate of increase in vehicle speeds downstream of the paver (already passed paver) appears to be less than with the blue lights off.

Table 5.11: t-Test Summary at 250 ft. Intervals (Case Study 3)

Category	Statistics	Distance Upstream of Paver (before passing paver)				Distance Downstream of Paver (already passed paver)			
		1,000 - 750 ft.	750 - 500 ft.	500 - 250 ft.	250 - 0 ft.	0 - 250 ft.	250 - 500 ft.	500 - 750 ft.	750 - 1,000 ft.
Blue Lights Off	N	130	166	111	127	113	131	394	187
	Average speed	46.6	47.3	44.7	42.1	41.6	41.7	44.9	42.1
	Standard Deviation	9.5	10.0	10.5	11.3	10.8	12.6	12.6	15.1
	Minimum speed	12.6	22.2	24.3	14.7	19.4	13.1	8.4	12.0
	Maximum speed	67.8	80.3	83.6	91.8	66.4	91.2	92.8	101.0
	85th Percentile speed	56.5	55.1	53.3	52.0	53.5	54.6	56.3	55.5
Blue Lights On	N	239	213	258	146	187	295	440	350
	Average speed	45.3	43.5	42.3	41.8	38.1	31.5	39.4	40.4
	Standard Deviation	10.2	8.6	10.6	10.2	10.4	10.2	9.5	12.3
	Minimum speed	22.9	19.5	15.0	21.6	14.7	15.3	16.1	15.4
	Maximum speed	79.1	65.5	86.7	79.3	73.0	72.2	76.2	92.1
	85th Percentile speed	55.7	52.6	52.6	51.6	48.3	43.8	49.7	53.0
Comparison	Difference in mean speed (Off-On)	1.3	3.8	2.4	0.3	3.5	10.2	5.6	1.7
	t-Stat	1.169	3.921	1.989	0.233	2.758	8.821	7.266	1.381
	p-Value	0.243	0.000	0.047	0.816	0.006	0.000	0.000	0.168

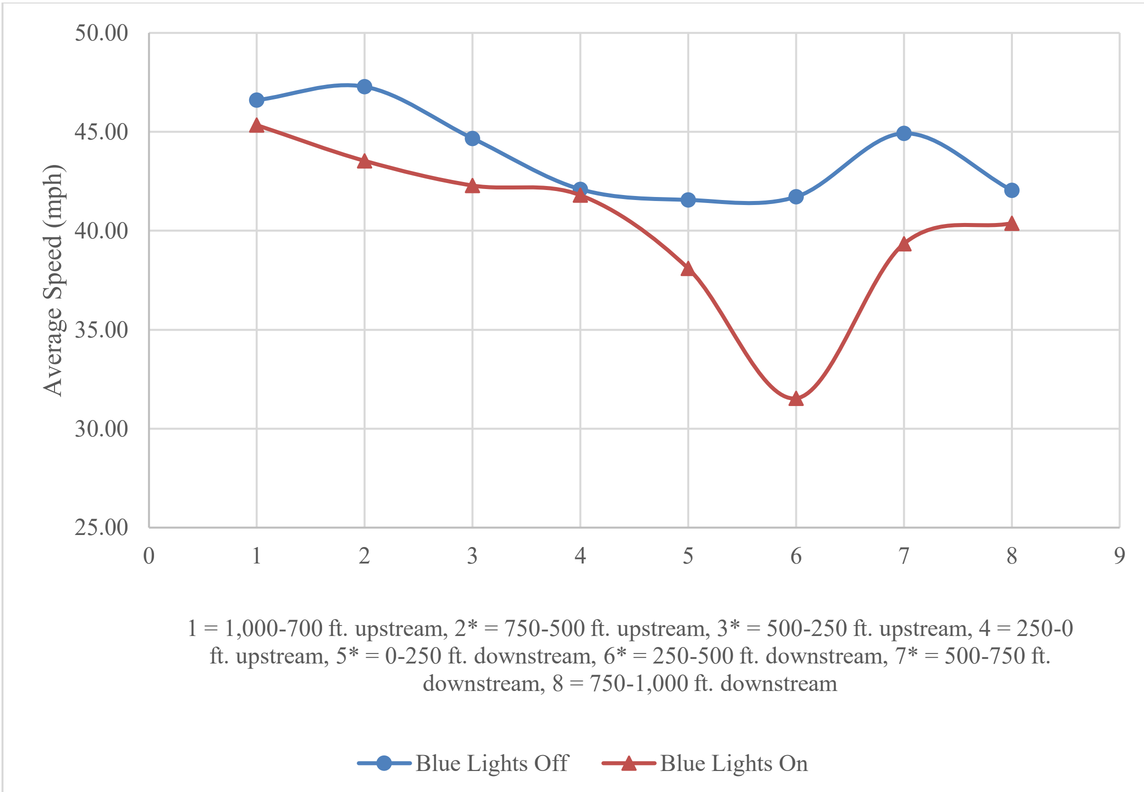

Figure 5.31: Speed distribution across the work zone at 250 ft. intervals (Case Study 3) (* p-value < 0.05)

5.3.4.3 Two Sample t-Test for 500 ft. Interval

The same dataset was used to compare the effect of the blue lights at 500 ft. intervals as shown in Figure 5.32. In this case, the larger distance bins have normalized the end effects and both ends (1,000 – 500 ft. both upstream and downstream) show statistically significant difference in speed; on days with the blue lights turned on the speeds were lower than on days with the blue lights turned off (Table 5.12). However, at the location of the paver, significant difference was not observed for this case study as well.

Table 5.12: t-Test Summary at 500 ft. Intervals (Case Study 3)

Category	Statistics	Distance Upstream of Paver (before passing paver)		Distance Downstream of Paver (already passed paver)	
		1,000 - 500 ft.	500 - 0 ft.	0 - 500 ft.	500 - 1,000 ft.
Blue Lights Off	N	296	238	244	581
	Average speed	47.0	43.3	41.6	44.0
	Standard Deviation	9.7	11.0	11.8	13.5
	Minimum speed	12.6	14.7	13.1	8.4
	Maximum speed	80.3	91.8	91.2	101.0
	85th Percentile speed	53.3	52.0	56.3	55.5
Blue Lights On	N	452	404	482	790
	Average speed	44.5	42.1	34.1	39.8
	Standard Deviation	9.5	10.4	10.7	10.8
	Minimum speed	19.5	15.0	14.7	15.4
	Maximum speed	79.1	86.7	73.0	92.1
	85th Percentile speed	52.6	51.6	49.7	53.0
Comparison	Difference in mean speed (Off-On)	2.5	1.2	7.6	4.2
	t-Stat	3.479	1.369	8.670	6.380
	p-Value	0.001	0.171	0.000	0.000

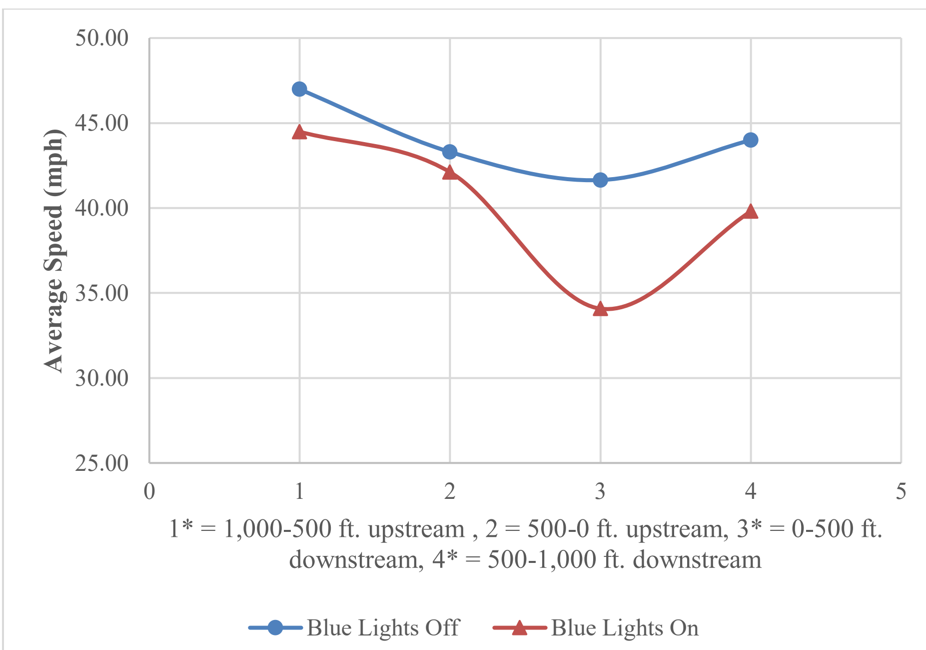

Figure 5.32: Speed distribution across the work zone at 500 ft. intervals (Case Study 3) (* p-value < 0.05)

5.3.4.4 *Speed Reduction Analysis*

For Case Study 3, a similar observation was made regarding the differential in speed between the RWA sign and active work area: the treatment has a statistically significant effect in increasing speed differential between the RWA sign location and within the active work area. Table 5.13 summarizes the outcome for this test. The same data structure that was used in the previous analysis was used for this analysis as well.

Table 5.13: Speed Reduction Significance Test (Case Study 3)

Blue Light Status	Mean Speed Differential (mph)	N	p-Value	t-Value	Degrees of Freedom	Standard Deviation
Off	25.4	408	0.000	29.663	414	15.3
On	32.4	770				

6.0 CONCLUSIONS AND RECCOMENDATIONS

The research study provided an opportunity to investigate the effectiveness of flashing blue lights mounted on construction equipment during mainline paving operations at night 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 are drawn from the analyses of the data collected as well as the literature review, researchers' observations while on the case study sites, and informal, on-site conversations with those involved in the case studies.

The research study focused on three case study projects, each involving paving on Interstate 5 in Oregon. The case study 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 blue lights on the paver used in the nighttime paving operations. Data collection efforts successfully recorded passing vehicle data (speed, length, location, and time) on four separate paving days for each case study, two days with the blue lights on and two days with the blue 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 blue 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. Therefore, this study presents a preliminary assessment of the use of blue lights on pavers as a potential intervention, and only represents an initial investigation to determine if additional analysis is needed. The dynamic nature of the mobile paving operation and the traffic conditions, along with unknowns related to driver behavior (e.g., distractions) and characteristics (e.g., age), 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. However, the results obtained from the present study provide an acceptable initial assessment of the impact of blue lights on vehicle speed that can be used to guide and inform decisions about the use of blue lights and future research. As described above, much of the impact on vehicle speed associated with the dynamic construction operations is controlled for in the mean speed differential analyses and, therefore, the results related to mean speed differential carry a higher level of confidence.

Analyses of the data reveal that vehicle speed is affected by the presence of flashing blue lights. The magnitude of the impact on vehicle speed differed from one case study to another, as anticipated. The magnitude also differed between locations relative to the paver. In general, with the blue lights flashing and at distances upstream of the paver where the driver can see and react to the blue lights, mean vehicle speeds tended to be lower compared to when the blue lights were off. Closer to, immediately adjacent, and downstream of the paver, the amount of reduction in mean speed was sometimes less or none at all with the blue lights on. At some locations, the mean speeds were higher with the blue lights on. These general trends are revealed in the statistical analyses.

Prior work zone studies by ODOT that did not involve the use of flashing blue lights also revealed reductions in speed when adjacent the paver. The amount of reduction measured in the present study is similar to that seen in the prior studies. The analyses conducted in the present study are independent, and not reliant on prior studies. Comparisons are made within a specific case study.

The analyses conducted to evaluate the impact of the blue lights in terms of speed differential clearly show reductions in speed differential with the blue lights on. Speed differential was defined as the difference between the mean speed at the RWA sign and the mean speed at the first exposure to the paver (1,000 ft. upstream of the paver). Mean speed differentials for each day of data collection were calculated. The mean speed differential with the blue lights on was then compared to the speed differential with the blue lights off. The differences in mean speed differential ranged from 3 to 7 mph, and are summarized below:

- Case Study 1:
    - The difference in mean speed differential was found to be approximately 3 mph, with the differential greater with the blue lights <u>on</u> (blue lights off differential = 29.7 mph, and blue lights on differential = 32.6 mph).
    - However, <u>no</u> statistically significant difference was found between the speed differentials.
- Case Study 2:
    - The difference in mean speed differential was found to be approximately 7 mph, with the differential greater with the blue lights <u>on</u> (blue lights off differential = 17.1 mph, and blue lights on differential = 25.0 mph).
    - The speed differential was found to be statistically significant.
- Case Study 3:
    - The difference in mean speed differential was found to be approximately 7 mph, with the differential greater with the blue lights <u>on</u> (blue lights off differential = 25.4 mph, and blue lights on differential = 32.4 mph)
    - The speed differential was found to be statistically significant.

Additional analyses were conducted with respect to the speeds within the active work area. Analyses were conducted at various distances from the paver at 250 ft. and 500 ft. intervals up to 1,000 ft. as depicted in Figures 5.16 and 5.17. For the 250 ft. intervals between 1,000 ft. upstream and 1,000 ft. downstream of the paver, mean speeds ranged as follows for the different case studies:

- Case Study 1: Hassalo, Portland:
  - Mean speed ranged from 28.8 to 49.3 mph with the blue lights off, and from 24.6 to 40.0 mph with the blue lights on.
- Case Study 2: Grants Pass I:
  - Mean speed ranged from 37.0 to 45.1 mph with the blue lights off, and from 36.0 to 44.0 mph with the blue lights on.
- Case Study 3: Grants Pass II:
  - Mean speed ranged from 41.6 to 47.3 mph with the blue lights off, and from 31.5 to 45.3 mph with the blue lights on.

The quantitative analyses of the speed data on each case study revealed the following statistically significant impacts on vehicle speed when considering speeds in 250 ft. intervals within 1,000 ft. both upstream and downstream of the paver:

- Case Study 1: Hassalo, Portland
  - Mean vehicle speeds with the blue lights on ranged from 3.6 to 15.95 mph slower at locations greater than 500 ft. upstream of the paver and greater than 250 ft. downstream of the paver.
  - Mean vehicle speeds with the blue lights on ranged from 2.7 to 2.6 mph faster at locations between 0 and 500 ft. upstream of the paver.
- Case Study 2: Grants Pass I
  - Mean vehicle speeds with the blue lights on ranged from 3.6 to 4.7 mph slower 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.
  - Mean vehicle speeds with the blue lights on ranged from 2.7 to 2.6 mph faster at locations between 750 and 1,000 ft. downstream of the paver.
- Case Study 3: Grants Pass II
  - Mean vehicle speeds with the blue lights on ranged from 2.4 to 10.2 mph slower at the following locations: 250-750 ft. upstream of the paver, and 0-750 ft. downstream of the paver.
  - No locations relative to the paver were found to have mean vehicle speeds faster with the blue lights on.

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. In addition, while some differences in mean speeds may have been found to be statistically significant, the practical difference may be minimal. That is, a difference (either increase or decrease) in mean speed of 3 mph or less, for example, may not be noticeable to workers in the work zone and may not result in any difference in the frequency and/or severity of crashes. 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 blue lights on vehicle speeds. However, given the limitations of the study and additional questions of interest, further research is recommended to capture the impacts of the blue lights with greater confidence and comprehensively. In addition, it should be noted that the current use of blue lights is permitted under interim guidance from the ODOT Chief Engineer, and that the State's need for additional research will depend in part on the regulatory context for future use of blue lights.

If further research is conducted, it is recommended that the research explore additional options associated with the blue lights. The following are recommended topics for additional research on the topic:

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

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

- 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 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.

- Temporal investigation to evaluate if the impact of the intervention changes over time (i.e., whether the amount of reduction in vehicle speed decreases as drivers become more used to seeing the blue lights in work zones).

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 blue lights in a laboratory setting where variables can be controlled and alternative designs can be safely tested.

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APPENDIX

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.

Sensitivity Analysis Results (Case Study 2: Grants Pass I)

Category	Statistics	Distance Upstream of Paver (before passing paver)				Distance Downstream of Paver (already passed paver)			
		1,000 - 750 ft.	750 - 500 ft.	500 - 250 ft.	250 - 0 ft.	0 - 250 ft.	250 - 500 ft.	500 - 750 ft.	750 - 1,000 ft.
Blue Lights Off	N	201	437	251	145	167	231	341	285
	Average speed	43.4	42.0	40.1	42.7	43.0	39.7	42.0	38.0
	Standard Deviation	8.1	14.0	9.3	12.3	9.9	12.1	9.3	8.0
	Minimum speed	23.2	11.6	19.4	16.1	24.5	15.5	15.5	18.3
	Maximum speed	66.8	78.1	75.6	75.1	79.6	83.3	82.0	55.5
	85th Percentile speed	49.7	47.9	49.4	51.9	53.5	47.8	49.1	45.5
Blue Lights On	N	97	201	207	152	83	191	131	145
	Average speed	46.5	35.8	39.0	34.5	37.7	37.8	36.3	40.6
	Standard Deviation	11.1	8.1	8.1	9.3	8.5	9.4	11.3	13.0
	Minimum speed	25.2	26.2	13.1	18.6	10.8	11.5	17.9	21.4
	Maximum speed	68.5	64.9	60.7	60.0	52.9	67.3	69.5	76.9
	85th Percentile speed	56.4	50.4	46.3	43.4	46.8	48.4	47.3	55.1
Comparison	Difference in mean speed (Off-On)	-3.150	6.142	1.083	8.166	5.295	1.946	5.697	-2.593
	t-Stat	-1.437	3.795	0.797	4.219	3.078	1.111	2.976	-2.474
	p-Value	0.154	0.000	0.427	0.000	0.003	0.268	0.003	0.014