IMPLEMENTING SPEED REDUCTIONS AT SPECIFIC INTERSTATE WORKZONES FROM 65 MPH TO 35 MPH

Final Report

SPR 751

Oregon Department of Transportation

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16. Abstract

Interstate preservation projects are commonly conducted at night and often require working in close proximity to ongoing traffic. Vehicle speed and speed variability in work zones is inextricably connected to the work zone design and the selected traffic control devices. To provide guidance on how to effectively and efficiently reduce traffic speeds, the Oregon Department of Transportation conducted a research study to investigate the impact of selected traffic control devices on vehicle speed within highway paving project work zones. The research centered around two case studies on multi-lane paving projects in Oregon. On each case study, the researchers implemented multiple traffic control devices (PCMS signs, radar speed display, police officer presence, tubular markers and drums on both sides of travel lane) and evaluated their impact on vehicle speed, construction productivity, cost, and motorist and worker safety. A police officer parked on the site was found to effectively reduce traffic speeds and should be used if available and feasible. The research findings also suggest using a combination of temporary reduced speed limit signs, radar speed monitoring display, and PCMS signs on both trailers and rollers. Further research is needed to validate the research findings and better identify the advantages of one traffic control device over another.

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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
		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

NOTE: Volumes greater than 1000 L shall be shown in m^3.

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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DISCLAIMER

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 construction work zones, especially Gregory A. Priest of Salem, OR, who was hit and killed by a car driven by a drunk driver while working as a Traffic Control Supervisor to install safety flags on warning signs in a construction work zone during the course of this study. Our work is dedicated to their lives and to preventing additional worker and motorist injuries and fatalities in the future.

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1.0 INTRODUCTION

1.1 BACKGROUND

Roadway interstate pavement preservation projects (e.g. pavement overlays, "chip seal" operations, etc.) typically require construction workers to conduct their work in close proximity to ongoing traffic. Pavement preservation projects commonly reduce traffic flow to a single lane while work is undertaken in an adjacent lane. During the lane closures, the paving operations place workers on the roadway within a protected work zone. In some places the workers only have a line of cones and a few feet, separating them from passing traffic. This situation creates considerable safety risk for both the workers and passing motorists. Inattentive or speeding drivers, careless workers, misplaced cones, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities. The severity of a crash intensifies as the speed of traffic increases. As a result, preservation projects on high-speed roadways present an increased risk of serious and/or fatal injuries to workers, motorists, and their passengers.

Vehicle speed is directly connected to the performance of work zone designs. There is a widely held perception that speed is one of the most significant factors in road crashes *(Mahoney et al. 2007)*. However, safely controlling and reducing vehicle speeds through work zones to reduce the risk can be difficult on high-speed roadways. On such roadways, it has been suggested that reducing traffic speeds to 35 mph would enhance the safety of the workers and traveling public. However, a reduction in speed from 65 mph to 35 mph is significant, and evaluation of the impacts of this differential in speed on interstate highways has been limited to only a few case studies as examples (one recently in Oregon). Additional safety measures in planning, signage, and notification to the driving public are needed to reduce the significant risks to motorists as they navigate through the active work zone and react to the large difference in speed. In addition, large speed reductions during nighttime work – a time when preservation projects are often conducted – can complicate the situation more, be difficult to implement, and may increase safety risks. Current speed reduction and traffic calming methods under these conditions may be adequate, however since there are only a few case studies available to draw from, it is difficult to identify the best traffic control measures to use in such situations.

Previous research reveals that work zone speed limit reductions of more than 10 mph show an increase in the number of crashes due to a greater speed differential between vehicles *(WSDOT 2009)*. In response to concerns from the Associated General Contractors Oregon-Columbia Chapter and the Oregon Trucking Association about speed through work zones, the ODOT Traffic Roadway Section requested that ODOT Research investigate interstate preservation job safety enhancements. The request, made in the summer of 2011, was to assess the practicality and effectiveness of reducing speeds from 55-65 mph to 35 mph under these specific conditions.

As an initial step, ODOT conducted a pilot study in September 2011 to investigate practical and safe means for significant speed reductions. The pilot study was conducted on Interstate 5 near Cottage Grove, OR. The traffic control plan included a 30 mph speed reduction from 65 to 35 mph implemented in two stages (65 to 50 mph, then 50 to 35 mph) using multiple OSP officers and other traffic control measures along the roadway prior to and within the work area. This strategy is similar to the use of a system of stepped speed limits (SSL) that was recently studied and recommended in the United Kingdom (*ITS International 2011*). On the pilot study, with law enforcement vehicles visible to passing motorists, passenger vehicle speed measurements through the work zone showed a mean speed of 33.0 mph for cars (n = 108 vehicles; 85th percentile speed = 36 mph; 22% of cars exceeding posted speed). For trucks, the mean speed was 33.23 mph (n = 145 vehicles; 85th percentile speed = 36 mph; 19% of trucks exceeding posted speed).

Current research on controlling and reducing speeds on high-speed roadways, and on significant speed reductions, provides limited guidance for practical implementation. In a study of speed reduction measures conducted by Iowa State University on behalf of the Iowa Department of Transportation, the authors state that the most effective speed reduction will probably involve some combination of speed reduction techniques, as opposed to the use of just one type of control measure *(Maze et al. 2000)*. The researchers in Iowa conducted a survey of state transportation agencies and found that only a few agencies even consider reducing speed limits by 20 mph or more. The study also revealed that the use of regulatory speed limit signs and police enforcement is the most common practice for controlling and reducing speeds.

Due to the limited nature of the pilot study conducted by ODOT and the gap in current literature, further study is desired by ODOT. ODOT would like to study possible strategies to safely reduce speeds and subsequently improve the overall safety of the work zone – for drivers, passengers, and workers. The research presented in this report is intended to augment the pilot study and provide additional data necessary to confidently make practical conclusions and recommendations to ODOT for achieving significant speed reductions on highway pavement preservation projects.

1.2 RESEARCH OBJECTIVES AND METHODS

The overall goal of the research is to assist ODOT with enhancing the safety of motorists and workers in construction work zones on high-speed roadways. To do so, the research aims to examine the reasonableness, practicality, and ability to reduce traffic speeds through specific pavement preservation project work zones by as much as 30 mph, and if such speed reductions are found to be acceptable and practicable, to develop guidance for implementing significant speed reductions through targeted engineering practices. Work zone design guidelines, such as the *Manual on Uniform Traffic Control Devices* (MUTCD) and the *ODOT Traffic Control Plans Design Manual*, have been developed that guide the design and implementation of the wide variety of available traffic control devices. Using this knowledge and the results of the pilot study as a starting point, the research attempts to identify those traffic control practices and designs that are especially effective at reducing speeds by a significant amount and that are also cost effective, safe to implement, not disruptive to the construction work, and not a significant impediment to traffic flow.

The specific objectives for this research study are to:

1. Evaluate the traffic control methods and findings of the initial pilot study conducted in September 2011.

2. Identify traffic control measures that could potentially control speed variability and reduce vehicle speeds through highway preservation project work zones by as much as 30 mph.

3. Implement selected traffic control measures on highway preservation projects. Compare the performance of the identified traffic control measures with traditional traffic control measures based on their ability to lower speeds a significant amount, ability to minimize speed variability, and their ease of use and cost.

4. Develop guidance for ODOT and construction contractors to reference when planning and implementing traffic control measures on highway preservation projects.

The research focuses on effective means to reduce actual speeds in work zones. The initial focus of the research was to effectively reduce the speeds to 35 mph (i.e., 30 mph reduction from 65 mph to 35 mph) through the combination of posted speed reductions to 35 mph and selected traffic control measures. As part of the development of the research plan in consultation with the ODOT Technical Advisory Committee (TAC) for the study, the research focus shifted to identifying means to reduce vehicle speeds below a posted 15 mph speed reduction. That is, if the posted speed is reduced to 50 mph (15 mph reduction), how can the actual speeds be lowered below 50 mph through the application of additional traffic control measures without posting a lower speed limit. This includes methods to safely reduce legal posted speeds as well as finding measures that reduce actual speed without relying on a further posted speed reduction. Research products may include advanced traffic control plans and guidelines for police activities under these conditions.

The most significant benefit of the research is expected to be a means for ODOT to further improve the safety of highway workers and the traveling public during preservation project operations. It is ODOT's responsibility to provide a safe environment for highway workers and the driving public, and this research takes an incremental step towards enabling further improvement. In addition, successful completion of the research and implementation of the research results is expected to strengthen ODOT's partnerships with the AGC Oregon-Columbia Chapter and the Oregon Trucking Association.

Table 1.1 shows the planned tasks that are undertaken to conduct the entire study.

Table 1.1: Research Tasks

ID	Research Tasks
1	**Research Study Initiation and Literature Review** Task 1 involves reviewing existing literature to gather information related to recommended methods for reducing vehicle speeds in work zones on high-speed roadways. The literature review includes: • Documenting the suggested traffic control measures and practices along with any identified limitations and drawbacks. • Documenting the nature and extent of typical preservation projects undertaken in Oregon, the work practices and procedures typically carried out on preservation projects, and the typical traffic control measures and work zone designs implemented on preservation projects. In addition, this task includes identifying case study projects for application of the identified traffic control measures for high speed reduction. The research plan includes targeting 2 - 3 case study projects for the research. If available, additional case study projects on which the identified traffic control measures are not implemented are selected and used as comparison projects.
2	**Review and Evaluate Pilot Study Results** Task 2 involves an in-depth examination of the findings from the pilot study conducted in 2011 on a preservation project on Interstate 5 near Cottage Grove, OR. This task includes collecting recorded data from the study to determine the impacts of the measures taken. Also, a survey and/or interviews of those involved in the study (including contractors), and those ODOT personnel who are familiar with traffic control design, is planned to gather their perspectives of the barriers, enablers, and impacts of the speed reduction measures implemented along with recommendations for future practice.
3	**Identification of Potential Traffic Handling Measures, Work Zone Design, and Implementation Practices** For Task 3, the research team develops initial recommendations for significantly reducing speeds through work zones based on the results of Tasks 1 and 2. The research team presents these recommendations to the TAC for review and input, and to identify those traffic control measures and practices to deploy and evaluate on the case study projects.
4	**Case Study Application and Monitoring** Task 4 involves implementing and monitoring the selected traffic control measures on the case study projects. The researchers work with ODOT, OSP, and the construction contractors to implement the traffic control measures and monitor their impact on the work zones and traffic. The timing and location of implementation depends on the selected case study projects. Data collection includes recording performance relative to the following metrics: time, cost, and resources required to implement the traffic control measures; limitations/barriers to implementing the measures; vehicle speeds and volumes through the work zone; speed variability through the work zone; construction worker safety, safety perception, and productivity; and motorist safety. In addition, the researchers document the ability to implement the traffic control measures based on project and site attributes (e.g., size, location, type of roadway, etc.).
5	**Data Analysis and Evaluation** The data collected from the case study projects is analyzed to determine the impacts of the applied traffic control measures and their viability on future projects. The evaluation is based on the performance metrics listed above in Task 4. The results relative to each performance metric are aggregated to determine the overall performance of the implemented traffic control measures. Comparisons are made between the case study projects and comparison projects (if available) to evaluate the benefits and impacts provided by the implemented traffic control measures.
6	**Final Research Report** Prepare and submit a draft report to ODOT for review and comment. Revise the draft report based on comments received, and submit a final report for publication. If appropriate, develop a guidance document for inclusion in the final report with recommendations for ODOT's use of the identified traffic control measures.

1.3 IMPLEMENTATION

It is expected that the outcomes of this research study will be implemented by the ODOT Traffic and Roadway Engineering Section through procedures outlined for the Region Tech Centers by the State Traffic-Roadway Engineer. The outcomes will also be implemented by the Statewide Construction Office on similar preservation projects through communication and education of the Statewide Construction Project Managers as approved by the Statewide Construction and Materials Engineer. The results will be used by the Transportation Safety Division through the request of police agencies participating in these types of projects and by the Region Transportation Safety Coordinators in each Region through contact with the police agencies providing enforcement efforts.

2.0 LITERATURE REVIEW

2.1 AGENCY DESIGN MANUALS

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

2.1.1 ODOT Traffic Control Plans Design Manual

The ODOT Traffic Control Plans Design Manual provides an organized collection of traffic control plan design standards, guidelines, policies, and procedures to be used in the development of a Temporary Traffic Control Plan (*ODOT 2011*). This manual includes an introduction to Traffic Control Plans (TCP), a list of temporary traffic control devices (TCD), descriptions of traffic control measures (TCM), standard specifications and drawings, traffic control plans designs, and traffic control cost estimating.

Traffic Control Plan:
The principal function of a TCP is to provide safe an efficient movement of road users through or around work zones while protecting workers, incident responders, and equipment. In addition, the TCP is intended to provide for the efficient construction and maintenance of the highway (*ODOT 2011*). Safety is the primary concern in designing a traffic control plan. ODOT uses the guidance of the Manual on Uniform Traffic Control Devices (MUTCD) in the design of TCPs. Mandates within the Oregon Administrative Rules and the Oregon Revised Statutes require the use of the MUTCD as the reference for the specifications of uniform standards for traffic control devices for use upon highways within this state (*ODOT 2011*).

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

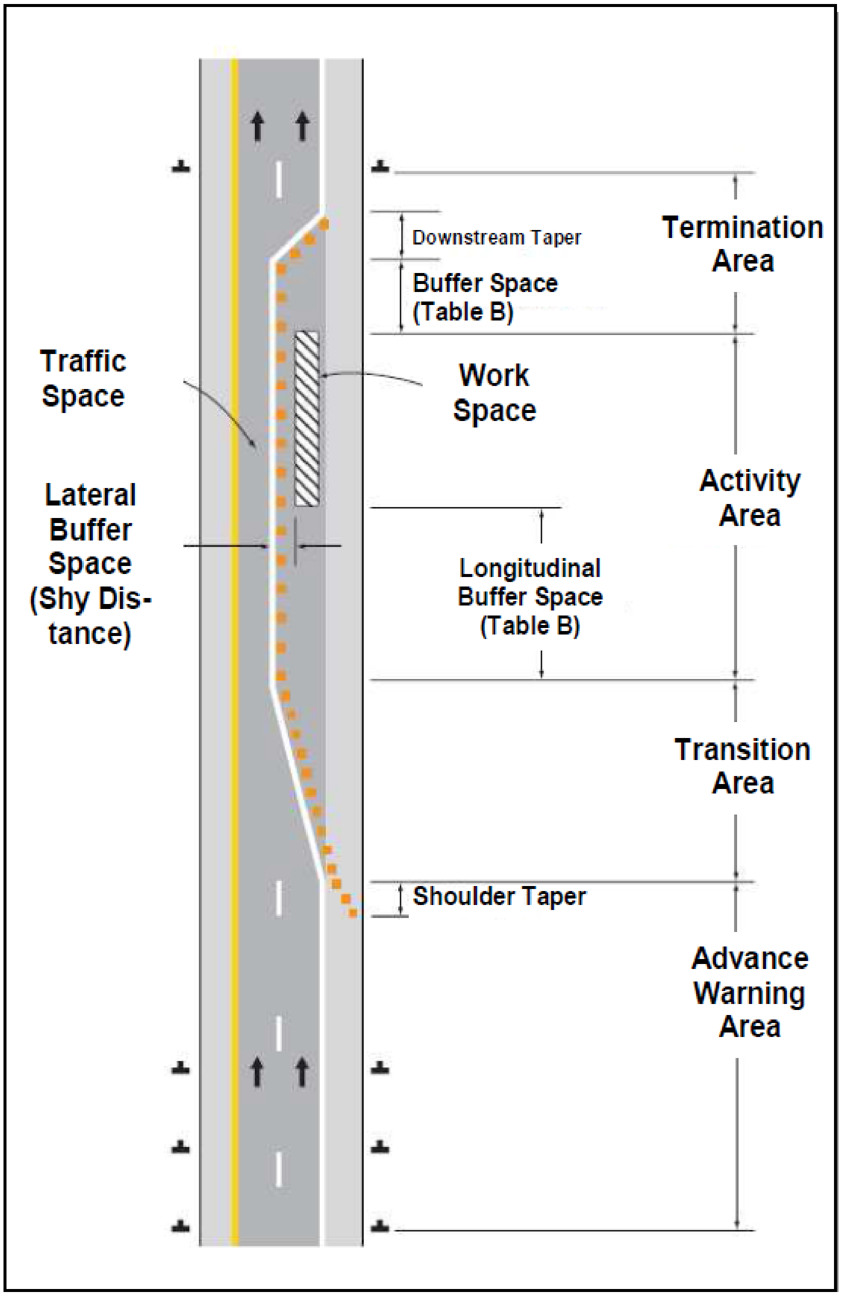

Figure 2.1: Four Areas in a Work Zone (*ODOT 2011*)

Device Spacing:

Spacing between traffic control devices is needed in order to all for motorists to see and comprehend the devices at the traveling speed. If the spacing between devices is small, drivers may not have sufficient time to comprehend and react to the signs. For high speed roadways, the required spacing of channelization devices is 40 feet. For temporary signing, spacing is speed-dependent as well. Spacing dimensions, 'A', 'B' and 'C' are defined in Table 2.1, where dimension A represents the distance between the beginning of taper and the 1st warning sign, B represents the distance between the 1st warning sign and the 2nd warning sign, and C represents the distance between the 2nd warning sign and the 3rd warning sign.

Table 2.1: Traffic Control Devices Spacing (*ODOT 2011*)

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

Traffic Control Devices:
Traffic control devices are used to regulate and guide the traffic and warn the drivers so that a safe and efficient environment will be provided for both construction workers and motorists. The five principles of setting up traffic control devices are to: 1) fulfill a need, 2) command attention, 3) convey a clear and simple meaning, 4) command respect from the road user, and 5) give adequate response time (*ODOT, 2011*). FHWA policy requires all TCDs used in a work zone on the National Highway System to be crashworthy. For a TCD to be crashworthy, it must meet the established testing and evaluation criteria of the AASHTO Manual for Assessing Safety Hardware (MASH). Work zone traffic control devices are classified into the following four categories (*ODOT 2011*):

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

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

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

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

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

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

Figure 2.2: Tubular Markers on Roadway

Temporary Plastic Drums – Plastic drums (barrels) are the largest, most visible deformable channelization devices. Plastic drums are usually used to delineate travel lanes, identify work areas, construct lane closure tapers, and delineate portable changeable message sign (PCMS) and temporary traffic signal installations (*ODOT 2011*).

Figure 2.3 shows plastic drums in use on a roadway.

Figure 2.3: Plastic Drums on Roadway

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

Figure 2.4: Type III Barricade (*ODOT 2011*)

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

Figure 2.5: Examples of Temporary Signs (*ODOT 2011*)

Temporary Sign Support (TSS) – A temporary sign support may be needed to temporarily support a sign when no permanent support options are available.

A temporary sign support can be used under any of the following conditions:

- A sign is to be located on existing pavement surface in the roadway
- Roadside ground is too hard or too soft to make the installation of a post practical
- A sign is expected to move several times over the life of the project
- A sign is in place for a short duration
- The location of the sign conflicts with utility locations

If a TSS is exposed to live traffic, and not behind a guardrail or concrete barrier or removed a substantial distance from the roadway, the TSS must be delineated by placing a Type III barricade in front of it (*ODOT 2011*).

Portable Sign Support (PSS) – A portable sign support is used to mount a roll-up sign for short-term or intermittent work. A PSS is only to be installed for a maximum of 48 consecutive hours according to ODOT construction contracts. If the sign is needed for a longer period of time, the sign should be installed on a TSS or post. A PSS should be removed when workers are not present. Figure 2.6 shows an example of potable sign support supporting a regulatory speed sign.

Figure 2.6: Portable Sign Support

Concrete Barrier Sign Support – Concrete barrier sign supports are used to install temporary signs on concrete barrier where space for a TSS or post-mounted sign is not available. The support provides a connection directly to the top of the concrete barrier. Figure 2.7 shows an example of a concrete barrier sign support.

Figure 2.7: Concrete Barrier Sign Support (*ODOT 2011*)

Temporary Impact Attenuators – Temporary impact attenuators, also called crash cushions, are crashworthy systems that mitigate the effects of errant vehicles that strike obstacles. When struck by a vehicle, the impact attenuator is designed to lessen the impact of the crash on the traveling vehicle and on the supporting structure. A truck mounted attenuator (TMA) is a mobile impact attenuator attached to a work or shadow vehicle that is used to temporarily protect objects or a work area. One or more TMAs are usually located in advance of an object, work area, equipment, or workers. A TMA should not be used for long-term protection of barrier or other fixed objects. Figure 2.8 shows an example of a TMA.

Figure 2.8: Truck Mounted Attenuator and Sequential Arrow Board

Sequential Arrow Signs – Sequential arrow signs or arrow boards are large truck- or trailer-mounted lighted signs used to indicate the direction which traffic needs to merge as part of a lane closure. These devices are not to be used to indicate a lane closure. Figure 8 above shows an example of sequential arrow board mounted on top of a truck.

Portable Changeable Message Sign (PCMS) – PCMS's are large lighted signs used to display programmable, dynamic messages that reflect upcoming work zone conditions to be encountered by approaching traffic. PCMS's can be mounted on either a trailer or work vehicle. Figure 2.9 shows an example of trailer-mounted PCMS. Figure 2.10 shows an example of a work vehicle-mounted PCMS.

Figure 2.9: PCMS on Trailer

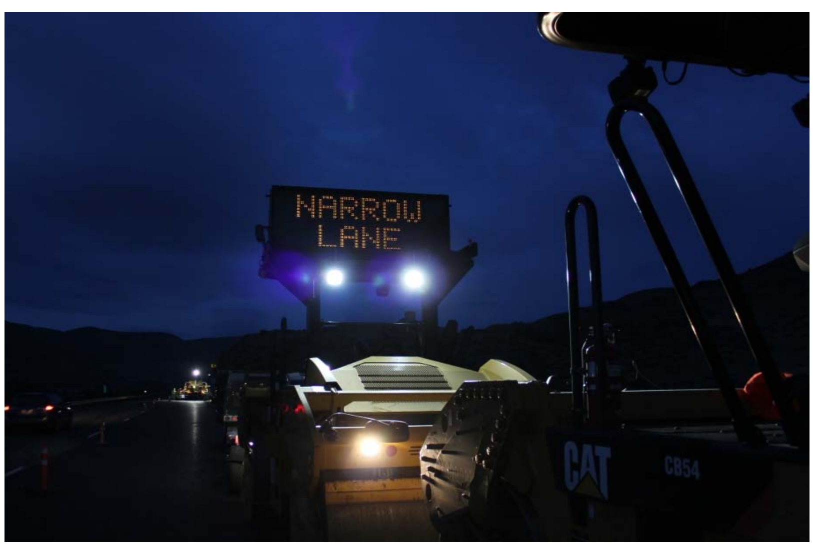

Figure 2.10: PCMS on Roller

The messages displayed on a PCMS should be complete, independent thoughts. Displaying a message that relies on a second message to complete the thought should be avoided. In practice, one message should be used to describe a situation or condition. The second panel should be used to convey supplemental information, an additional warning, or direction for drivers (*ODOT 2011*).

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

2.1.2 FHWA Manual on Uniform Traffic Control Devices for Streets and Highways

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2 RELATED RESEARCH ON TRAFFIC CONTROL DEVICES

2.2.1 Effect of Speed Photo-radar Enforcement

The Illinois DOT conducted a research study to explore the effect of speed photo-radar enforcement (SPE), also referred to as "automated speed enforcement" (*Benekohal et al. 2010*). In this research study, an advanced warning sign (shown in Figure 2.11) was placed on the roadway to inform the motorists of the implementation of SPE in the work zone. A self-contained van was used to implement the SPE as shown in Figure 2.12. Figure 2.13 provides a graphical view of how the SPE system works.

Figure 2.11: Special Signs for Speed Photo Enforcement *(Benekohal et al. 2010)*

Figure 2.12: Photo Enforcement Vehicle (*Benekohal et al. 2010*)

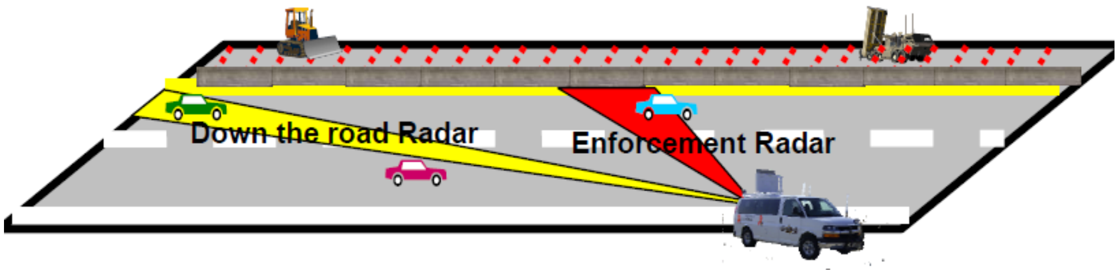

Figure 2.13: Operation of the Photo Enforcement (*Benekohal et al. 2010*)

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

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

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

2.2.2 Evaluation of Work Zone Speed Reduction Measures

In 2000, the Iowa DOT sponsored research on the evaluation of work zone speed reduction measures (*Maze et al. 2000*). Based on a summary of current practices, Maze et al. describe current speed reduction practices and concluded that flagging and police enforcement are the most effective methods. However, due to limited resources, the use of police officers in work zones is infrequent by many agencies. Replacing police enforcement by photo-radar enforcement machines may be more practical and cost-effective. One activity within the research study involved conducting a survey of state agencies about the practices which the agencies implement to reduce work zone speeds. Based on the survey results, the researchers concluded that the most effective speed reduction method involved some combination of traffic control devices.

In their report, Maze et al. provide a review of the effects of a several traffic control devices on traffic speed. The researchers mention that narrow lane widths are effective in reducing traffic speeds to some extent. A few studies have been conducted to explore the effect of narrow lane widths on traffic speed. The 1994 Highway Capacity Manual considers 12 feet as the ideal lane width. In estimating free-flow speed on multi-lane highways, the manual suggests considering

1.9 and 6.6 mph reductions in free-flow speed when the lane widths are reduced to 11 feet and 10 feet, respectively (*Maze et al. 2000*).

Maze et al. also report on the effect of drone radar on traffic speed. Drone radar is an electronic radar system that transmits in the microwave-frequency band. Vehicles equipped with radar detection devices perceive transmitted radar signals from the drone as the presence of police enforcement. As a result, motorists slow down because they believe that there must be police enforcement nearby. This study further analyzed the data to determine whether the fastest motorists were indeed the most likely to be affected by drone radar. The speed reduction of vehicles traveling faster than 65 mph was determined to be 0.2-2.6 mph greater than the average speed reduction for slower vehicles (*Maze et al. 2000*).

Removable rumble strips are a type of rumble strips that can be easily placed and removed from the roadway. This type of rumble strips is available with polymeric tape treated with pre-applied adhesive, and can be applied on both asphalt and concrete road surfaces. When motorists drive on rumble strips, they feel the jolts and hear the noise of their vehicle striking the strips. The intent of the rumble strips is to make drivers more attentive to and aware of the potential nearby hazards. The research done by Maze et al. (*2000*) indicates that while the strips were effective in reducing mean speeds, the strips had a negative impact on the stop compliance of motorists at the work zone. The percentage of drivers who came to a complete stop at the work zone after the rumble strip installations dropped by 20 percent (*Maze et al. 2000*).

2.2.3 Other Related Research

Meyer (*2004*) tested the application of optical speed bars within a highway work zone. Optical speed bars, also known as transverse strips, are innovative pavement markings that have been used to reduce traffic speed on curves and in other high risk locations. This technique has been used in several countries, most notably Great Britain, where the technique has become a typical device used at approaches to roundabouts. Figure 2.14 shows an example of optical speed bars. Meyer tested the effects of different optical speed bar patterns on traffic speed, and concluded that the pattern did not appear to have any effect on traffic speed or speed variations.

Figure 2.14: Optical Speed Bars (*Meyer 2004*)

Similar to the Iowa study, Elghamrawy (*2012*) conducted research to explore the performance of temporary rumble strips at the edge of highway construction zones. The main goals of this research were to analyze and compare the effectiveness of various layouts of temporary rumble strips and to provide practical recommendations to improve the design and layout of temporary rumble strips. The conclusions drawn from the research indicate that temporary rumble strips generate adequate sound levels to alert inattentive drivers, and the effectiveness of temporary rumble strips can be improved by increasing the number of strips per set and by using wider strips (*Elghamrawy et al. 2012*).

A research study conducted in the UK addressed the use of a system of stepped speed limits to reduce traffic speeds (*ITS International 2011*). The stepped speed limits method entails using multiple speed reduction stages to slow down traffic gradually by posting an intermediate mandatory speed before the final work zone mandatory speed. The results of the study show that using stepped speed limits can improve travel time through work zone, and traffic queuing approaching the work zone is reduced. As a result of using the stepped speed limits, vehicle headway improved by up to 14 meters. This method of speed reduction was employed in the ODOT pilot study, which is discussed in the next section.

2.3 PILOT STUDY

As mentioned in the Introduction to this report, ODOT conducted a preliminary study of traffic speed reduction on the I-5 Willamette River to Martin Creek paving project in 2011. A total posted speed reduction of 30 mph was applied from September 6 to 20, 2011. The traffic control for the speed reduction consisted of a posted, two stage speed reduction method, first reducing speed from 65 mph to 50 mph, then reducing speed from 50 mph to 35 mph. The measurements of success for the traffic control were the extent to which the vehicle speeds decrease and the amount of variability in the vehicle speeds.

Figure 2.15 shows the work zone traffic control plan for the pilot study. Three law enforcement vehicles were used. The first officer parked his vehicle at the beginning of the taper. The second OSP officer parked at the beginning of the work starting point. Finally, the third officer was placed downstream at the end of the work zone. An intermediate speed limit ‘XX’ sign was placed at the end of taper. This sign was followed by a radar speed reader board showing vehicle’s speed. The final work zone speed limit ‘YY’ sign was placed after the speed reader board, but before the start of paving work. For the pilot study, the intermediate speed was 50 mph, and the final work zone speed was 35 mph.

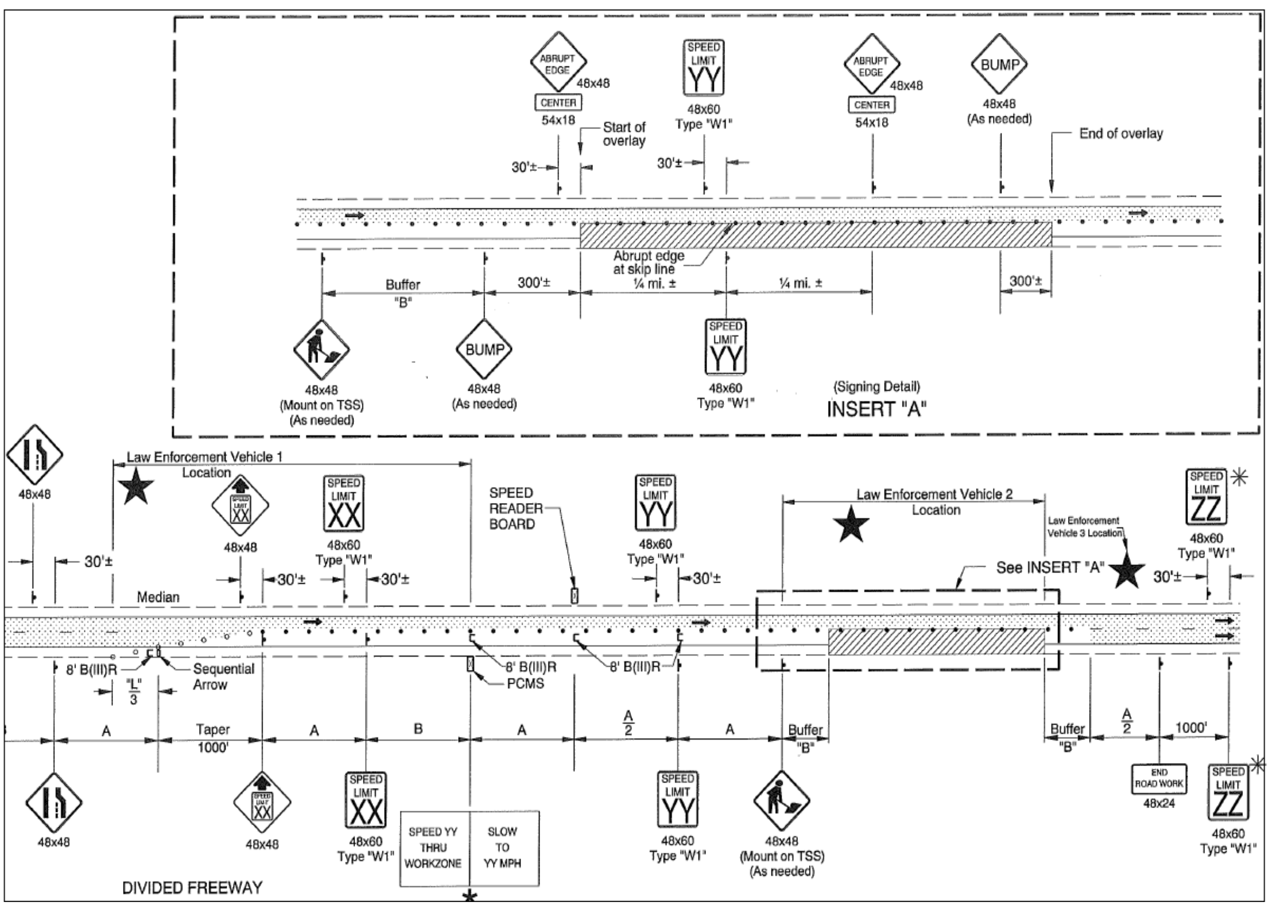

Figure 2.15: Pilot Study Traffic Control Plan Using Two Stage Speed Reduction

Speed data on the project was collected on September 9, 2011 from 12:45am to 4:45am (early Friday morning). The speeds were recorded by a handheld radar speed gun located near the paver, in the northbound direction at approximately MP 169. The speeds of free flowing passenger vehicles and commercial trucks were recorded, and are summarized in Figure 2.16 and Figure 2.17: Pilot Study Speed Data Summary for Commercial Trucks. Figure 2.16 shows the data summary for passenger vehicles, and Figure 2.17 shows the data summary for commercial trucks.

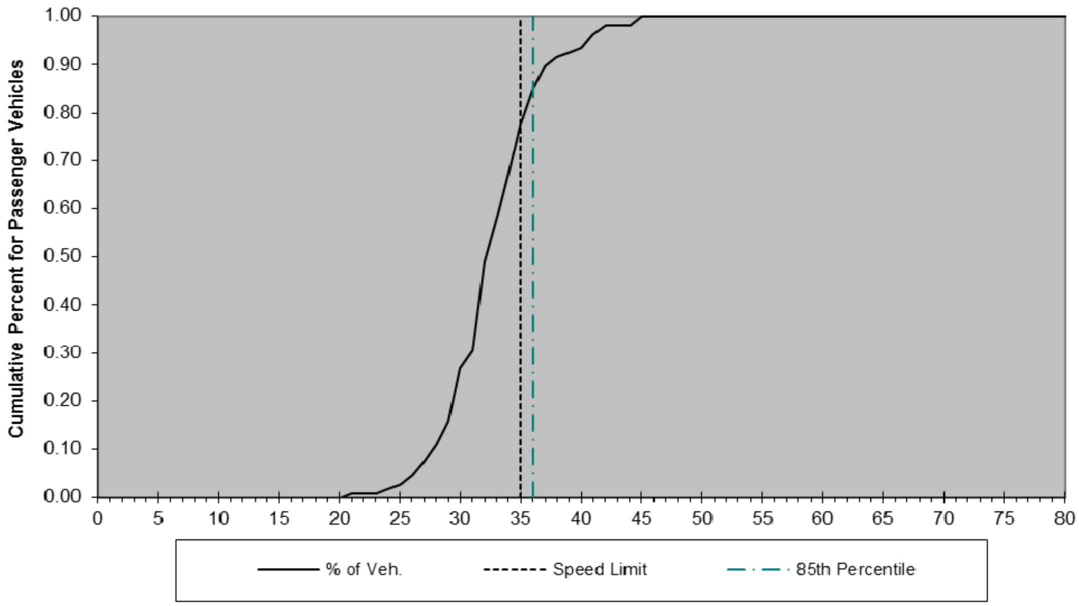

Figure 2.16: Pilot Study Speed Data Summary for Passenger Vehicles

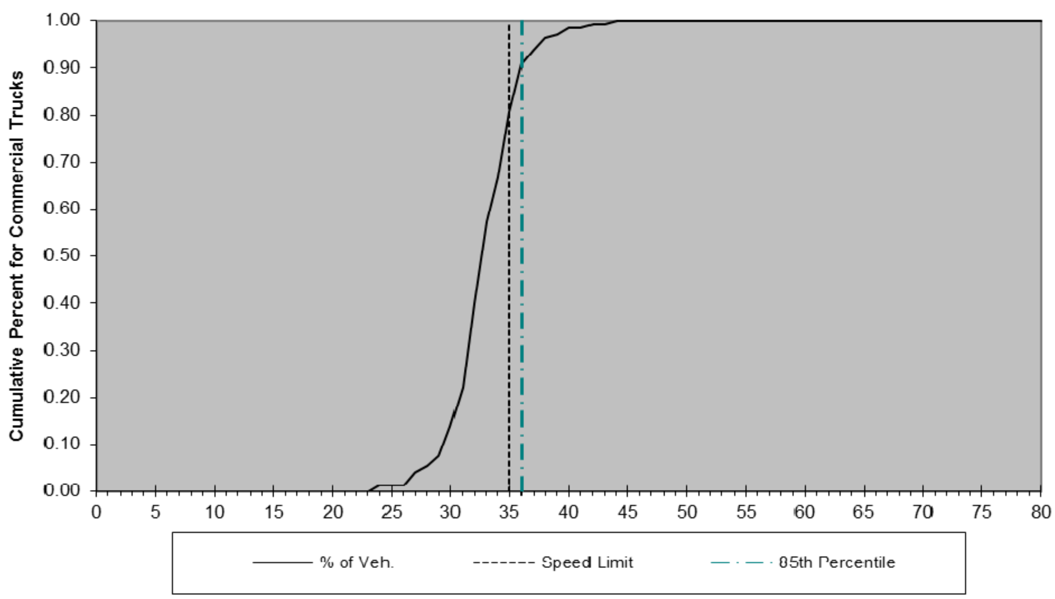

Figure 2.17: Pilot Study Speed Data Summary for Commercial Trucks

The speeds for a total 108 passenger vehicles were recorded. The 85th percentile speed for all passenger vehicles recorded was 36 mph, and the mean speed was 33 mph with a standard deviation of 4.10 mph. The percent of vehicles exceeding the posted speed (35 mph) was 22%. For trucks, the speeds for a total of 145 commercial trucks were recorded. The 85th percentile speed for all of the trucks recorded was 36 mph, and the mean speed was 33.23 mph with a standard deviation of 2.98 mph. The percent of trucks exceeding the posted speed was 19%.

Implementation of the additional traffic control measures resulted in extra cost to the project. The final change order cost to implement the additional measures is shown in Table 2.4, not including the cost for the OSP officers.

Table 2.4: Change Order Cost for Additional Pilot Study Speed Reduction Measures

Item	Unit	Unit Price	Quantity	Amount
Speed reduction TCS	Each	$910.00	6	$5,460.00
Speed reduction signage	SQFT	$16.74	340	$5,691.60
Total	--	--	--	$11,151.60

In summary, the pilot study applied a two stage speed reduction method and utilized three police officers to successfully reduce traffic speeds by approximately 30 mph. However, only one day of speed data was collected for analysis and the time period for the data collect was when the traffic was the lightest (12:00am to 5:00am). Additional research is needed to validate the results of the pilot study and determine the applicability to other project types and locations.

2.4 SUMMARY OF TRAFFIC CONTROL DEVICES

A wide variety of traffic control devices are available and have been studied. The traffic control devices shown in the following list were identified from the literature review, and were considered as viable options for inclusion in the present research. The actual devices used in the research study are described in the following section. Additional ideas for traffic control devices were solicited from those interviewed as part of each case study project.

- **Tubular markers and cones:** Commonly used to delineate travel lanes.
- **Temporary plastic drums (barrels):** Used to delineate travel lanes. They are the largest and most visible of the deformable channelization devices.
- **Barricades:** Placed at regular intervals within a closed lane to remind drivers that the lane is unavailable to them.
- **Temporary signs:** Multiple types of traffic control signs used temporarily in the work zone.
- **Sign flags:** Flags on the top of signs to catch the attention of passing drivers.
- **Sequential arrow signs:** Large truck- or trailer-mounted lighted signs used to indicate the direction traffic needs to merge as part of a lane closure.

- **Portable changeable message signs (VMS):** Large lighted signs used to display programmable, dynamic messages that reflect work zone conditions to be encountered by approaching traffic.

- **Radar speed monitoring display:** Measures and displays the vehicle speed ("Your speed is XX") along with the posted speed limit.

- **Police enforcement**: Police car with police officer inside the car located at the work zone. The patrol car's red/blue warning lights may or may not be turned on.

- **Speed photo-radar enforcement:** Measures and displays the vehicle speed, and automatically takes pictures of the vehicle and driver for enforcement purposes when motorists are speeding in the work zone.

- **Ghost police vehicle:** Police car with no police officer inside located at the work zone.

- **Lane narrowing:** A narrowing down of the travel lane width. Narrower lanes leave less lateral distance between vehicles in adjacent lanes or between vehicles and shoulder obstructions, requiring more motorist attention and control, and passively influencing motorists to reduce speeds.

- **Drone radar:** An electronic radar system that transmits in the microwave-frequency band. Vehicles equipped with radar detection devices perceive transmitted radar signals from the drone as the presence of police enforcement. In response, believing that a police car is nearby, the vehicles reduce their speeds, which in turn cause other vehicles to slow down.

- **Removable rumble strips:** Easily placed and removed rumble strips that produce slight jolts and audible rumble effects when motorists drive over them.

- **Optical speed bars:** Solid pavement markings placed at varying intervals across a lane. Optical bars affect a driver's perception of their speed. The gradually decreasing distances between the strips create an illusion that the driver is speeding, resulting in speed reductions.

- **Ambulance/Fire truck:** An ambulance or fire truck parked at the work zone to gain the drivers' attention.

- **Traffic Control Supervisor (TCS):** An employee of the contractor whose role is to coordinate the implementation of the TCP, ensure proper traffic control devices are placed correctly, and ensure that workers are adequately protected and performing their duties safely.

3.0 CASE STUDIES

3.1 INTRODUCTION TO CASE STUDIES

Task 4 of the research work plan involves implementing traffic control devices on case study projects and monitoring their impact on the work zones and traffic. The identification of case study projects and the selection of specific traffic control devices to implement on the case study projects were based on discussions during the first TAC meeting in April 2012. For each case study, the speed of passing vehicles is recorded by traffic monitors (NC-200 Portable Traffic Analyzers) located at various points within the travel lane(s). Additional observational data on the implementation and impacts of the traffic control devices is collected through interviews of the site personnel and through researcher observations. The researchers worked closely with ODOT, OSP, and the construction contractors to implement the traffic control devices and monitor their impact on the work zones and traffic.

3.2 PROJECT IDENTIFICATION

The overall goal of the research is to assist ODOT with enhancing the safety of motorists and workers in construction work zones on high-speed roadways. To be more specific, ODOT and AGC are most interested in rural area freeway pavement preservation projects. ODOT provided a list of freeway pavement preservation projects which were scheduled to be worked on during the summer of 2012. Table 3.1 shows the list of potential projects provided by ODOT.

Table 3.1: Initial List of Potential Projects

No.	Project Name	Contract No.
1	I-5: Holladay – Marquam	C14304
2	I-205: SE Foster Rd – SE 82nd Dr	C14417
3	I-5: Linn County Line – McKenzie River	C14380
4	I-5: Seven Oaks – Jackson	C14406
5	I-5: Azalea – Canyonville	C14434
6	I-84: Fifteen Mile – Celilo	C14414
7	I-84: Meacham – Glover	C14392

Detailed descriptions of each of the potential projects can be found in Appendix A. The beginning and ending milepoints of each project were determined by searching through the ODOT digital video log. After determining the exact location of the potential projects, the location of each project was noted on a state of Oregon map. Figure 3.1 shows the location of the potential projects, and Figure 3.2 shows an example view of the ODOT digital video log.

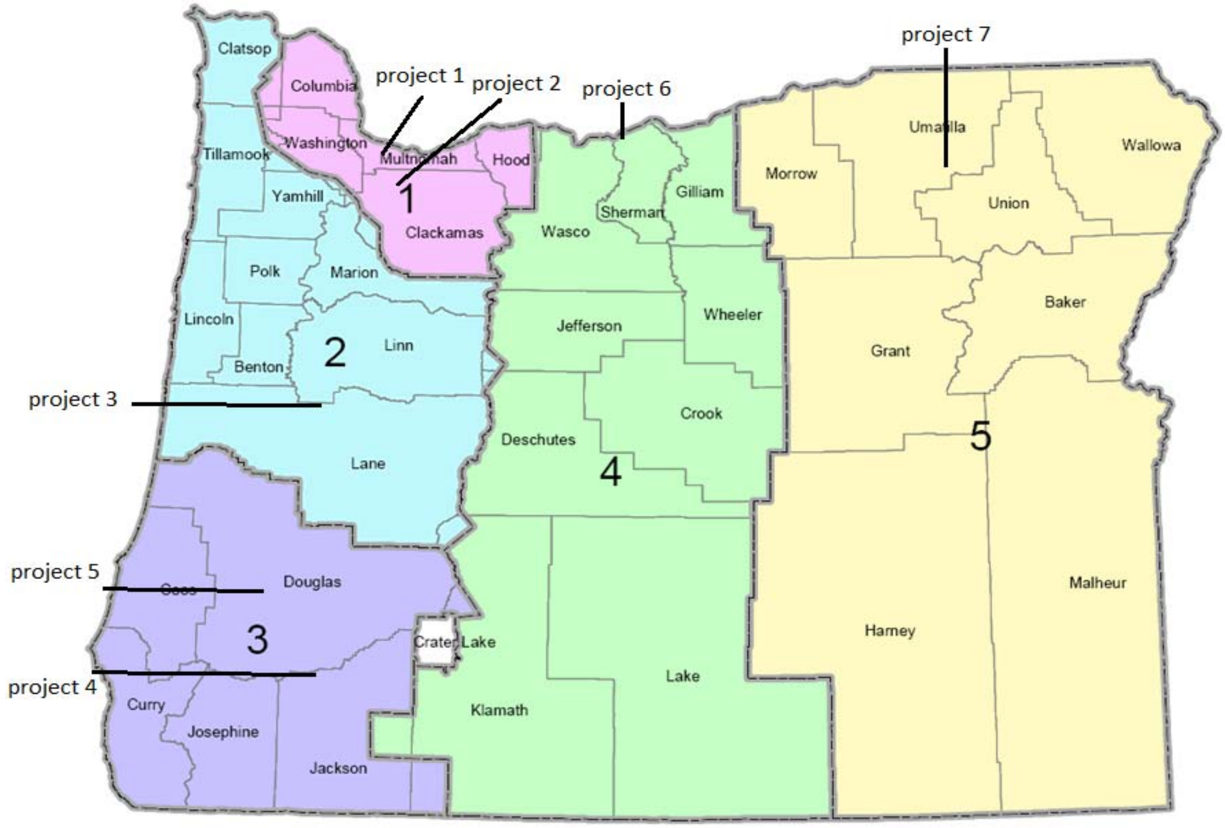

Figure 3.1: Location of Potential Case Study Projects

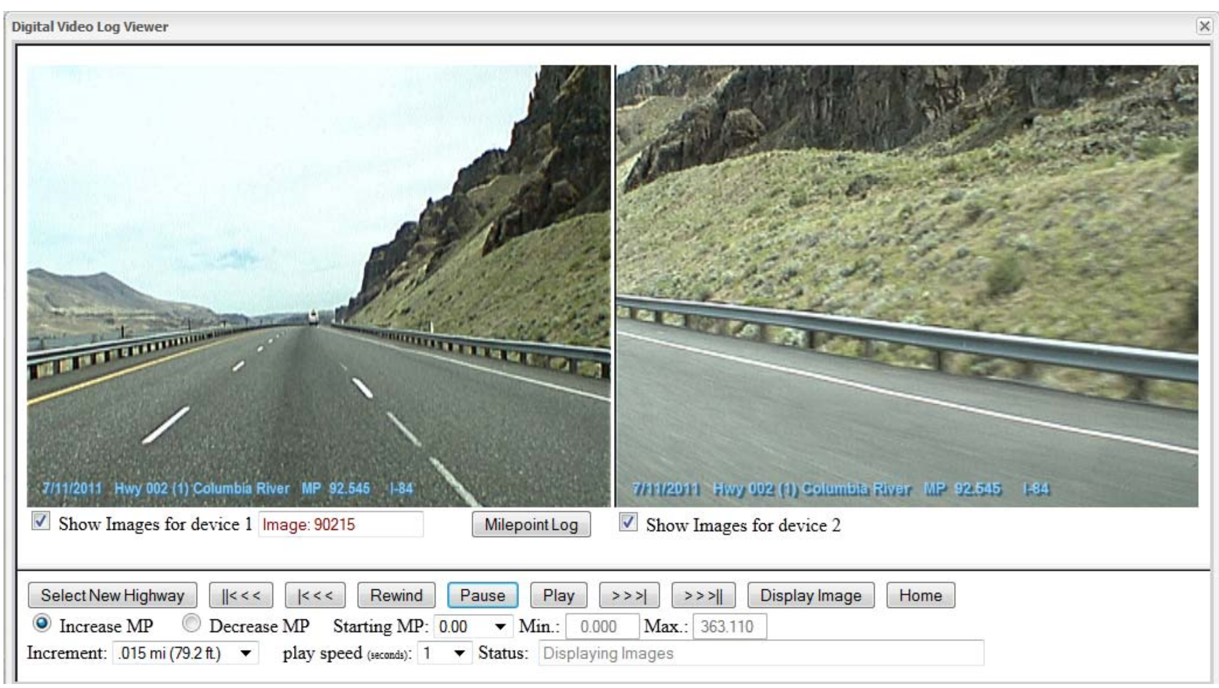

Figure 3.2: ODOT Digital Video Log

Two projects were chosen from the list of potential projects: I-84 Fifteen Mile to Celilo, and I-5 Linn County Line to McKenzie River. The I-84 Fifteen Mile to Celilo project was selected because the location of the project met the research objective and the contractor on the project was interested in and willing to assist with the research. The I-5 Linn County Line to McKenzie River project was chosen because the timing of the project fit well with the study timeline, the location of the project was convenient, the project met the research objectives, and the project site was similar in nature to the I-84 case study project (rural/suburban freeway with two lanes in each direction).

3.3 DATA COLLECTION MATRIX

Using the study objectives as a starting point, the researchers identified measurements and data collection activities to undertake for the research. Each was selected to provide requisite data to meet the study objectives. A summary of the planned measurements and observations recorded, and how they link to the research objectives, is shown in Table 3.2.

Table 3.2: Data Collection Matrix

Research Objectives	**Measurements and Observations Recorded**			
	A	**B**	**C**	**D**
	Vehicle Speed	**Interview ODOT personnel**	**Interview contractor personnel**	**Researcher site observations**
Time, cost, and resources required to implement the traffic control devices		X	X	X
Limitations and enhancements to implement the traffic control devices		X	X	X
Vehicle speeds and volumes through the work zone	X			
Speed variability through the work zone	X			
Construction worker safety, safety perception, and productivity	X	X	X	X
Motorist safety	X	X	X	X
Ability to implement the devices based on project and site attributes		X	X	X

A. *Vehicle Speed*: Vehicle speed was recorded to evaluate the impact of the traffic control devices on the passing motorists. Based on motorist's reaction to the traffic control devices, vehicle speed is considered to be an indication of the impact of the traffic control devices on motorist safety and construction worker safety in the work zone. Portable traffic analyzers (speed monitors) were used to record vehicle speeds, volumes, lengths. Other than the speed of vehicles, the portable traffic analyzers also record the time when a vehicle passes the analyzer and the length of the vehicle. More information about the portable traffic analyzers is provided in the next section of this report.

   To fully understand motorist behavior and vehicle speed through a long paving construction work zone, five portable traffic analyzers were placed on the roadway for each work period (night of paving). Two analyzers were placed near the "Road Work Ahead" sign, which is typically approximately one mile upstream before the vehicles reach the work zone. One analyzer was placed at the end of taper, and the remaining two analyzers were placed in the travelling lane at different points in the work zone. The actual location and spacing of the last two analyzers in the work zone was dependent on the amount and location of work being performed on that night. Figure 3.3 shows an example of a plan view of the portable traffic analyzer placement for a typical night. No traffic analyzers were placed beyond the end of the work zone.

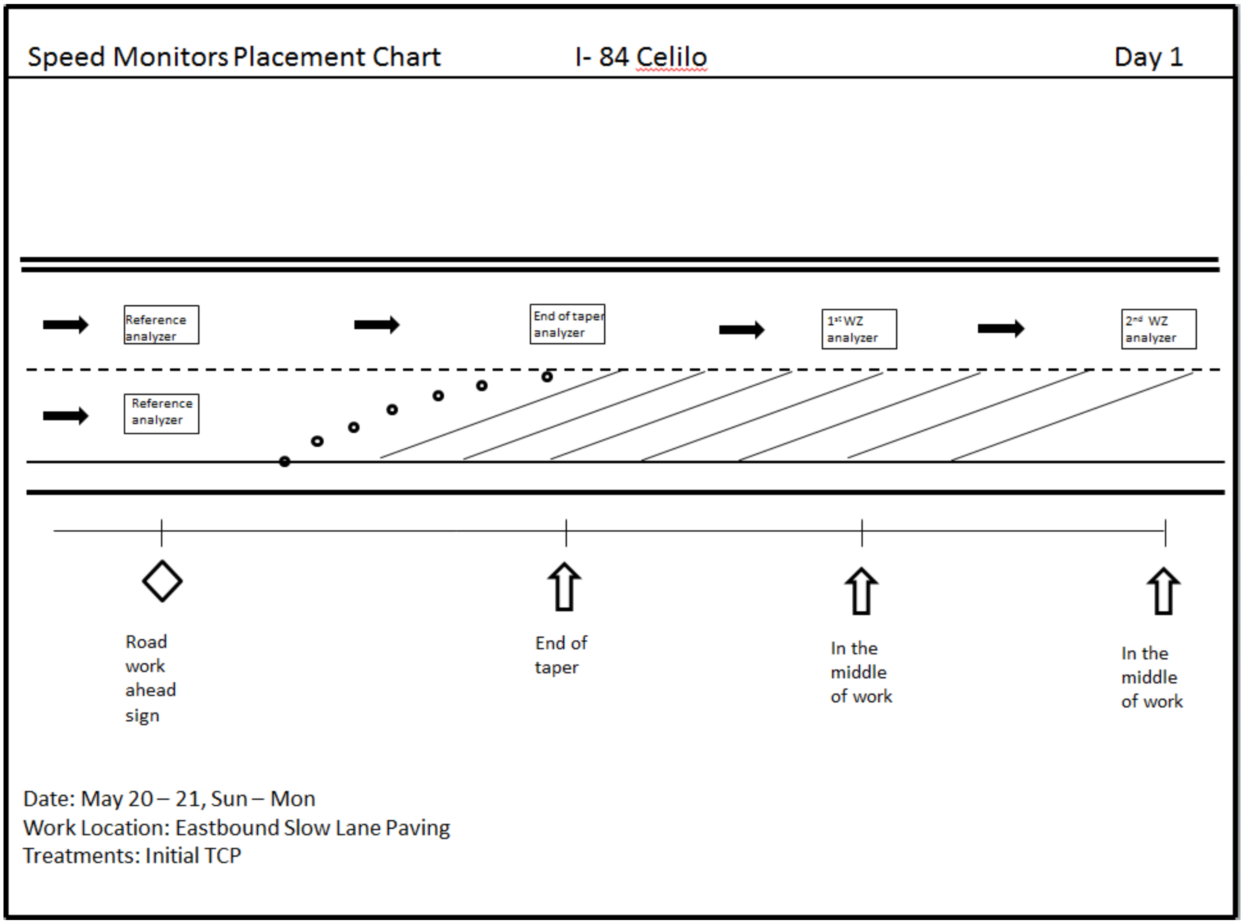

Figure 3.3: Plan View Drawing Showing Location of Traffic Analyzers

B. *Interview ODOT Personnel*: Different traffic control devices were tested on different work days (nights) during the case study projects. To get the information related to the time, cost, and resources required to implement the traffic control devices, as well as the limitations and enhancements to implement the devices, the researchers interviewed the ODOT project manager and inspector for the project on the site. Appendix B shows the interview form used for the interviews.

C. *Interview Contractor Personnel*: The researchers also conducted interviews of the contractor superintendent, traffic control supervisor, and work crew members using the same interview form as that used to interview ODOT personnel. Asphalt truck drivers were also interviewed to get their opinion of the traffic control devices. For the truck driver interviews, the researchers asked the questions shown in Appendix C. A different set of questions was used to interview the truck drivers because the truck drivers are motorists driving through work zone. Their focus and perspective will be different from the working crew members on the ground.

D. *Researcher Site Observations*: Researchers conducted their own observations during each work period and documented information regarding environmental conditions, roadway conditions, traffic control device implementation, and the construction work progress. Appendix D shows the researcher observation form used for the first day. After the first day of the on-site data collection, the researchers found that the information on the asphalt truck arriving time, and the progress of the paver, is recorded by the contractor on the truck ticket taker's form. Therefore, it was unnecessary for the researchers to record the work progress. As a result, beginning with the second night of data collection, the researchers stopped filling out the second part of the researcher observation form and obtained this data directly from the contractor after the work day was complete.

3.4 EQUIPMENT AND TOOLS USED FOR DATA COLLECTION

A variety of different pieces of equipment, tools, and resources were used by the researchers for data collection. For subjective data collected via interviews and observations, the researchers used pre-defined questions and forms as described in the Data Collection Matrix section of the report above. For vehicle speed data, portable traffic analyzers were used as described below.

3.4.1 Portable Traffic Analyzer

The portable traffic analyzer NC-200 is manufactured by Vaisala. Figure 3.4 shows an example of the traffic analyzer and a cover used to protect it on the roadway.

Figure 3.4: Potable Traffic Analyzer NC-200 (*Vaisala 2012*)

The traffic analyzer is designed to provide accurate traffic counts, speed, and classification (vehicle length) data. The analyzer is placed directly in the traffic lane to measure and record the passing traffic. The sensor utilizes Vehicle Magnetic Imaging technology to detect vehicle count, speed, and length (*Vaisala 2012*). Table 3.3 shows the technical specifications of the NC-200 portable traffic analyzer.

Table 3.3: Technical Specifications of Portable Traffic Analyzer NC-200

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

The portable traffic analyzer is fairly easy to program and place on the roadway. After use, the vehicle data is easy to download from the analyzer to any computer. Appendix E shows detailed information of how to use the traffic analyzer.

3.4.2 Adhesive Tape and Placement of Portable Traffic Analyzer

The traffic analyzer manufacturer indicates that the analyzer be nailed down to the pavement through nail holes on the cover as shown in Figure 3.5. However, for highway preservation projects, it is unrealistic to put nail holes in the newly paved asphalt mat, and the short duration of use (one night of work) each time the analyzer is used makes it inefficient to nail down the analyzers. Therefore, an alternative method to fix the analyzer on the roadway was used. The analyzers were secured to the pavement using adhesive tape which completely covered the analyzer cover and the analyzer. Figure 3.6 shows an example of how to use adhesive tape to keep the analyzer at the desired location.

Figure 3.5: Placement of Portable Traffic Analyzer by Nails (*Vaisala 2012*)

Figure 3.6: Placement of Portable Traffic Analyzer by Adhesive Tapes

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

However, a few problems occurred while using the tape to secure the analyzers:

1. The tape is very sticky, not only to the pavement but also to the cover used to protect the portable traffic analyzer. It is very difficult to remove the tape from the cover after each usage. A simple solution was found to solve this problem. The researchers put a piece of thick paper, which is about the same size as the cover, on the cover to separate the tape from the cover so that the tape did not directly contact the cover. Only the perimeter of the tape contacted and stuck to the pavement.

2. The tape performs poorly in wet conditions. The tape material is waterproof, but the water can penetrate the pavement around it and affect the adhesive layer from underneath. After the adhesive layer loses its strength, it is very easy to dislodge the cover and the analyzer when impacted by the high-speed traffic.

3. The tape performs poorly under high temperatures. The tape's adhesive layer softens significantly under high temperatures. When the adhesive layer softens, it is very easy for the cover and the analyzers to be dislodged by the on-going high-speed traffic. Therefore, it was not acceptable to place the tape directly on the roadway during high temperature summertime conditions. If traffic data is to be recorded in a high temperature environment, alternative ways to place the analyzer on the ground need to be used.

The researchers also encountered some issues related to the location and orientation of the analyzers on the pavement. The analyzers work best when vehicles pass directly above them. Therefore, the best location to put down the analyzers is at the center of the traveling lane. However, during a paving operation, the line of traffic is usually shifted a bit outside the normal travel lane to the shoulder or median to provide more room for the construction work. The shifted lane is delineated by a line of cones. Motorists usually drive very close to the shoulder/median line or even beyond the shoulder/median line to avoid hitting the cones. This driving behavior makes locating the best spot for the analyzers difficult. The researchers tended to place the analyzers close to the shoulder line, but there were many motorists still driving in the center of the lane. As a result, the vehicles would either bypass or hit the analyzers, which increases the possibility of inaccurate data or even potential damage to the analyzers.

3.4.3 Other Equipment

Many other pieces of equipment were used to assist with data collection. A camera was used to take pictures and videos of traffic control devices, construction work equipment, and the work process. A laptop computer was brought to the work zone in case the traffic analyzers could not be placed on the roadway before the programmed start time and they needed to be reprogrammed to start at a later time. A distance measuring wheel was used to measure short distances, for example from a traffic control device to a milepost, or the length of vehicles. After placing each analyzer, the researchers used reflective spray paint to mark the location of the analyzer on the edge of the pavement (see Figure 3.6) so that the analyzers could be located easily at the end of the work period.

3.4.4 Researcher Checklist

A researcher's checklist was developed to guide the researchers on the implementation of the research plan for each case study. The checklist outlines the activities undertaken at the site to coordinate with ODOT and the contractor, place the traffic analyzers on the roadway, collect observational data, conduct interviews, and demobilize from the site. The checklist was as follows:

- Prior to site visit:

    1. Coordinate with ODOT on meeting time and location
    2. Coordinate with ODOT to make sure of the construction work start time and location
    3. Charge the traffic analyzers and program them for next use
    4. Cut tape and attach a piece of paper to each cover of the analyzer
    5. Check all gear and equipment: safety gear (helmet, glasses, boots, vest, flashlight), thick clothes, camera, clipboard, pens, forms for survey and observation, site drawing for putting monitors numbers, GPS and other equipment to measure milepoints, traffic analyzers and covers, tapes, a knife to cut the tape, extra paper, reflective spray marker

- During the process of putting down traffic analyzers:

    1. Coordinate with ODOT and Contractor TCS with time and location to put down traffic analyzers
    2. Work with ODOT personnel and Contractor TCS to put down traffic analyzers, and write down the serial number of each analyzer and the location of where each analyzer is located on the drawings (see Figure 3.3).

- During the construction work operations:

    1. Interview ODOT project manager, ODOT inspector, contractor superintendent, traffic control supervisor, work crew, and asphalt truck drivers
    2. Fill out the researcher observation form
    3. Always have the cellphone numbers of project manager, inspector, superintendent, and TCS

- During the process of removing traffic analyzers:

    1. Work with TCS to remove traffic analyzers by using a knife to cut the cover out
    2. Separate the tape from the covers

- After each work day:

    1. Download the traffic data from the analyzers
    2. Charge the analyzers for next use, if necessary
    3. Email the raw data to the whole research team for backup

3.5 CASE STUDY #1: I-84 – FIFTEEN MILE TO CELILO PROJECT

3.5.1 Project Description

The I-84 – Fifteen Mile to Celilo case study project was located in Wasco County on the Columbia River Highway (I-84) near The Dalles. The limits of the project were between milepoints 88.07 and 96.77, including both eastbound and westbound lanes. Figure 3.7 shows the location of the project. Located east of The Dalles, the site is in a rural area where there are two lanes in each direction with light to medium traffic for most of the time. As a result, the researchers were able to put down traffic analyzers at approximately 4:00pm each work day without interrupting the ongoing traffic. The area was very cold and windy at night which makes the asphalt cool down very quickly from daytime temperatures.

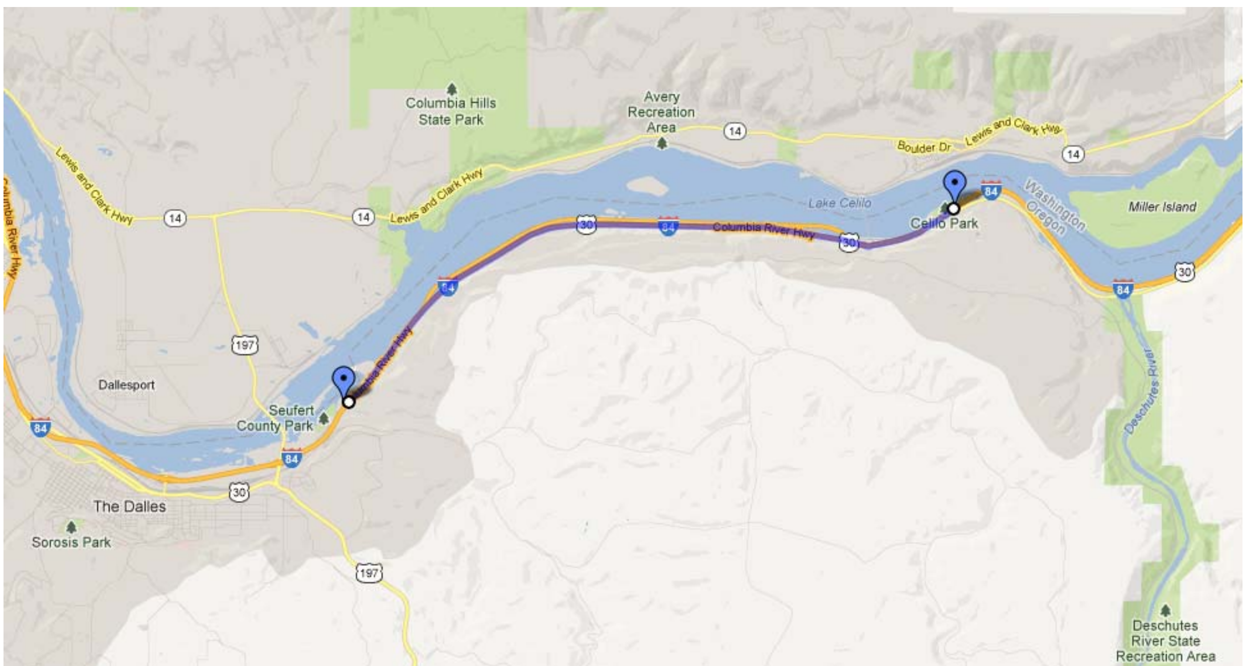

Figure 3.7: Location of I-84 – Fifteen Mile to Celilo Case Study Project

The paving work typically took place on Sunday and weekday nights only, from 7:00pm to 7:00am the next morning. In order to demobilize from the roadway and make both lanes open fully to traffic by 7:00am each day, the paver typically needs to stop paving before 6:00am. The contractor planned lane paving to start in the eastbound slow lane on May 16, 2012. However, due to weather issues and problems with asphalt production at the asphalt plant, the paving work was postponed several times and did not start until May 23.

3.5.2 Research Plan

The researchers contacted the contractor to obtain general information about the work plan and paving schedule. Based on the planned paving schedule, the researchers created a research plan to show the traffic control devices to be implemented on each day of paving work. The contractor changed the construction schedule periodically due to various reasons and, as a result, the plan was updated several times. Finally, the lane paving started on May 23, and continued intermittently through the middle of June. No paving occurred on some nights due to holidays, weather conditions, and issues at the asphalt plant. Table 3.4 shows the final research plan for the I-84 case study project. (Note: Treatment E, “PCMS on truck or trailer in shoulder or work area,” was initially considered for this case study. However, the TAC recommended that it be dropped from the list after the start of the research because it was determined that it would not be an available option on the case study. Therefore, in order to maintain clarity and consistency in treatment designations for research purposes, Treatment E was left in the table but shown crossed-out.)

Table 3.4: Final Research Plan for I-84 Case Study Project

	Treatment	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**	**Day 10**
		May 23-24	May 24-25	May 29-30	June 5-6	June 6-7	June 7-8	June 10-11	June 11-12	June 12-13	June 13-14
		Wed-Thurs	Thurs-Fri	Tues-Wed	Tues-Wed	Wed-Thurs	Thurs-Fri	Sun-Mon	Mon-Tues	Tues-Wed	Wed-Thurs
	Travel lane direction	East	East	East	East	East	East	East	East	East	West
	Travel lane	A	A	A	A	A	B	B	B	B	A
	Travel lane width	14.5’	14.5’	14.5’	14.5’	14.5’	22’	22’	22’	22’	14.5’
	OSP available?	No	No	No	Yes	Yes	No	No	No	No	No
A	TCP as initially designed	●	●	●	●	●	●	●	●	●	●
B	50 mph speed reduction signs		●	●	●	●	●	●	●	●	●
C	Contractor asphalt trucks travelling at 45 mph or less				●	●	●	●	●	●	●
D	PCMS on rollers			●	●	●		●	●	●	●
~~E~~	~~PCMS on truck or trailer in shoulder or work area~~										
F	Tubular markers on both sides of travel lane (reduce lane width to 15 feet)							●			
G	Drums, if available, on both sides of travel lane (reduce lane width to 15 feet)								●		
H	Speed monitoring display						●			●	●
I	OSP patrolling with active enforcement				●						
J	OSP parked on-site (if available)					●					

For the I-84 – Fifteen Mile to Celilo case study project, the traffic control plan as initially designed by ODOT included signage indicating the work ahead and lane closures. The TCP as initially designed did not include a speed reduction. To help reduce traffic speeds, the contractor planned to instruct the asphalt truck drivers to drive at 45 mph or less through the work zone. The contractor also made special efforts to place PCMS signs on two of the rollers for use as part of the research study. Based on the work scope and contractor productivity, the total paving length was initially expected to be up to 3 – 4 miles long each night. However, the actual length of paving each night varied and was typically less. The travel lane width varied from 14.5 ft. (A, fast lane) to 22 ft. (B, slow lane), depending on which lane was closed for paving.

For the research study, different traffic control devices were implemented each work day over a total of ten work days to evaluate their impact on vehicle speed through the work zone. The combination of the initial TCP, the posted speed reduction, and the asphalt trucks driving at 45 mph or less is considered the control for this case study. Additional treatments were implemented to determine if the devices slow the traffic down to speeds lower than the posted 50 mph. Only one OSP officer was available on only two work days (Day 4 and Day 5 as described below).

Prior to each work day, portable traffic analyzers were placed in the travel lane before, and at several locations within, the work zone as described above. The analyzers remained in place during the entire duration of the work operations on each day. At the end of each work day, the analyzers were removed and the speed data downloaded for analysis. The analyzers were reprogrammed and relocated for the next work day.

The list below provides a description of the research treatments on each work day:

- **Day 1:** Implement the TCP as initially designed (Treatment A only). This is planned for the first day to let the traffic get used to the work area and closure prior to adding the extra devices.

- **Day 2:** Place regulatory speed signs reducing the speed limit to 50 mph (Treatments A and B). The speed reduction began after the taper, and additional reduced speed signs were placed periodically throughout the work zone. The speed reduction did not overlap with the taper down to one lane.

- **Day 3:** Turn on the PCMS signs on the rollers (Treatments A, B, and D). On the finish roller, the message alternated every few seconds between “Slow for Workers” and “Narrow Lane”. On the intermediate roller, the message alternated every few seconds between “Workers on Road” and “Slow for Workers”. The same messages were used on the rollers throughout the study when the PCMS signs were turned on.

  The contractor initially utilized only three rollers for the project. After measurements showed that the required asphalt density was not being achieved regularly on the first few days of paving, the contractor brought in a fourth roller to help compact the asphalt. This increased the distance between the rollers with the PCMS signs and the paver.

- **Day 4:** Instruct the asphalt truck drivers to drive at 45 mph or less when travelling through the work zone, and add an OSP car patrolling around the work area with active enforcement (Treatments A, B, C, D, and I). The OSP enforcement took place as is typically conducted on ODOT projects. The officer began patrolling at the start of the work and left the work area at 12:00am, prior to completion of the work on that day.

- **Day 5:** OSP officer parked on the site rather than patrol around the site (Treatments A, B, C, D, and J). The officer parked his vehicle within the closed lane at the end of the taper such that his car was visible to oncoming traffic. The OSP vehicle had its flashing red/blue lights turned on to increase its visibility. The officer did not relocate with the paving operation as it moved up the roadway, and was not required to leave the work site to take care of other enforcement activities. The officer arrived at the site when the work began and left the work area at 12:00am, prior to completion of the work on that day.

- **Day 6:** Add a radar speed monitoring display, and turn **off** the PCMS signs on the rollers (Treatments A, B, C, and H). The display showed the posted speed limit (50 mph) along with the vehicle's speed. The display was located immediately prior to the paving operation and in the closed lane such that it was visible to the passing traffic. The display remained in place and was not relocated as the paving operation moved up the roadway.

- **Day 7:** Add a second line of tubular markers on the opposite side of the 22 ft. wide travel lane and turn **on** the PCMS signs on the rollers (Treatments A, B, C, D, and F). Include an additional line of tubular markers to narrow down the lane width to 15 feet. On the finish roller, the message alternated every few seconds between "Slow for Workers" and "Narrow Lane". On the intermediate roller, the message alternated every few seconds between "Workers on Road" and "Slow for Workers".

- **Day 8:** Add a second line of drums on the opposite side of the 22 ft. wide travel lane (Treatments A, B, C, D, and G). An additional line of drums was added to narrow down the lane width to 15 feet. Not enough drums were available for the entire length of the closure. Drums were placed as far as possible on both sides. When no more drums were available, the drums were replaced by tubular markers on both sides of the travel lane for the remainder of the lane closure.

- **Day 9:** Add a radar speed monitoring display and turn **on** the PCMS signs on the rollers (Treatments A, B, C, D, and H). The display showed the posted speed limit (50 mph) along with the vehicle's speed. The display was located immediately prior to the paving operation and in the closed lane such that it was visible to the passing traffic. The display remained in place and was not relocated as the paving operation moved up the roadway.

- **Day 10:** Repeat the treatments used on Day 9 for the westbound, slow-lane paving (Treatments A, B, C, D, and H). The radar speed display showed the posted speed limit (50 mph) along with the vehicle's speed. The display was located immediately prior to the paving operation and in the closed lane such that it was visible to the passing traffic. The display remained in place and was not relocated as the paving operation moved up the roadway.

3.5.3 Description of and Lessons Learned from Each Working Day

Day 0, 5/21-5/22
Day 0 was the first day in which the researchers visited the jobsite and met with ODOT and contractor personnel. The contractor decided to pave a part of eastbound shoulder (not part of the initial research plan) to test the asphalt plant's production capacity. The eastbound slow lane was half-closed for this shoulder work. It rained early that day, so the ground was wet. The researchers tried to dry the pavement using a blow torch and put down two traffic analyzers to test if they could work under the wet conditions. Two hours later, when researchers tried to cut the tape and retrieve the covers and analyzers, the researchers found that the tape was barely stuck to the ground and it was very easy to remove the entire piece of tape off the ground. Therefore, the researchers decided not to put down analyzers when the ground was wet, and if it rained later, the analyzers needed to be retrieved as soon as possible.

Day 1, 5/23-5/24
On this day the first lane paving began. The work extended from milepoints (MP) 88.122 to 89.20 on the eastbound slow lane. The initial TCP was implemented to obtain reference data. The taper began at MP 87.1, and maintained a half-lane closure for a very long distance because there was a large horizontal curve and Exit 87 nearby. Full closure of the lane started from MP 88.07, very close to the start of that day's work.

Two traffic analyzers were placed at the "Road Work Ahead" sign, one in each lane. One analyzer was placed at the end of taper. The end of taper for that day was very close to the beginning of the work, and the place where the end-of-taper analyzer was placed (MP 87.38) had only a half-lane closure. As a result, the speed data recorded by the end-of-taper analyzer for that day may be different from the other days. The first work zone (WZ) analyzer was placed at MP 88.26, and the second WZ analyzer was placed at MP 88.76. Both analyzers were within the extent of completed work for that day. For a typical freeway paving operation day, it is common to pave 3-4 miles per night. Due to the asphalt plant production problem, the contractor scheduled to pave only one mile for that night. The researchers were aware of this information beforehand, so they could place both speed analyzers within the extent of the paving work. Therefore, timely communication between the research team, ODOT, and the contractor was essential to successfully implement the research plan.

For a typical freeway paving day, the contractor starts to put out drums and cones to close one lane at approximately 7:00pm, and the grinder starts to work around 8:00pm after the lane closure is completed. The paver starts paving after 9:00pm following the grinding of the initial section of roadway. For Day 1, the paver started paving at 10:12pm, and stopped at 12:45am due to the asphalt plant problem. Work resumed at approximately 1:40am, and finished at 3:50am.

ODOT tried a piece of new equipment on the paver on Day 1. A temperature sensor was attached to the back of the paver to automatically measure the temperature of the pavement. The temperature sensor is shown in Figure 3.8 (yellow and black bar on back of paver with attachments). The sensor measures the temperature of the newly paved asphalt mat and records the location of the measurement. If ODOT is going to use this temperature sensor on all pavers, it will be much easier to know exactly where the paver is at different times during the work period.

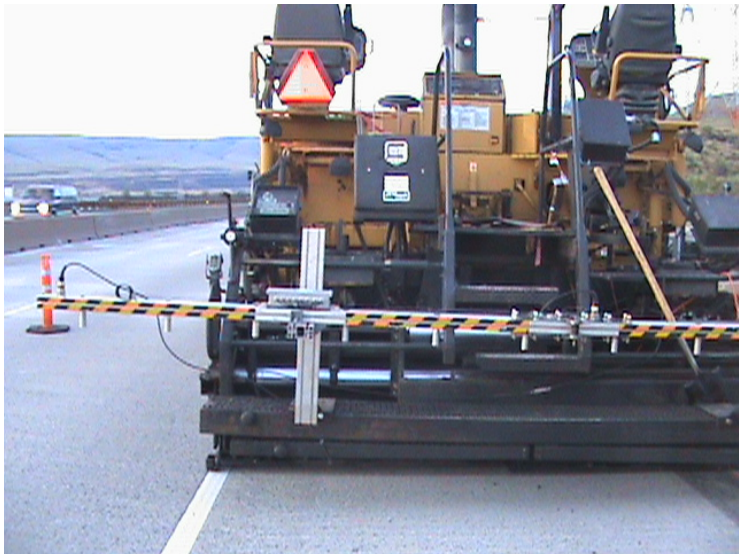

Figure 3.8: Pavement Temperature Sensor on Paver

The traffic analyzers were placed on the roadway at approximately 4:30 pm. The traffic was light at that time. There were many 30–60 second gaps between vehicles which allowed the researchers to walk into the lane and quickly place the analyzers on the pavement. The ODOT project coordinator and contractor's TCS assisted the researchers with this process. During this operation, the researchers always had one person spotting for oncoming traffic and telling everyone to exit the lane before any vehicle got too close.

Day 2, 5/24-5/25

On Day 2, the contractor continued to pave the eastbound slow lane, from MP 89.198 to 91.06. Because of the exit nearby, the contractor placed a half-lane closure for a long distance similar to the previous day, so the end-of-taper analyzer was at a half-lane closure location again. As for Day 1, this may affect the speed data recorded from the analyzer at the taper. The researchers were initially told that the contractor would try to pave three miles that night, so the second WZ analyzer was placed at MP 92.18. However, since the paving work was stopped at MP 91.06, the second WZ analyzer was outside the work area. Therefore, the data from second WZ analyzer for that night cannot be treated as recording work zone data.

In addition, Day 2 was the Thursday night before the Memorial Day weekend. The night traffic was heavier than normal, and police cars were observed a few times that night. One police car parked at the end of the work zone for a while, and the researchers were told that a police car parked at Exit #87 all day long during the day time. These impacts may be due to the holiday traffic.

The treatment for Day 2 consisted of regulatory speed signs reducing the speed limit to 50 mph (Figure 3.9). The speed reduction began after the taper, and additional reduced speed signs were placed periodically throughout the work zone. The speed reduction did not overlap with the taper down to one lane. PCMS signs on rollers were turned on at the beginning of the work, but turned off after researchers reminded the roller operators that they were not supposed to be turned on for that day.

Figure 3.9: Temporary 50 mph Speed Sign on I-84 Case Study Project

The contractor's TCS brought a truck mounted attenuator to protect the researchers during placement of the traffic analyzers. While the vehicles were stopped to place one of the analyzers, a passing vehicle almost hit the attenuator and subsequently was almost rear-ended by a second vehicle. There were no injuries, but the near miss showed the dangers of utilizing an attenuator on the road while motorists are driving at normal speed. The researchers were protected but the motorists were in danger as a result of inattentive drivers.

Day 3, 5/29-5/30

Day 3 included eastbound slow lane paving from MP 91.056 to 92.675. The PCMS signs on the rollers were turned on. On the finish roller, the message alternated every few seconds between "Slow for Workers" and "Narrow Lane". On the intermediate roller, the message alternated every few seconds between "Workers on Road" and "Slow for Workers" (Figure 3.10). The same messages were used on the rollers throughout the study when the PCMS signs were turned on.

Figure 3.10: PCMS on Rollers for I-84 Case Study Project

On this night, the paver stopped at approximately 12:50am due to asphalt compacting issues near MP 91.92. To achieve the desired compaction rate, the contractor brought in an additional roller.

Day 4, 6/5-6/6

Due to the compaction issue, the paving work was postponed for approximately 6 days. The work resumed on the eastbound slow lane with paving from MP 92.648 to 94.668. The treatment on this day included an OSP car patrolling around the work area with active enforcement and the asphalt truck drivers driving 45 mph or less when travelling through the work zone. The OSP enforcement took place as is typically conducted on ODOT projects. The officer pulled over a few cars at the end of the work zone, but only gave one ticket that night. The officer began patrolling as the paving work commenced, and left the work area at 12:00am prior to the end of the work period.

Day 5, 6/6-6/7

Paving continued on the eastbound slow lane from MP 94.665 to 96.786. On this day, an OSP officer parked on the site rather than patrol around the site. The officer parked his vehicle within the closed lane at the end of the taper such that his car was visible to oncoming traffic as shown in Figure 3.11. Figure 3.11 also shows an example of putting temporary signs on a permanent reflecting pole. This placement depends highly on the location and availability of poles.

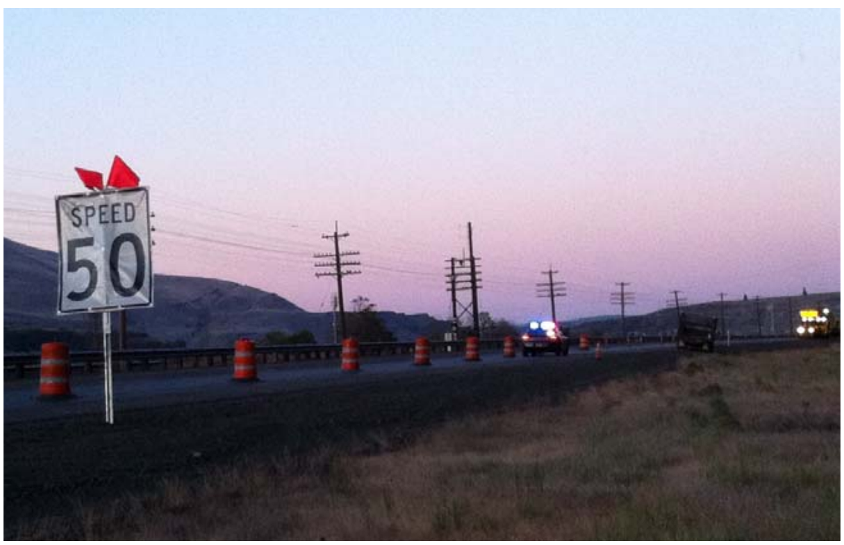

Figure 3.11: OSP Parked at the End of Taper with Lights On

The OSP vehicle had its flashing red/blue lights turned on to increase its visibility. The officer did not relocate with the paving operation as it moved up the roadway, and was not required to leave the work site to attend to other enforcement activities. The officer left the work area at 12:00am prior to the completion of the work period.

Day 6, 6/7-6/8

Day 6 was the first day of eastbound fast lane paving. On this day, paving was completed from MP 88.122 to MP 90.40. The treatment for this day was the radar speed monitoring display. The display showed the posted speed limit (50 mph) along with the vehicle’s speed (Figure 3.12). The display was located immediately prior to the start of the paving operation at MP 88.122, and in the closed lane such that it was visible to the passing traffic. The display remained in place and was not relocated as the paving operation moved up the roadway.

Figure 3.12: Radar Speed Monitoring Display

The radar speed monitoring display was placed and turned on at 9:30pm, and PCMS on the rollers were turned off at 11:00 pm. The PCMS on the rollers were supposed to be turned off that night but the contractor did not communicate this instruction to the roller operators. In addition, one of the traffic analyzers (located at the end of the taper) did not operate correctly on this night.

Day 7, 6/10-6/11

Day 7 included eastbound fast lane paving from MP 90.40 to MP 92.50. The treatment applied was tubular markers on both sides of the travel lane (Figure 3.13). The contractor received permission from ODOT to start the work earlier in the day, so the grinding work started at 6:15pm and paving started at 9:20pm.

Figure 3.13: Tubular Markers on Both Sides of Travel Lane

Day 8, 6/11-6/12

Paving on Day 8 was in the eastbound fast lane from MP 92.498 to MP 94.10. The treatment applied on this day was drums on both sides of the travel lane (Figure 3.14). An additional line of drums was added to narrow down the lane width from 22 feet to 15 feet. Not enough drums were available for the entire length of the closure. Drums were placed as far as possible on both sides. When no more drums were available, the drums were replaced by tubular markers on both sides of the travel lane for the remainder of the lane closure.

Figure 3.14: Drums on Both Sides of Travel Lane

The grinding work started at 6:00pm on this day, and paving started at 12:45am due to asphalt plant problems. The PCMS on the rollers were turned on at 1:00am. The PCMS on the intermediate roller was not working properly and could not display any messages.

Day 9, 6/12-6/13

Day 9 was the last day of eastbound fast lane paving. On this day, paving extended from MP 94.098 to MP 96.787. The treatment consisted of PCMS signs on rollers and radar speed monitoring display. The grinding work started at 6:00pm and paving work started at 9:00pm. The PCMS on the rollers were turned on at 10:00pm. The temporary 50 mph signs and radar speed monitoring display were placed at approximately 11:20pm because the dedicated TCS had to leave the project prior to this work day. The TCS had another job to work at, and this project was supposed to be finished already. So without the help from the dedicated TCS, the contractor had to wait for the other TCS on the project to complete his lane closure work before putting out the 50 mph signs and speed monitoring display. The PCMS on the intermediate roller was still broken.

Day 10, 6/13-6/14

Day 10 was the first day of westbound slow lane paving. The paving took place from MP 96.756 to MP 93.906. The treatment on this day was still the PCMS signs on rollers and radar speed monitoring display. The taper ended before the Exit #97 on-ramp. The PCMS signs on the rollers were turned on at 9:00pm and paving started at 10:00pm. The 50 mph signs and radar speed monitoring display were placed at approximately 10:30pm.

3.6 CASE STUDY #2: I-5 – LINN COUNTY LINE TO MCKENZIE RIVER PROJECT

3.6.1 Project Description

The Interstate 5 – Linn County Line to McKenzie River project is located in Lane County near Coburg, OR. The project extends from milepoint 197.45 to milepoint 203.55, including both northbound and southbound lanes. Figure 3.15 shows the location of the project.

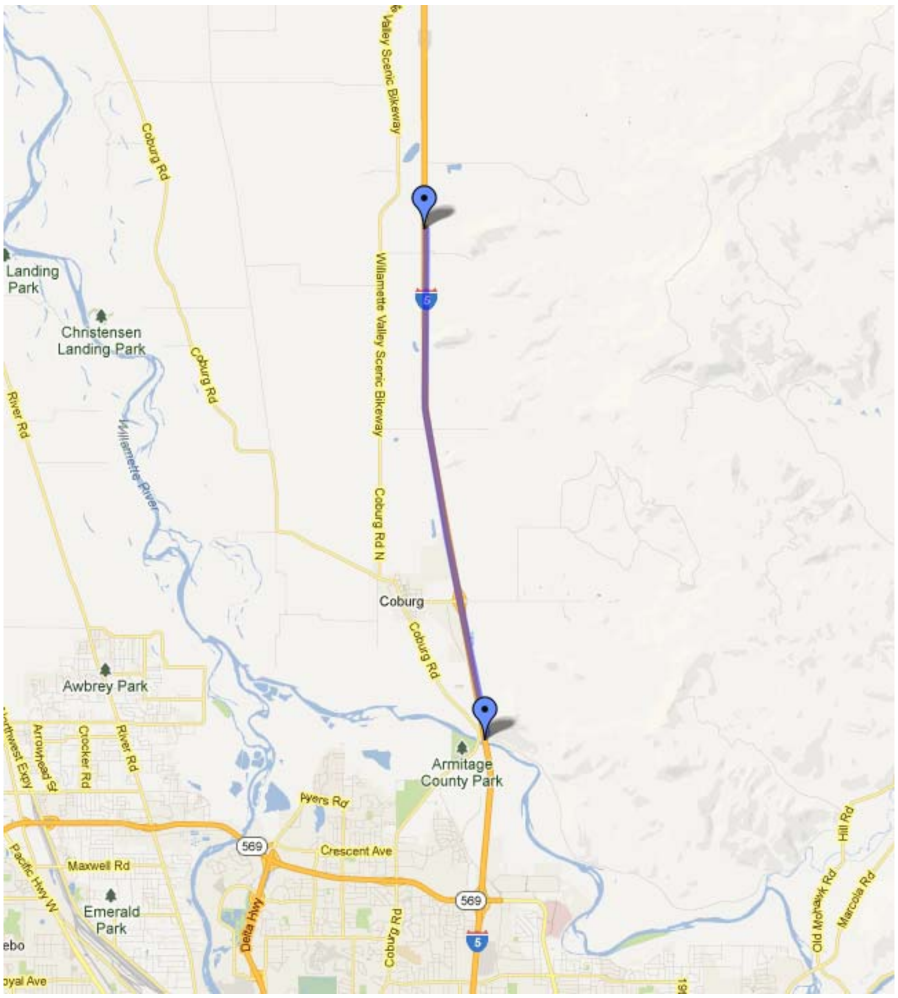

Figure 3.15: Location of I-5 Linn County Line to McKenzie River Case Study Project

The traffic on this section of freeway is heavier than on the I-84 case study project, especially before sunset. As a result, the researchers could not use the same methods to place the traffic analyzers before the project start time each day because there was not enough distance between vehicles for the researchers to safely enter the roadway and put down the traffic analyzers. The researchers had to wait until approximately 10:00pm when the traffic volume decreased enough to allow for accessing the roadway.

To protect the researchers and provide enough time to put down the traffic analyzers, the contractor used the rolling slowdown method. This method involves having two trucks drive slowly side-by-side on both lanes for a certain distance before the location where the analyzers will be placed. By doing so, a large gap is created between the oncoming traffic and the researchers on the roadway. However, there were some problems with using this method. First, it was very difficult to gauge how far away the contractor's trucks were during the night, and it was also difficult to tell if the upcoming vehicles were the contractor's trucks or normal traffic. Second, some drivers who were slowed by the trucks drove to the shoulder, passed the trucks, and rushed right toward the researchers on road. It was a very dangerous situation. No matter what the protection was, the researchers always needed to have one person spot the traffic. Lastly, due to the need to wait until the traffic volumes subsided, the analyzers could only collect the data from the second half of the night, which greatly impacts the ability to draw meaningful conclusions from this case study.

3.6.2 Research Plan

The contractor started paving work on the main lanes on Tuesday, June 10, and continued the work periodically over the next two weeks for a total of eight paving days. Similar to the I-84 case study project, no paving occurred on some nights due to weather conditions, weekend nights, and asphalt compaction issues. There were a total of eight days of paving, however there were only seven days of data collection. One of the paving days was on a weekend night (Friday-Saturday, July 20-21), on which no research data was collected due to the anticipated high traffic level, high traffic speeds, and atypical make-up of the traffic.

Paving took place on the fast lanes (A lanes) over the first four days, in the northbound direction first and then southbound. Paving of the northbound slow lane (B lane) was started on the fifth day, after which the contractor moved to southbound slow lane. The nightly work typically started at approximately 7:00pm with the closure of the paving lane. The placement of the new pavement typically started around 9:00pm following the grinding and preparation of the roadway. Table 3.5 shows the final research plan for the I-5 case study project.

As with the I-84 case study research plan, some treatments that were initially considered were not implemented because they were considered to be not effective following the I-84 case study, were not available for use on the I-5 case study, or due to the limited number of paving days on the I-5 case study. For the I-5 case study, those treatments not implemented were: Treatment C – Contractor asphalt trucks travelling at 45 mph or less; Treatment D – PCMS on rollers; Treatment F – Tubular markers on both sides of travel lane; and Treatment G – Drums on both sides of travel lane. These treatments are shown crossed-out in the table.

Table 3.5: Research Plan for I-5 Linn County Line to McKenzie River Case Study Project

	Treatment	Day 1	Day 2	Day 3	Day 4	Day 5		Day 6	Day 7
		July 10-11	July 11-12	July 16-17	July 17-18	July 18-19	July 20-21	July 22-23	July 23-24
		Tues-Wed	Wed-Thurs	Mon-Tues	Tues-Wed	Wed-Thurs	Fri-Sat	Sun-Mon	Mon-Tues
	Travel lane direction	North	North	South	South	North	North	South	South
	Travel lane	B	B	B	B	A	A	A	A
	Travel lane width	15’	15’	15’	15’	15’	15	15’	15’
	OSP available?	No	No	No	No	No	No	No	Yes
A	TCP as initially designed	●	●	●	●	●		●	●
B	50 mph speed reduction signs			●	●	●		●	●
~~C~~	~~Contractor asphalt trucks travelling at 45 mph or less~~								
D	~~PCMS on rollers, if available~~								
E	PCMS on truck or trailer in shoulder or work area				●	●		●	
~~F~~	~~Tubular markers on both sides of travel lane (reduce lane width to 15 feet)~~								
~~G~~	~~Drums, if available, on both sides of travel lane (reduce lane width to 15 feet)~~								
H	Speed monitoring display				o	●		●	
I	OSP patrolling with active enforcement								
J	OSP parked on-site at beginning of work area								●

For the I-5 McKenzie River case study project, the traffic control plan as initially designed included signage indicating the work ahead and lane closures. The TCP as initially designed (Treatment A) did not include a speed reduction. To help reduce traffic speeds, the contractor agreed to implement the treatments indicated in the matrix above through a change order. Based on the work scope and contractor productivity, the total paving length planned for each night was approximately three miles long. The travel lane width remained at 15’ for paving both the A (fast) and B (slow) lanes in each travel direction.

For the research study, different devices (treatments) were implemented each work day over a total of seven work days to evaluate their impact on vehicle speed through the work zone. The combination of the initial TCP and the posted speed reduction is considered the control for this case study. Additional treatments were implemented to determine if the devices slow the traffic down to speeds lower than the posted 50 mph.

The contractor on this case study did not plan to instruct the asphalt truck drivers to travel at 45mph or less as was planned on the I-84 project. This treatment was not included in the I-5 case study because it is very difficult to monitor and verify, and the asphalt truck drivers tend to drive at slower speeds regardless of the contractor’s instructions.

Similarly, the tubular markers and drums on both sides of the travel lane were not included as treatments in this case study. Based on the results of the I-84 case study, these treatments were not viewed as feasible and did not perform as well as other treatments in terms of reducing traffic speeds. Additionally, given the limited number of paving days on the I-5 case study project, conducting multiple assessments of the other treatments were preferred in order to improve confidence in the research results for the treatments that initially performed well.

An OSP officer was available to come out to the site on two work days. An officer came out to the site on Thursday, July 19, however the paving was cancelled that day due to rainy weather. An officer also came out to the site on July 23 as indicated in the matrix above.

At the beginning of each work day, after the traffic control was implemented, vehicle speed measuring sensors (traffic analyzers) were placed in the travel lane before, and at several locations within, the work zone. The sensors remained in place during the entire duration of the work operations on each day. Initially, the sensors were left in place for two nights of paving. However, when the researchers went to the site after the second day of paving, many of the sensors were dislodged from their location and damaged, and no data could be downloaded from the sensors. The sensors are placed on the roadway such that a vehicle straddles the sensor with the lane closure present. When there is no lane closure during the daytime, the passing vehicles shift over in the lane and the sensors that remain on the roadway are located such that they are in the wheel path of the vehicles. As a result, the sensors get repeatedly run over. In addition, the daytime weather over the first two days was very hot, making the tape which holds the sensors to the pavement very plastic. These two issues are believed to be the causes for the sensors getting dislodged and damaged. Therefore, for the remaining data collection efforts, all of the sensors were picked up off of the roadway after paving operations completed for the work day (between about 4:00 and 6:00am). At the end of each work day, the sensors were removed and the speed data downloaded for analysis. The sensors were then relocated for the next work day in the evening when the temperature was lower.

The list below provides a description of the research treatments on each day in which data collection took place:

- **Day 1:** Implement the TCP as initially designed (Treatment A only). This is planned for the first day to let the traffic get used to the work area and closure prior to adding the extra devices.

- **Day 2:** Implement the TCP as initially designed (Treatment A only). The contractor did not have the additional treatments available at this time.

- **Day 3:** Place temporary regulatory speed signs reducing the speed limit to 50 mph (Treatments A and B). The speed reduction began after the taper, and additional reduced speed signs were placed periodically throughout the work zone. The speed reduction did not overlap with the taper down to one lane.

- **Day 4:** Place stationary PCMS signs on trailers (Treatments A, B, and E). PCMS signs on rollers were not available for this case study. Two PCMS signs on trailers were used, one at the beginning of the work area and one in the middle of the work zone. The first PCMS sign, located at the beginning of the work area, showed a message that alternated every few seconds between “Slow for Workers” and “Narrow Lane”. The second PCMS sign was located a short distance down the roadway (approximately 1,000ft) from the first sign and had a message that read “Slow for Workers”.

- **Days 5 and 6:** Add a radar speed monitoring display (Treatments A, B, E, and H). The speed monitoring display showed the posted speed limit (50 mph) along with the vehicle’s speed. The display was located immediately prior to the initial starting point of the paving operation such that it was visible to the passing traffic.

- **Day 7:** Add an OSP officer parked on the site; remove the PCMS signs and speed monitoring display (Treatments A, B, and J). The officer parked his vehicle within the line of drums near the end of the taper such that his car was visible to oncoming traffic. The OSP vehicle had its flashing red/blue lights turned on to increase its visibility. The officer did not relocate with the paving operation as it moved up the roadway, and was not required to leave the work site for other enforcement activities. The officer left the work area at 1:00am.

3.6.3 Description and Lessons Learned from Each Working Day

Days 1-2, 7/10 - 7/12

The first two days of work involved paving on the northbound, fast lane (A lane). Since the contractor did not have the temporary 50 mph signs ready, the typical TCP was used for the first two days. The researchers were told that the traffic was heavy at the project location on I-5, so they needed to wait until midnight to put down the traffic analyzers. In order to capture more data, the researchers decided to leave the analyzers on the roadway for two days so that they did not have to place the analyzers again and could record a full night of data for the second night.

Day 3, 7/16

The paving for this night took place in the southbound, fast lane (A lane), and the treatment was the typical TCP plus the temporary 50 mph advisory signs. The contractor was asked to use a TSS to support the signs. To do so, the contractor needed a large truck to haul the TSS to the desired location. This process took additional time. Figure 3.16 shows an example of using a TSS to support a temporary sign.

Figure 3.16: Temporary Signs on TSS

Day 4, 7/17

Paving in the southbound, fast lane continued on Day 4. The treatments during the paving operation were the typical TCP, 50 mph signs, and PCMS signs on trailers. Figure 3.17 shows an example of a PCMS sign on a trailer located on the median.

Figure 3.17: PCMS Sign on Trailer for I-5 Case Study Project

On this work day, the contractor located a radar speed monitoring display on an adjacent exit ramp (Exit #199) within the work area. The TCS felt that there were already many signs and other devices located at the beginning of the work zone and that it would be better to place the speed monitoring display elsewhere so that it was more prominent. Therefore, the TCS located it at approximately the middle of the section to be paved that night, which was adjacent the exit ramp. There were also drums located at the exit which were being used to control the exiting traffic. The drums provided a protected location for the radar speed monitoring display. However, in this location the display was located such that it was not very visible to passing vehicles.

Day 5, 7/18

The paving on this work day took place on the northbound, slow lane (B lane), and the treatments were the typical TCP, 50 mph signs, PCMS signs on trailers, and radar speed monitoring display. Two PCMS signs and one radar speed display were placed near the end of taper. The presence of these devices next to each other made the location somewhat crowded with an extensive amount of information for the motorists to process in a short distance.

Day 6, 7/22

On this work day the contractor continued paving on the southbound, slow lane. The treatments during this work period were the same as the previous night of paving (typical TCP, 50 mph signs, PCMS signs on trailers, and radar speed monitoring display). The work took place on a Sunday night, and the traffic volume was greater than on the weekdays.

Day 7, 7/23

Paving on the southbound, slow lane continued on this night. The treatments included the typical TCP, 50 mph signs, and an OSP officer parked at the end of taper. The officer parked on the jobsite from 8:00pm until 1:00am. Figure 3.18 shows where the OSP officer parked. As seen in the figure, the officer parked his vehicle at the end of the taper and immediately upstream of a truck with a TMA.

Figure 3.18: OSP Parked at the End of Taper for I-5 Case Study Project

4.0 RESULTS

4.1 RESULTS FOR I-84 – FIFTEEN MILE TO CELILO CASE STUDY PROJECT

This section of the report presents the results of the I-84 – Fifteen Mile to Celilo case study project, including the interview responses, researcher observations, cost summary for traffic control devices, and recorded vehicle speeds.

4.1.1 Interview Results Summary for I-84 Project

Interviews of ODOT on-site personnel and contractor personnel were conducted to gather their opinions of the traffic control devices placed on the roadway each day. The researchers used the interview form (shown in Appendix B) to conduct the interviews and record the information regarding the time, cost, and resources required to implement the traffic control devices, as well as the limitations and enhancements to implement the traffic control devices. Contractor asphalt truck drivers were also interviewed to get their opinion of the traffic control devices. For the truck driver interviews, the researchers asked the questions shown in Appendix C. A different set of questions was used to interview the truck drivers because the truck drivers are motorists driving through the work zone. Their focus and perspective will be different than the working crew members on the ground.

The interview data is summarized below for each work day. On some days, a combination of traffic control devices was used, and the interviews for those days may be related to multiple traffic control devices.

Day 1: Initial TCP
For the first day, no extra traffic control devices were applied, only the initial TCP was implemented. The resources required to implement the initial TCP were a cone truck, a pickup truck, an attenuator with an arrow board on it, and three workers including the TCS. To implement the initial TCP and conduct the preparatory research tasks, one hour was needed for data collection (to place the traffic analyzers on the roadway) and another 1 to 1.5 hours was needed to put down the drums and tubular markers. Roadway attributes, such as the existence of curves, on- and off-ramps, narrow bridges, and narrow shoulders, can affect the placement of drums and markers. For that day, due to a large horizontal curve and an exit near the beginning of the paving work, a one mile buffer with drums in front of the beginning of the paving work was applied, which was not the normal case.

The researchers individually interviewed the ODOT project manager, coordinator, inspector, contractor superintendent, TCS, and asphalt truck drivers. All of the interview participants agreed that the initial TCP was very useful in enhancing both construction worker safety and motorist safety, and that it had no effect on typical construction productivity. As usual, the tubular markers affected the asphalt truck drivers' ability to enter and exit the work zone. Many trucks ran over tubes when the drivers tried to pull into or out of the paving lane. The spacing between tubes was 40 feet, and the length of the asphalt trucks was about 60 feet. It was not easy to cross the line of tubes at a relatively high speed and not hit a tube.

The lights on the paver that were used to illuminate the work area were very bright (see Figure 4.1). As a result, the asphalt truck drivers had difficulty seeing the oncoming traffic when they tried to pull out of the paving lane into the travel lane. The lights on the paver were so bright that they reduced the visibility of the asphalt truck drivers, and the drivers needed a ground crew member to tell them when it was safe to pull out into the travel lane. However, there were some advantages of using bright lights. Those working on the ground around the paver were more visible to motorists, and the bright lights drew the motorists' attention to the construction work and made them more aware of what was going on.

Figure 4.1: Paver for I-84 Project

ODOT specification 00225.02 – General Requirements requires the installation of a "CONSTRUCTION VEHICLE DO NOT FOLLOW" sign on rigid substrate on the back of all material or equipment delivery vehicles (Figure 4.2) for all freeway and high-speed, multi-lane projects. The sign is intended to instruct the driver in the vehicle behind the asphalt truck to not follow the truck. However, not all of the contractor asphalt trucks used on the project had a sign on the back. In some instances, unfortunately some motorists mistakenly followed the asphalt truck into the paving lane which created a dangerous situation. It should be noted that the sign could be misinterpreted. That is, when the asphalt truck is simply traveling down the through lane, the succeeding vehicles should follow the truck and not go into the paving lane. However, when the truck pulls into the paving lane, the vehicles should not follow the truck. Drivers in trailing vehicles may not know when to follow the truck and when not to, especially under nighttime conditions in a crowded and active work zone and when there are large distances between the tubular markers.

Figure 4.2: Contractor Asphalt Trucks

It was also mandatory that all contractor asphalt trucks have back up alarms that alert the construction crew members while the truck is backing up. However, not all of the asphalt trucks used on the project had the back-up alarms.

Day 2: 50 mph signs

As mentioned previously, the supports for the temporary 50 mph roll-up signs were light and easy to implement, and fold up and store in a truck. The resources required to locate all additional signs were a dedicated TCS, a pickup, and 30 minutes. The limitations of implementing additional signs were the existence of roadway curves, exits, and narrow shoulders. Of those interviewed on this day (four people), it was agreed that the additional signs enhanced construction worker safety and motorist safety by attracting the attention of the motorists and letting them know that they needed to slow down. The additional signs had no effect on construction productivity.

Day 3: PCMS on Rollers

The initial installation of one PCMS sign on a roller took the contractor’s mechanic seven hours. For two PCMS signs it took a total of fourteen hours. In addition, about one hour was required for the roller operators to learn how to program the PCMS, and after that, it only took a few minutes each day to raise it up and turn it on. The initial cost of the PCMS signs was very high. Besides the signs, the contractor needed to procure some accessories for installing the PCMS signs on the rollers. Detailed information about the costs will be discussed in later sections of this report. The maintenance cost of the PCMS signs is not known.

The PCMS signs needed to be lowered during transportation of the rollers because they added additional height to the rollers. The initial cost was very high which might limit their application on other projects. Those interviewed felt that the signs were highly visible to the traffic, and helped to slow down the oncoming vehicles because the motorists would know that there were people on road, not only equipment, and construction workers were nearby. However, some interviewees thought that the signs were a distraction for motorists because the motorists needed to pay attention to the signs to read the words instead of paying attention to the road and traffic.

A total of three asphalt truck drivers were interviewed. The truck drivers agreed that the PCMS signs on rollers would not affect the asphalt truck drivers' ability to drive into and out of the paving lane, and that there is no effect on construction productivity.

Day 4: OSP Patrolling and Asphalt Truck Drivers Driving at 45 mph
It took the ODOT coordinator one week to communicate with OSP and schedule a time to have OSP on the construction site. The ability to have OSP patrolling on the site is limited by the availability of police officers and the length of time it takes an officer to return to the start of the work zone after passing through it. A good relationship between ODOT and OSP's regional office enables the utilization of OSP on construction sites. A wide shoulder also makes it easier to pull over vehicles if needed.

A total of eight ODOT and contractor personnel were interviewed on this day. Those interviewed felt that the overall effect of OSP patrolling is positive. Construction crew members felt safer with a police officer in the area. Motorists slowed down when they saw a police car nearby. Asphalt truck drivers were also glad to see a police car around the work zone, and they believed that motorists would behave better with a police officer present. One interviewee suggested putting a message board saying "OSP on duty" to alert the motorists. However, the interviewee felt that having OSP patrolling would not make a lot of difference in reducing speeds if the 50 mph signs were not present. The 50 mph signs are highly visible on both sides of the road, and if the police officer pulls over a motorist, the motorists have no excuse for speeding.

The asphalt truck drivers felt that driving 45 mph could have a positive impact on traffic speed. However, they are also concerned that it increases the potential for rear-end collisions. Some asphalt truck drivers also commented that motorists tailgating asphalt trucks was a big problem. Although the trucks have a sign on the back of the truck stating "Construction vehicle, do not follow", it is not enough to alert the vehicles behind them. If there were flashing lights on the back of each asphalt truck, motorists may be more aware of what was going on.

Day 5: OSP Parked on the Site
The resources required to have an OSP vehicle parked at the work zone are the same as having an OSP officer patrolling around the work zone. The police car needs to be placed at a safe and highly visible location. Of the five ODOT and contractor personnel interviewed, all agreed that having OSP parked at the beginning of work zone helped to reduce the traffic speeds, made construction workers feel safe and allowed them to focus more on their work. Those interviewed also felt that having an OSP vehicle parked on the site helped to enhance motorist safety by giving them more time to respond and reduce the chance of rear-end collisions. Since the traffic speed was lower, asphalt truck drivers felt that it was easier for them to pull into and out of the paving lane. Some asphalt truck drivers commented that having a police car around also gave them pressure to slow down because the drivers could get tickets for speeding too and it would affect their ability to get future work. One interviewee felt that OSP parking on the site worked well on this project because it was not common to have a police car parked at a work zone in Oregon and the motorists would take it seriously. Once they get used to OSP officers present, however, they may start to ignore it.

Day 6: Radar Speed Monitoring Display

It took one person, one pickup with a trailer, and 30 minutes to put out a radar speed monitoring display on the project. Setting up of the speed monitoring display was very easy. To safely locate the display, a wide shoulder or a closed lane is needed. The display used for this project was visible, but may not have been big or tall enough. A total of four people were interviewed on this work day. Those interviewed felt that the display helped to slow down the traffic, and it had to work together with the 50 mph speed reduction signs. Some interviewees believed that motorists would slow down after they read their speed from the speed monitoring display, but if the motorists did not care about it, then it would not affect them. Some motorists slowed down when they passed the speed monitoring display and sped up afterward, similar to what the drivers did when seeing the parked police vehicle.

Day 7: Tubular Markers on Both Sides of Travelling Lane

The resources required to place tubular markers (tubes) on both sides of the travelling lane were an extra cone truck and an extra worker. It took approximately 30-45 minutes to place the extra markers. Limitations to implementing the tubular markers on both sides of the travel lane were the availability of markers, and the extra labor and time to maintain the markers on the roadway because they were easily knocked down if struck by a passing vehicle. While the tubular markers were not adjacent the passing vehicles at some locations (due to the long distance between markers), the additional line of markers helped to keep traffic in a line. The additional markers also helped to gain motorists' attention and to provide guidance when there was no fog line.

Day 8: Drums on Both Sides of Travelling Lane

The resources required to put out the drums (barrels) on both sides of the travelling lane were an extra TMA pickup truck, a cone truck, extra drums, six people, and two extra hours. In addition, it took a longer length of time to pick up the drums. One worker was always in a dangerous position standing behind the cone truck to load the drums. Of those people interviewed (four interviews), it was felt that the reflectivity of the drums was so overwhelming that it might create a hazard for the motorists. Additionally, with drums on both sides, the drums were more frequently struck by the passing vehicles. The additional drums can become an obstacle and hazard. As a result, it was felt by many of those interviewed that locating drums on both sides of the travelling lane was a dangerous situation for the motorists.

Those interviewed believed that the drums did help to slow down the traffic and it made the construction workers feel safer. The drums on both sides worked better when the road was straight compared to on a curve. The reflectivity of the drums plus presence of a curve could confuse motorists so much that they may not know where to drive. At one point in the work period, a passing vehicle stopped in the middle of the closed lane because the driver did not recognize the travel lane.

The asphalt truck drivers did not like the drums because, while they could run over tubular markers to pull into the paving lane, they could not hit the drums without potentially damaging their truck. Given the large diameter of the drums, the spacing between the drums seems narrower and it became difficult for the truck drivers to pull into the paving lane.

Unlike tubular markers which are designed to stand back up by themselves after being run over, the drums do not have that ability. The drums must be lifted and positioned manually by a ground crew member. In addition, the drums are very heavy which makes maintaining the line of drums more difficult for the traffic control crew.

Overall, according to those interviewed, it was agreed that drums were good for the taper, and maybe on one side to replace the tubular markers, but not good for use on both sides of the travel lane.

Days 9 and 10
The traffic control devices on Days 9 and 10 were the PCMS signs on rollers and the radar speed monitoring display, which was similar to the devices implemented on Days 3 and 6. The interview results from Days 9 and 10 are summarized together with the results from Days 3 and 6 presented above.

4.1.2 Researcher Observation for I-84 Project

The researchers conducted their own observations during each work period and documented information regarding environmental conditions, roadway conditions, traffic control device implementation, and the construction work progress. Appendix D shows the researcher observation form used for the first day. The following is a summary of the observations made by the researchers:

- The traffic typically slows down as it passes the paver, and then speeds up after the paver, irrespective of the treatment. The speed data collected shows this slowdown for every treatment. The speed to which the traffic slows down, and the rate at which it slows down, depends on the treatment.

- An OSP officer was seen passing through the work zone on at least one night in which no OSP officer was planned to be on the site according to the research plan. The presence of the OSP officer passing through the work area may impact the recorded vehicle speeds.

- All of those interviewed (ODOT and contractor personnel, as well as the asphalt truck drivers) appreciate the efforts being made to slow down traffic. They have really noticed the PCMS signs on the rollers, OSP patrolling, and OSP parked on the site.

- Some of those interviewed provided suggestions for other treatments. The following are some of the suggested treatments:

    - A line of temporary striping across the lane (similar to a rumble strip)

    - Placing flares periodically along the work area (this was mentioned by the OSP officer and is done regularly by the ODOT Bridge Maintenance crew in Portland)

    - Placing a worker with a “Slow” paddle in front of the paver

    - Placing illuminated sequential arrow signs on the back of the asphalt trucks for use when going into/out of the work area

- Placing radar emitting devices in the work zone to make it appear to those vehicles with radar detectors that there is an OSP officer nearby checking speeds.

- The work operations regularly place workers in hazardous locations. Below are some examples of the hazardous situations. No protection was provided to these workers during the work operations. **Altering the work operations is needed to minimize the risk of injury.**

  - The worker who helps to back-up the asphalt trucks and then operates the controls on the truck to dump the asphalt stands right on the cone line and sometimes in the lane adjacent traffic. To prevent this, the controls for dumping the asphalt should be located on **both** sides of the truck.

  - When a new section of asphalt is started, workers rake the asphalt along its edge to create a smooth edge for the rollers. The workers stand in the travel lane to rake the asphalt.

  - Workers at the grinder are regularly measuring and checking the edge of the pavement along the travel lane, placing themselves on the cone line.

4.1.3 Traffic Control Devices Cost Summary for I-84 Project

The costs associated with implementation of the traffic control devices on the I-84 case study project are listed in Table 4.1. The cost information was provided by the ODOT project manager.

Table 4.1: Cost Summary of I-84 Project

Cost Item	Unit Price	Quantity	Total Price
TCS	$950	11 shifts	$10,450
PCMS signs on rollers	$5,375	2	$10,750
Temporary speed signs	$300	6	$2,400
Radar speed monitoring display	$500 (rental)	1	$500
Additional traffic control to place tubular markers on both sides of travel lane	$450	1 shift	$450
Additional traffic control to place drums (barrels) on both sides of travel lane	$600	1 shift	$600
Total	--	--	$25,150

Having an OSP officer on the construction site costs approximately $79 per hour. The unit cost for each traffic control device is listed in Table 4.2. The cost of the temporary speed signs, PCMS signs on rollers, and radar speed monitoring display is allocated to each day according to the number of paving days that occurred (10 days in total).

Table 4.2: Cost for Each Traffic Control Device for I-84 Project

Traffic Control Device	Cost of Traffic Control Device
Typical TCP	$0
Temporary 50 mph signs (added to all treatments except typical TCP)	$950 (1 shift TCS) + $240 (signs per day) = $1,190
PCMS signs on rollers	$10,750 / 10 days (2 PCMS on rollers) = $1,075
OSP patrolling site	($79/hr)*(4 hrs) = $316 per 4 hour shift
OSP parked on site	($79/hr)*(4 hrs) = $316 per 4 hour shift
Radar speed monitor display	$500 / 10 days = $50
Tubular markers on both sides	$450
Drums on both sides	$600

The information in the above table shows the cost for each traffic control device, not the total cost for each day of the study. A combination of devices was used for most of the days, so the cost for each day is different from the cost for each traffic control device. For example, OSP patrolling, PCMS signs on rollers, and temporary 50 mph signs were used for Day 4. The cost of Day 4 will be the cost of OSP patrolling ($316) plus the cost of PCMS signs on rollers ($1,075) plus the cost of the 50 mph signs ($1,190) which equals $2,581. The cost for each day in the study is listed in Table 4.3.

Table 4.3: Cost for Each Day of I-84 Project

Day	Treatment	Cost for Each Day
1	Typical TCP	$0
2	50 mph signs	$1,190
3	PCMS signs on rollers and 50 mph signs	$1,075
4	OSP patrolling, PCMS signs on rollers, and 50 mph signs	$2,581
5	OSP parked, PCMS signs on rollers, and 50 mph signs	$2,581
6	Radar speed monitoring display and 50 mph signs	$1,240
7	Tubular markers on both sides, PCMS signs on rollers, and 50 mph signs	$2,715
8	Drums on both sides, PCMS signs on rollers, and 50 mph signs	$2,865
9	PCMS signs on rollers, radar speed monitoring display, and 50 mph signs	$2,315
10	PCMS signs on rollers, radar speed monitoring display, and 50 mph signs	$2,315

The cost for extra labor and equipment to help the research team implement the speed sensors is very high. The traffic control device costs summarized above are not the expected device costs for normal projects that do not have research involvement. The costs shown above include the cost of helping the research team implement the traffic control devices plus the cost of the devices themselves. For a typical project, the extra cost will be lower than shown above.

4.1.4 Speed Data Summary

On the I-84 case study project, ten days of speed data were recorded. For each day, five traffic analyzers at four locations were used: two analyzers in the fast and slow lanes near the Road Work Ahead signs, one in the traveling lane near the end of taper, and two in the traveling lane within the work zone about one mile apart from each other. For each day, the speed data is summarized by location, vehicle type, and time of the day. For each location of each day, the researchers created tables and figures showing the hourly summary of vehicle speed and vehicle length. As a result, there are approximately 200 pages of tables and figures for the I-84 project speed data. These are provided in Appendix F. Only the figures and tables for the first traffic analyzer in the work zone on Day 1 are described and provided below. Presentation and interpretation of the figures and tables for the other days and locations shown in Appendix F are similar to the following presented for Day 1.

Table 4.4 shows the hourly summary of vehicle speeds for first work zone (WZ) traffic analyzer on Day 1. The data was recorded from 7:00pm to 5:00am. Vehicle speed is organized into 5 mph speed bins, and the first column shows these speed ranges. The second column, labeled "Total", shows the vehicle speed information for all hours of the work day combined. The following columns show the information for each hour during the work period. The information in each column includes the percentage of vehicles in each speed bin, total number of vehicles for that day, average speed of all vehicles for that day, standard deviation for the average speed, the 85th percentile of all vehicle speeds, the minimum and maximum speeds for that day, and the range of all vehicle speeds. The yellow bars and red bars provide a graphical view of the distribution of vehicle speed. The yellow bars show that the speed for all vehicles is approximately normally distributed, with a center near 50-54 mph. The red bars indicate that the speed distribution changes from hour-to-hour, with a trend of decreasing from 7:00pm to midnight and increasing after midnight.

Table 4.4: Hourly Summary of Vehicle Speed for Day 1 First WZ Analyzer

	Hour										
Vehicle Speed (all vehicles)	**Total**	19:00-20:0	20:00-21:0	21:00-22:0	22:00-23:0	23:00-00:0	00:00-01:0	01:00-02:0	02:00-03:0	03:00-04:0	04:00-05:0
MPH											
< 10	0.2%	0.0%	0.0%	0.0%	0.8%	0.8%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.9%	0.0%	0.4%	0.0%	3.9%	1.6%	2.4%	0.0%	0.0%	0.0%	0.0%
15-19	1.5%	0.0%	1.9%	0.0%	4.7%	3.3%	1.2%	0.0%	0.0%	0.0%	2.6%
20-24	3.1%	0.0%	5.0%	1.0%	4.7%	11.4%	0.0%	0.0%	0.0%	1.3%	0.0%
25-29	4.5%	0.0%	4.6%	9.6%	7.1%	8.9%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	7.1%	1.1%	8.1%	8.2%	15.0%	14.6%	3.5%	0.0%	0.0%	0.0%	5.1%
35-39	8.3%	1.1%	9.6%	11.5%	16.5%	10.6%	4.7%	2.8%	3.0%	0.0%	7.7%
40-44	12.3%	10.0%	16.5%	19.7%	11.8%	10.6%	8.2%	7.0%	1.5%	8.0%	2.6%
45-49	15.6%	7.8%	19.2%	21.2%	15.7%	10.6%	22.4%	18.3%	4.5%	10.7%	5.1%
50-54	17.0%	12.2%	16.2%	15.4%	7.9%	15.4%	28.2%	26.8%	34.3%	14.7%	10.3%
55-59	13.7%	14.4%	8.8%	10.1%	7.1%	8.9%	14.1%	23.9%	31.3%	25.3%	28.2%
60-64	7.7%	21.1%	5.4%	1.9%	1.6%	1.6%	14.1%	8.5%	14.9%	18.7%	12.8%
65-69	4.6%	14.4%	2.3%	1.4%	2.4%	1.6%	1.2%	9.9%	9.0%	9.3%	12.8%
70-74	2.3%	11.1%	1.2%	0.0%	0.8%	0.0%	0.0%	1.4%	1.5%	12.0%	2.6%
>=75	1.2%	6.7%	0.8%	0.0%	0.0%	0.0%	0.0%	1.4%	0.0%	0.0%	10.3%
Total # of vehicles	1146	90	260	208	127	123	85	71	67	75	39
Average speed	47.2	59.4	44.6	43.9	38.6	38.9	49.4	54.3	55.7	57.2	56.5
St. Dev.	13.2	11.0	12.1	9.4	13.2	13.0	10.2	7.6	6.8	9.6	13.5
85th percentile	60.0	72.0	56.0	54.0	53.0	53.7	59.4	61.5	64.0	67.8	67.3
Min	8.0	34.0	13.0	24.0	8.0	9.0	14.0	39.0	35.0	20.0	19.0
Max	121.0	82.0	76.0	68.0	71.0	66.0	69.0	76.0	71.0	74.0	83.0
Range	113.0	48.0	63.0	44.0	63.0	57.0	55.0	37.0	36.0	54.0	64.0

The total number of vehicles row shows the traffic volume for that day. The traffic count for each hour shows the hourly traffic volume. However, this information may not be consistent among different traffic analyzers. Depending on the location of the traffic analyzer in the lane, some vehicles may not travel over the traffic analyzer and therefore not be recorded by the analyzer. Therefore, for the statistical analysis of the data, the traffic counts recorded by the reference analyzers (the analyzers at the Road Work Ahead signs) are used.

The rows of standard deviation and range reveal the information regarding variance of vehicle speed. If the standard deviation decreases, the variance also decreases.

Table 4.5, Table 4.6, Table 4.7, and Table 4.8 show similar information to that shown in Table 4.4, for a specific vehicle type based on the length of the vehicle. The vehicles are categorized into four types depending on their length. Table 4.5 shows the speed information for vehicles less than 25 feet long, which are normal passenger cars and small pick-ups without a trailer. Table 4.6 shows speeds for vehicles between 25 and 49 feet long, which are mostly long vans, one trailer pick-ups, and small trucks. Table 4.7 shows the speeds for vehicles from 50 to 74 feet in length, which are mid-size, semi-trucks with trailers. Contractor asphalt trucks fall into his category. Table 4.8 shows the speeds for vehicles longer than or equal to 75 feet, which are long trucks.

Table 4.5: Hourly Summary of Vehicle (0-25 ft long) Speed for Day 1 First WZ Analyzer

	Hour										
Vehicle Speed (0-25 FT Vehicles)	**Total**	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-00:00	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00
MPH											
< 10	0.5%	0.0%	0.0%	0.0%	1.9%	2.2%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	1.8%	0.0%	0.9%	0.0%	7.4%	2.2%	5.3%	0.0%	0.0%	0.0%	0.0%
15-19	2.8%	0.0%	3.7%	0.0%	7.4%	2.2%	5.3%	0.0%	0.0%	0.0%	11.1%
20-24	3.3%	0.0%	3.7%	0.0%	5.6%	11.1%	0.0%	0.0%	0.0%	16.7%	0.0%
25-29	7.3%	0.0%	9.2%	9.2%	11.1%	11.1%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	8.9%	2.0%	11.9%	8.0%	11.1%	15.6%	5.3%	0.0%	0.0%	0.0%	0.0%
35-39	9.6%	2.0%	10.1%	9.2%	18.5%	8.9%	15.8%	0.0%	0.0%	0.0%	11.1%
40-44	14.4%	16.0%	13.8%	20.7%	11.1%	17.8%	10.5%	0.0%	0.0%	0.0%	0.0%
45-49	14.7%	10.0%	18.3%	23.0%	9.3%	4.4%	21.1%	10.0%	16.7%	0.0%	0.0%
50-54	12.4%	14.0%	11.0%	16.1%	3.7%	11.1%	10.5%	20.0%	50.0%	33.3%	0.0%
55-59	9.1%	8.0%	7.3%	10.3%	7.4%	11.1%	10.5%	30.0%	0.0%	0.0%	11.1%
60-64	6.3%	14.0%	6.4%	2.3%	0.0%	2.2%	15.8%	10.0%	33.3%	16.7%	11.1%
65-69	5.1%	14.0%	2.8%	1.1%	3.7%	0.0%	0.0%	30.0%	0.0%	16.7%	33.3%
70-74	2.0%	12.0%	0.0%	0.0%	1.9%	0.0%	0.0%	0.0%	0.0%	16.7%	0.0%
>=75	1.8%	8.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	22.2%
Total # of vehicles	395	50	109	87	54	45	19	10	6	6	9
Average speed	44.5	57.8	42.3	44.4	35.7	37.4	44.5	58.0	53.7	54.3	58.6
St. Dev.	14.4	12.5	12.9	9.2	15.0	13.3	14.0	6.3	5.4	18.6	19.0
85th percentile	59.9	72.0	56.0	54.0	50.2	53.4	59.6	65.0	60.3	67.8	74.4
Min	8.0	34.0	13.0	26.0	8.0	9.0	14.0	48.0	48.0	20.0	19.0
Max	79.0	79.0	76.0	65.0	71.0	64.0	63.0	65.0	61.0	73.0	78.0
Range	71.0	45.0	63.0	39.0	63.0	55.0	49.0	17.0	13.0	53.0	59.0

Table 4.6: Hourly Summary of Vehicle (25-50 ft long) Speed for Day 1 First WZ Analyzer

	Hour										
Vehicle Speed (25-50 FT Vehicles)	Total	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-00:00	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00
MPH											
< 10	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%	0.0%	0.0%	2.1%	2.5%	3.6%	0.0%	0.0%	0.0%	0.0%
15-19	1.2%	0.0%	1.0%	0.0%	2.1%	7.5%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	2.8%	0.0%	5.9%	2.4%	2.1%	7.5%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	2.5%	0.0%	2.0%	4.8%	2.1%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	4.6%	0.0%	3.0%	3.6%	17.0%	12.5%	0.0%	0.0%	0.0%	0.0%	7.1%
35-39	7.6%	0.0%	7.9%	14.5%	14.9%	7.5%	0.0%	3.2%	0.0%	0.0%	14.3%
40-44	10.4%	0.0%	17.8%	15.7%	10.6%	5.0%	3.6%	3.2%	0.0%	14.3%	7.1%
45-49	15.0%	3.0%	16.8%	24.1%	19.1%	15.0%	14.3%	12.9%	0.0%	10.7%	7.1%
50-54	19.8%	6.1%	19.8%	16.9%	17.0%	17.5%	28.6%	25.8%	41.4%	14.3%	21.4%
55-59	16.1%	21.2%	11.9%	13.3%	6.4%	7.5%	25.0%	25.8%	34.5%	21.4%	21.4%
60-64	9.0%	33.3%	6.9%	2.4%	4.3%	2.5%	21.4%	9.7%	6.9%	14.3%	7.1%
65-69	6.0%	18.2%	3.0%	2.4%	2.1%	5.0%	3.6%	12.9%	13.8%	10.7%	0.0%
70-74	3.2%	12.1%	3.0%	0.0%	0.0%	0.0%	0.0%	3.2%	3.4%	14.3%	7.1%
>=75	1.2%	6.1%	1.0%	0.0%	0.0%	0.0%	0.0%	3.2%	0.0%	0.0%	7.1%
Total # of vehicles	434	33	101	83	47	40	28	31	29	28	14
Average speed	49.6	63.2	47.7	45.6	42.4	40.3	53.2	56.3	57.2	57.1	53.2
St. Dev.	12.5	7.8	12.3	9.4	11.7	14.2	9.9	8.3	5.8	9.8	13.4
85th percentile	62.0	72.0	59.0	55.0	53.1	54.3	61.0	65.5	64.8	68.0	61.5
Min	12.0	46.0	16.0	24.0	12.0	14.0	14.0	39.0	50.0	42.0	33.0
Max	83.0	82.0	75.0	68.0	66.0	66.0	69.0	76.0	71.0	74.0	83.0
Range	71.0	36.0	59.0	44.0	54.0	52.0	55.0	37.0	21.0	32.0	50.0

Table 4.7: Hourly Summary of Vehicle (50-75 ft long) Speed for Day 1 First WZ Analyzer

	Hour											
Vehicle Speed (50-75 FT Vehicles)	Total	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-00:00	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00	05:00-06:00
MPH												
< 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%
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%
15-19	0.8%	0.0%	0.0%	0.0%	12.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	6.6%	0.0%	14.3%	0.0%	12.5%	25.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	7.4%	0.0%	0.0%	24.0%	25.0%	6.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	11.5%	0.0%	9.5%	24.0%	25.0%	18.8%	10.0%	0.0%	0.0%	0.0%	0.0%	0.0%
35-39	10.7%	0.0%	4.8%	12.0%	12.5%	25.0%	10.0%	10.0%	15.4%	0.0%	0.0%	0.0%
40-44	11.5%	25.0%	14.3%	28.0%	0.0%	0.0%	0.0%	20.0%	7.7%	0.0%	0.0%	0.0%
45-49	13.9%	0.0%	14.3%	4.0%	12.5%	6.3%	30.0%	20.0%	15.4%	33.3%	0.0%	0.0%
50-54	18.0%	50.0%	33.3%	4.0%	0.0%	12.5%	40.0%	40.0%	7.7%	8.3%	0.0%	0.0%
55-59	11.5%	25.0%	9.5%	4.0%	0.0%	6.3%	10.0%	10.0%	30.8%	25.0%	0.0%	0.0%
60-64	4.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	15.4%	25.0%	50.0%	0.0%
65-69	1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	7.7%	8.3%	0.0%	0.0%
70-74	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
>=75	1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	100.0%
Total # of vehicles	122	4	21	25	8	16	10	10	13	12	2	1
Average speed	44.4	50.3	43.5	36.9	29.9	35.6	48.0	48.4	52.0	55.3	72.5	121.0
St. Dev.	14.1	7.0	11.6	8.2	9.5	11.1	7.5	5.9	9.9	7.8	13.4	#DIV/0!
85th percentile	57.0	54.9	53.0	44.0	36.8	49.5	52.7	52.0	60.8	62.0	79.2	121.0
Min	18.0	41.0	21.0	25.0	18.0	21.0	34.0	39.0	35.0	45.0	63.0	121.0
Max	121.0	58.0	56.0	57.0	48.0	57.0	59.0	58.0	65.0	69.0	82.0	121.0
Range	103.0	17.0	35.0	32.0	30.0	36.0	25.0	19.0	30.0	24.0	19.0	0.0

Table 4.8: Hourly Summary of Vehicle (75+ ft long) Speed for Day 1 First WZ Analyzer

	Hour										
Vehicle Speed (+75 FT Vehicles)	Total	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-00:00	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00
MPH											
< 10	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%
15-19	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	1.5%	0.0%	0.0%	0.0%	5.6%	9.1%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	1.5%	0.0%	0.0%	15.4%	0.0%	4.5%	0.0%	0.0%	0.0%	0.0%	0.0%
30-34	6.2%	0.0%	10.3%	7.7%	16.7%	13.6%	3.6%	0.0%	0.0%	0.0%	7.1%
35-39	5.6%	0.0%	17.2%	7.7%	16.7%	9.1%	0.0%	0.0%	0.0%	0.0%	0.0%
40-44	12.8%	0.0%	24.1%	23.1%	22.2%	13.6%	14.3%	10.0%	0.0%	6.9%	0.0%
45-49	20.0%	33.3%	34.5%	23.1%	27.8%	18.2%	28.6%	30.0%	0.0%	3.4%	7.1%
50-54	19.5%	0.0%	10.3%	23.1%	0.0%	22.7%	35.7%	25.0%	36.8%	13.8%	7.1%
55-59	19.0%	33.3%	3.4%	0.0%	11.1%	9.1%	7.1%	25.0%	36.8%	34.5%	50.0%
60-64	9.2%	33.3%	0.0%	0.0%	0.0%	0.0%	10.7%	10.0%	21.1%	20.7%	14.3%
65-69	2.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	5.3%	6.9%	14.3%
70-74	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	13.8%	0.0%
>=75	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicles	195	3	29	13	18	22	28	20	19	29	14
Average speed	49.3	54.7	43.3	41.9	41.2	41.9	49.5	52.2	56.5	58.6	56.1
St. Dev.	9.9	7.8	6.1	8.1	8.3	10.9	6.8	5.4	5.2	7.7	8.0
85th percentile	59.0	59.8	48.8	50.2	49.0	52.9	56.9	57.3	62.6	66.0	60.3
Min	21.0	46.0	32.0	29.0	24.0	21.0	30.0	41.0	50.0	43.0	34.0
Max	74.0	61.0	56.0	53.0	56.0	59.0	61.0	62.0	68.0	74.0	67.0
Range	53.0	15.0	24.0	24.0	32.0	38.0	31.0	21.0	18.0	31.0	33.0

The above tables and interpretation show an example of how to understand the additional tables in Appendix F. For the I-5 case study project, similar tables are provided in Appendix G.

The speed data from all of the analyzers at the four locations is not available on some days. On Day 2, the data from the second WZ analyzer is not available due to the fact that the second WZ analyzer was out of the work zone during the entire work period (the work progress was stopped early due to problems with compaction and the work never made it all the way to the analyzer location). The second WZ analyzer was located in the A lane which was the traveling lane for that day. So the speed data recorded that day was mostly smaller cars. Therefore, only the summary table of all vehicles is provided in the Appendix. In addition, the analyzer at the end of taper location on Day 6 had some problems recording correct speeds. Upon inspection, the speed data recorded was found to be very different than other days and not in the range expected, so the Day 6 end of taper analyzer data is not included in Appendix F.

Figure 4.3 below shows a summary of the 85th percentile speed in each hour for all ten days for the I-84 case study project. The figure presents the data recorded from the first work zone traffic analyzer. From the figure, it can be seen that the last hour of data for some days are lower than the hour before. This may be due to the fact that the data for the full hour is not recorded for the last hour of the work period, so the 85th percentile speed of the last hour may not represent the actual traffic speeds over the entire hour.

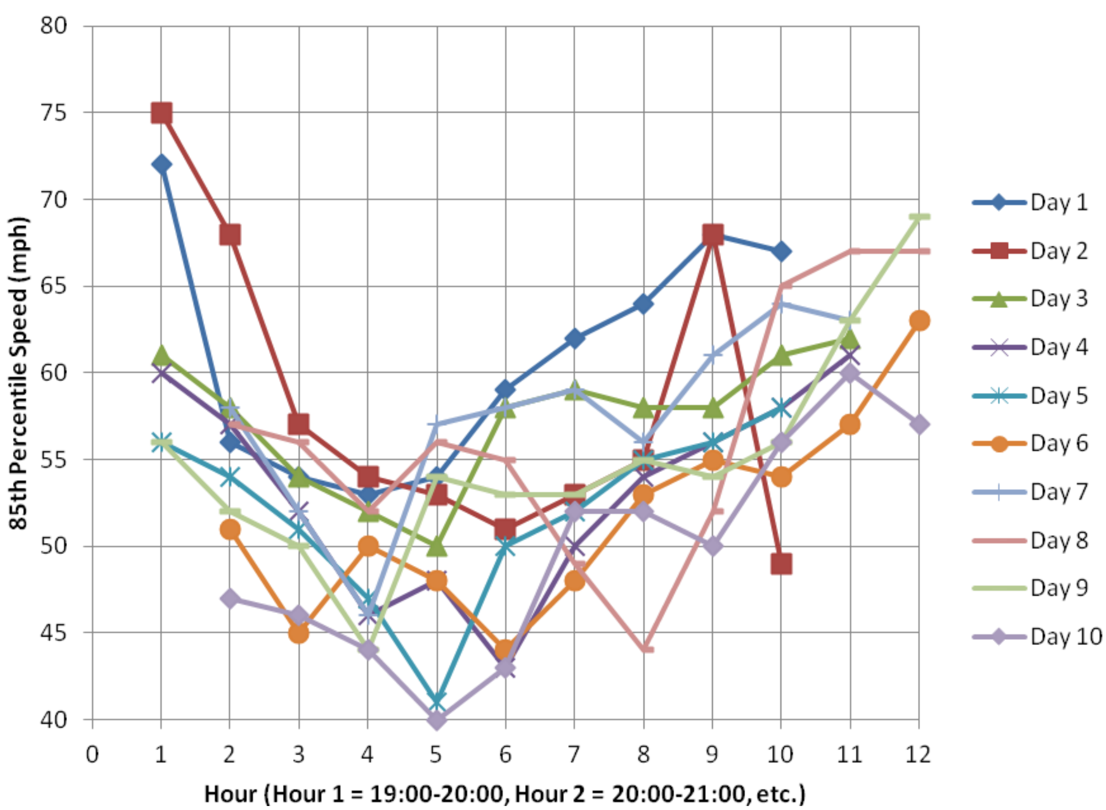

Figure 4.3: Hourly Vehicle Speed (85th Percentile) for 10 days of I-84 Project

Some hourly speeds for Day 2 are higher than on other days, which may be a result of the holiday traffic for that day. The figure shows that Day 10's speed is lower than the other days. Day 10 is the first day of westbound paving, and also it is the only westbound paving day of all the data collection days. As a result, the speed data for Day 10 should not be compared with the speeds from other days. For other days, it seems that the speed on Day 5 speed is low and has the lowest point from 11:00pm to 12:00am.

This figure gives a vivid view of each hour's speed for all days. However, it is inappropriate to compare the same hour's speed among days because for different days, the paver passed the first WZ traffic analyzer at different times. From the researcher's observations, it is obvious that vehicles tend to slow down when they approach the paver and speed up after they pass the paver. As a result, the time at which the lowest speed of each day occurs is highly dependent on when the paver passes the traffic analyzer. The speed relative to the distance to paver will be discussed in a later section.

Figure 4.4 shows the number of vehicles for each hour for all 10 days of the I-84 case study project. The data used for this figure comes from the first WZ traffic analyzer. There is a clear trend for all days that the traffic volume drops gradually from 7:00pm to 4:00am, and hits the lowest volume around 4:00am. After that time, the traffic volume increases. The traffic volume from 11:00pm to 12:00am is approximately 100 vehicles, and from 12:00am to 4:00am is about 75 vehicles per hour. The figure also shows that the traffic volumes for different days are different. The volume for Day 2 is the highest due to the holiday traffic, and the volumes on the other days are different but very similar.

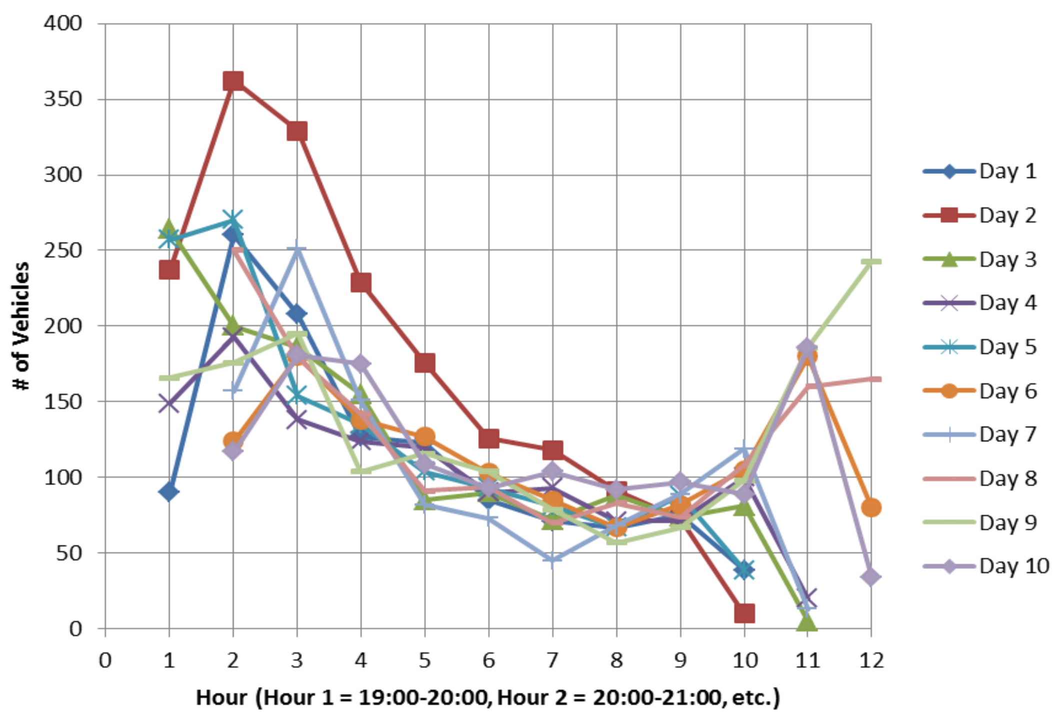

Figure 4.4: Hourly Traffic Volume for All days for I-84 Project

Figure 4.5 shows the ratio of the 85th percentile speed of each hour to the number of vehicles for each hour, based on first WZ traffic analyzer. The trends for all days are similar, which is the ratio goes up until 4:00am and goes down after that time. Day 2 seems to have the lowest ratio. As discussed above, Day 2 has the highest speed and highest traffic volume, but the ratio is low. This indicates that the high speed is associated with volume, but not only because of the traffic volume. If we adjust the speed by traffic volume, it may over-emphasize the effect of traffic volume on speed. Additionally, the relationship between speed and traffic volume may be not linear.

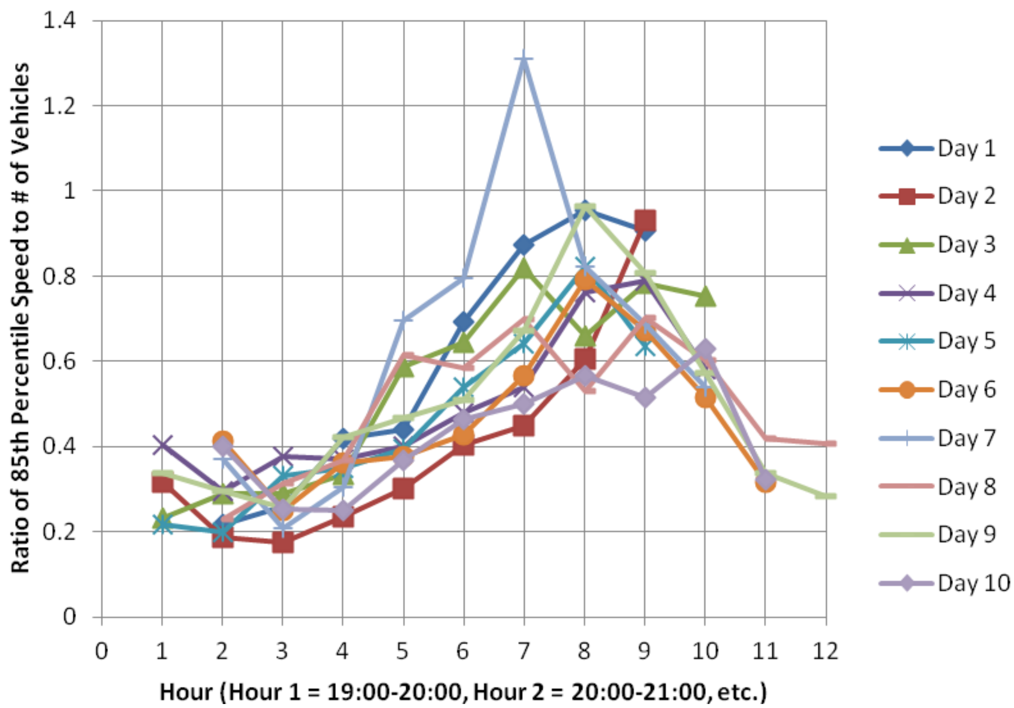

Figure 4.5: Ratio of Hourly Speed (85th Percentile) to Traffic Volume for All Days of I-84 Project

Figure 4.6 shows a summary of the 85th percentile speed for the periods before sunset, sunset to midnight, and after midnight for all days. The figure shows the data from all of the traffic analyzers combined. The figure reveals that Day 10 had the lowest speed for all time periods, followed by Day 6, and Day 2 had the highest speed for the first two time periods. The reasons for Day 2's high speed and Day 10's low speed are discussed above. From previous figures, it seems that Day 5 had the lowest speed. However, here Day 6's speed is lower than Day 5. This may be because for Day 6, the end of taper data is not available due to the problem with the traffic analyzer. This lack of data may affect the 85th percentile speed of all the traffic analyzers combined for that day. As mentioned previously, for Day 2, the second WZ traffic analyzer was unfortunately located out of the WZ during the work period and this may drive the Day 2 speeds even higher.

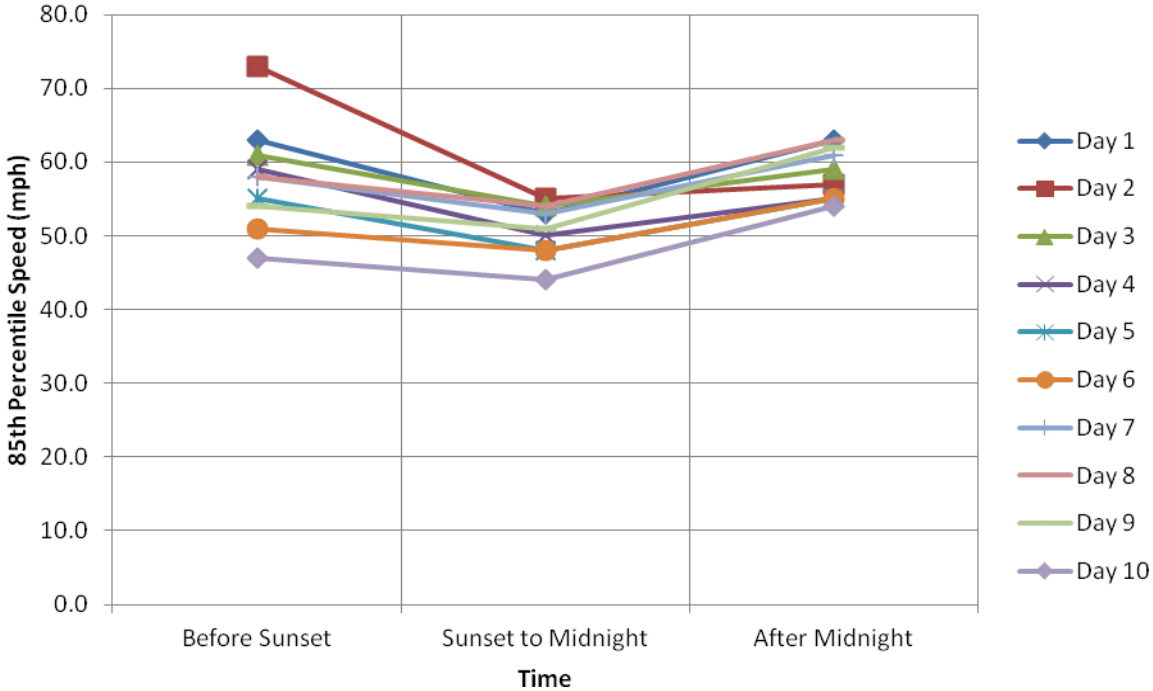

Figure 4.6: Vehicle Speed (85th Percentile) for Different Time Periods for All Days of I-84 Project

Figure 4.7 shows the 85th percentile speed for different types of vehicles for all days. The data used for this figure is based on all analyzers combined. It is clear that the speed of the smaller vehicles (less than 25 feet in length) is higher than that for other types of vehicles. The speed for 50-75 ft long vehicles is likely low because the contractor asphalt trucks fall into this category. This figure clearly shows slower speeds for all vehicles on Days 5 and 6 when an OSP parked on the site (Day 5) and a radar speed monitoring display (Day 6) were used.

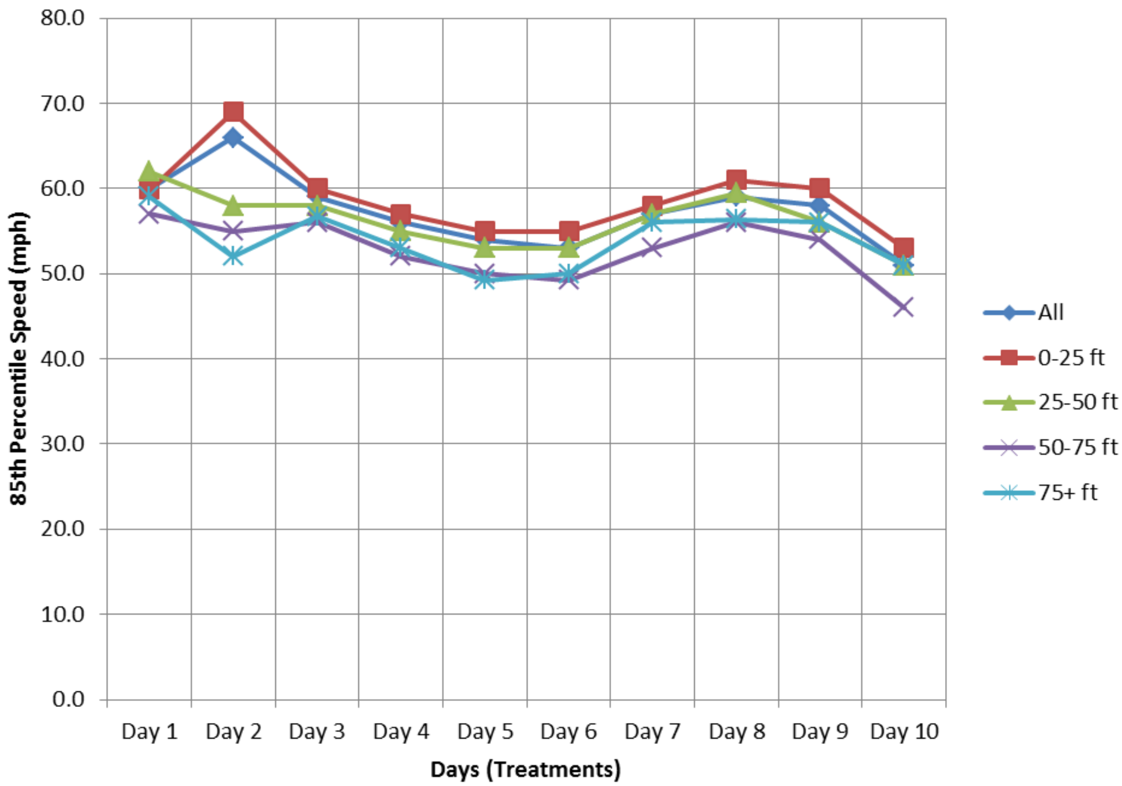

Figure 4.7: Vehicle Speed (85th Percentile) for Different Types of Vehicles for All Days of I-84 Project

Figure 4.8 shows the 85th percentile speed for different locations before and within the work zone for all 10 work days. The end of taper traffic analyzer for Day 6 was misplaced, and the data of that location was abnormal. The data for Day 2 is quite different from the other days as described above, so the data from Day 2 is excluded from the statistical analysis (see analysis in later section of this report).

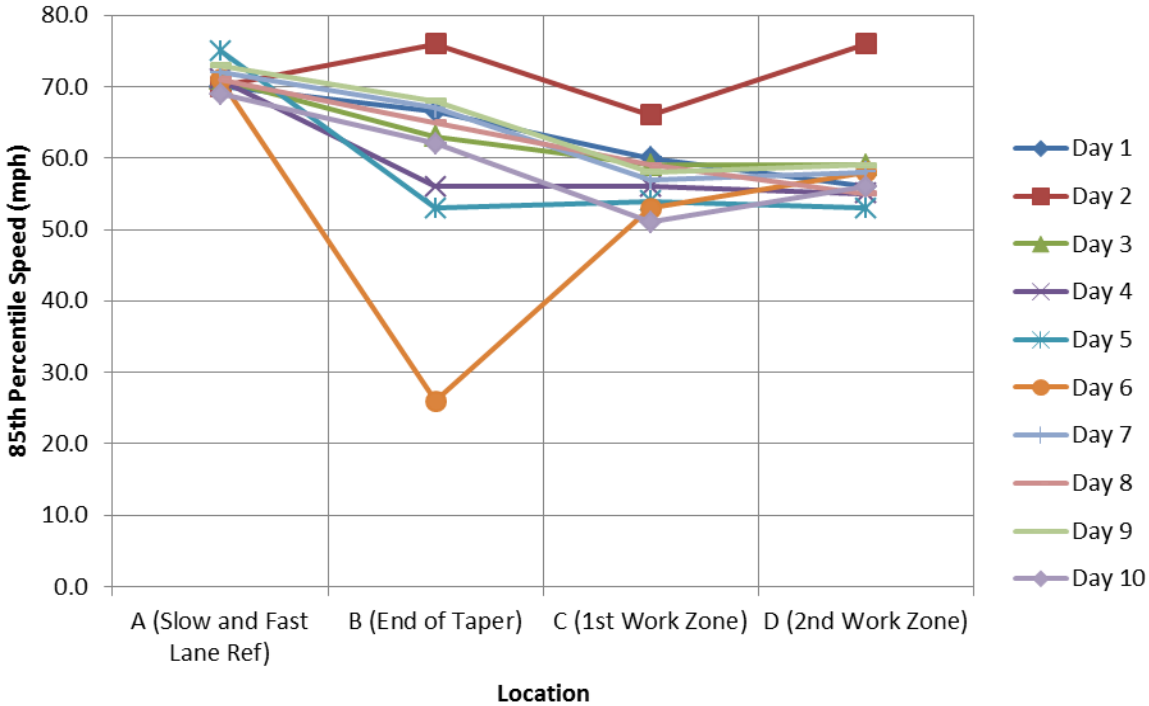

Figure 4.8: Vehicle Speed (85th Percentile) for Different Locations for All Days of I-84 Project

In general, the first and second work zone analyzer speeds are slower than end of taper speed, and the reference speed is the highest. The speed for each day at the reference location is different day-to-day, but all are within the range from 69 to 75 mph. The end of taper speeds for all days are very different, ranging from 53 to 68 mph (not including Days 2 and 6). The 85th percentile speeds for the first and second work zone analyzer data range from 50 to 60 mph.

4.2 RESULTS FOR I-5 PROJECT

4.2.1 Interview Results Summary for I-5 Project

For the I-5 case study project, the ODOT project inspector, contractor superintendent, TCS, and asphalt truck drivers were interviewed to get their opinions regarding the traffic control devices applied each day. The results of those interviews are summarized below.

Days 1 and 2, Initial TCP
The initial TCP was implemented for the first two days of main lane paving. Interview comments received regarding the initial TCP were similar to those recorded for the I-84 case study project. The roadway attributes on the I-5 project were a little different from the previous project. This section of I-5 is straight and with wide shoulders on both sides of the roadway. There is a large median between the northbound and southbound lanes. The site conditions made the site an ideal job for freeway paving.

One of the interviewees commented that the reflective vests worn by the workers should be changed to Class III (with reflective bands on sleeves) for all night work. Many of the workers on the roadway, such as the workers putting down the “stick and stomp” temporary lane markers, are located in a very dangerous situation and need to be more visible from all directions.

Day 3, 50 mph signs
The temporary 50 mph signs used on the I-5 case study project were mounted on a temporary sign support (TSS). The TSS weighed approximately 150 pounds and required two people, one trailer, and one truck a few hours to move the TSS to the proper locations. The actual time required varied depending on the traffic volume. The TSS must be located on level ground, with a Type III barricade to protect it.

Since the temporary speed limit was enforced throughout the work zone, the contractor needed to cover the existing, permanent speed limit signs. During the day time when no construction work took place requiring a lane closure, the temporary 50 mph signs needed to be turned sideways so that they were not readable by the motorists, and the permanent signs uncovered. However, one interviewee commented that the 50 mph signs should remain readable during the day time because the construction crew still had daytime activities on the road even though there was no lane closure needed.

Day 4, PCMS Signs on Trailers
It took one person and one truck approximately 30 minutes to one hour to move one PCMS sign to the desired location. The initial programming when the PCMS signs were brought to the site too approximately two hours to complete. The PCMS signs on the trailers were bigger and more visible than the PCMS signs used on the rollers on the I-84 case study project. However, the PCMS sign on the trailer also required a lot of space and therefore a big shoulder to sit on along with proper protection in front of it.

Those interviewed indicated that the PCMS signs would draw motorists’ attention to make them more aware of the construction work. Some interviewees felt that the PCMS signs also reduced the chance of vehicles following asphalt trucks into the paving lane.

Days 5 and 6, PCMS Signs on Trailer and Radar Speed Reader Display

Approximately 30 minutes was required to move one radar speed reader display to the proper location. One worker and one truck could easily do the work. The radar speed reader display was much smaller than the PCMS signs on the trailers, but it still required a fair amount of space to be safely positioned.

With the PCMS signs and speed display sitting at the beginning of the paving work, the entire working crew benefited from the lower speeds created by their presence. However, one interviewee commented that it was overwhelming to have so much information at the same location. The excessive information and signage became a distraction to motorists.

Some asphalt truck drivers thought that the radar speed reader display was not big enough and was not very visible to truck drivers. Some commented that the speed display was very effective in reducing vehicle speeds because it made motorists believe that there must be police cars nearby.

Day 7, OSP Parked on the Site

Unlike the Region where the I-84 project was located, there were enough police officers in the Eugene and Springfield region so that it was easier to have a dedicated OSP officer on the construction site. The cost to have an OSP officer present was approximately $70/hour, which includes officer overtime pay, fuel, and vehicle cost.

Having an OSP officer parked at the end of the taper can greatly reduce vehicle speed as was found on the I-84 case study project. Drivers pay more attention when they see police lights, and truck drivers commonly slow down because getting a speeding ticket would greatly affect their ability to get future jobs.

The police officer who was present on the I-5 site commented that it was a little boring to sit there but that he was still willing to do it because he knew that he was doing something to keep workers safe. It meant more to the officer to keep workers safe than to give tickets to speeding drivers. However, if a passing motorist was driving well over the speed limit, the officer would act to slow down the driver.

4.2.2 Researcher Observation for I-5 Project

The researchers conducted on-site observations on the I-5 case study project similar to that done on the I-84 case study project. The results of the researcher's observations are summarized below:

- The volume of traffic on this case study project was greater than that on the I-84 case study. With only one lane of traffic available to the motorists, this resulted in long queues in the traffic on some nights at the beginning of the work shift until the traffic volume decreased. As a result, the traffic speeds were very slow, and often came to a standstill prior to the merge. From a research perspective, it also made it more difficult to place and remove the speed sensors on the roadway. Placement of the sensors was typically delayed until later in the evening after the traffic volumes decreased. In one case, the sensors could be placed earlier because the traffic was at a standstill.

- The temporary 50 mph signs used on the project were larger and not as portable as those used on the I-84 case study project. As a result, it was more difficult and took additional time for the TCS to position the 50 mph signs. On future projects, consideration should be given to the size of sign needed and the ability to quickly and easily place and re-locate the signs. Those used on the I-84 case study project worked very well.

- The trailer-mounted PCMS signs took more time and effort to deploy than the PCMS signs on the rollers. Also, the project site contained a very large median and large shoulder which allowed for placement of the large PCMS signs. If a smaller median and shoulder are present, the trailer-mounted PCMS signs may not be usable.

- In addition to enhancing traffic control for the workers around the paver and grinder, traffic control measures need to consider the other ground personnel who also walk around the site (e.g., inspectors, QA/QC personnel, etc.). Some of these workers are located on the new pavement after the finish roller (between the finish roller and taper), in unlit areas, with no protective vehicles around them, and with no spotters to assist them.

- There is a tendency for vehicles to follow construction vehicles into the closed lane and work area. In addition to following asphalt trucks, this includes following other support vehicles that travel into and out of the work site regularly (e.g., contractor trucks, ODOT trucks, etc.). The asphalt trucks and possibly other construction vehicles should all have a sign on the back that reads "Construction vehicle, do not follow".

- Similar to the I-84 case study project, the work operations regularly place workers on the ground in hazardous locations, such as right next to the line of tubular markers adjacent passing traffic. Continued efforts should be made by the contractor to keep workers in safe locations.

- In addition to reducing the speed of passing traffic, consideration should be given to the following when selecting the traffic control measures and designing the traffic control plan:
  - Reducing the variability in the speed of the passing vehicles.
  - Providing devices, lights, messages, etc. which catch the attention of the drivers, and alert them to the need to be aware of and pay attention to the roadway.
  - Visibility of the workers
  - Work practices of the contractor's employees
  - Trucks entering/exiting the work area
  - Glare from the lighting used in the work area

4.2.3 Traffic Control Devices Cost Summary for I-5 Project

The costs associated with helping the research team implement the traffic control devices for the I-5 case study project are listed in Table 4.9. The cost information was provided by the ODOT project manager.

Table 4.9: Cost Summary of I-5 Project

Cost Item	Unit Price	Quantity	Total Cost
Laborer 1	$800	6 shifts	$4,800
Laborer 2	$800	6 shifts	$4,800
Crew Truck 1	$180	6 shifts	$1,080
Crew Truck 2	$90	6 shifts	$540
Reduced Speed Ahead signs	$184	2	$368
Speed Limit 50 Signs	$230	8	$1,840
Speed Limit 65 Signs	$230	2	$460
TSS	$190	12	$2,280
Freight on signs and TSS	--	--	$400
PCMS on trailer rental	$1,000	2	$2,000
Drums for PCMS	$50	12	$600
Type III barricades for PCMS	$100	2	$200
Speed monitoring display rental	$500	1	$500
Mobilize and de-mobilize labor and crew truck	--	--	$1,200
Total	--	--	$21,068

The cost for each traffic control device is listed in Table 4.10. The costs of the temporary speed signs, PCMS signs on trailers, radar speed monitoring display, and mobilization/de-mobilization are allocated to each day of the study (6 days in total). After the allocation, the labor and equipment cost for each day is calculated to be $2,070. The total cost related to temporary signs is $5,348, and the total cost associated with the PCMS signs on trailers is $2,800. Having an OSP officer on the construction site costs approximately $70 per hour, and $280 for 4 hours.

Table 4.10: Cost for Each Traffic Control Device for I-5 Project

Traffic Control Device	Cost of Traffic Control Device
Typical TCP	$0
Temporary 50 mph signs	$5384 / 6 days + $2,070 (labor & equipment) = $2,961
PCMS sign on trailer	$2,800 / 6 days = $467
Radar speed monitoring display	$500 / 6 days = $83
OSP parked only	($70/hr)*(4 hrs) = $280

The information in the table above shows the cost for each traffic control device, not the total cost for each day. A combination of devices was used for most of the days, so the cost for each day is different from the cost for each traffic control device. The cost for each day was calculated and is shown in Table 4.11.

Table 4.11: Cost for Each Day of I-5 Project

Day	Treatment	Cost for Each Day
1	Typical TCP	$0
2	Typical TCP	$0
3	Temporary 50 mph signs	$2,961
4	PCMS signs on trailers and 50 mph signs	$3,428
5	Radar speed monitoring display, PCMS signs on trailers, and 50 mph signs	$3,511
6	Radar speed monitoring display, PCMS signs on trailers, and 50 mph signs	$3,511
7	OSP parked on site and 50 mph signs	$3,241

As mentioned previously, the cost of extra labor and equipment to help with the research team is high, but it is not the normal cost for those traffic control devices on regular projects. The costs shown above include the cost of the extra labor and equipment, and if the traffic control devices are used on typical projects, the extra cost will be lower than that shown above.

4.2.4 Speed Data Summary

The hourly speed data summaries for each day in each location on the I-5 case study project are provided in Appendix G. The traffic analyzers were put down at approximately midnight for the first day of work, and left on the ground for two days. Therefore, for the first day, speed data is available starting after midnight while work began earlier in the evening. Due to the heat experienced during the daytime hours, the tape used to fix the analyzers to the ground became very plastic, and some of the analyzers were displaced by ongoing traffic. The number of vehicles which run over the analyzers increases when the lane closure is not present because of the location of the analyzers and the line of travel of the vehicles. Several of the displaced analyzers were either lost or severely damaged, and a lot of data for the first two days of testing was lost. The data on the first WZ analyzer from Days 1 and 2 was missing along with the data on the analyzer located at the end of taper. In addition, the vehicle speeds recorded for Day 2 were much higher than the speeds recorded on the other days. The accuracy of the data recorded on Day 2 is questionable. Moreover, the second WZ analyzer used on Day 3 was damaged, so there is no data available from the second WZ analyzer on Day 3.

Figure 4.9 below shows a summary of the 85th percentile speed in each hour for all vehicles on all seven days of the I-5 project. The data used for the figure is based on the record from the first work zone traffic analyzer except for Days 1 and 2. For the first two days, the first WZ analyzer data was not available as describe above, so the second WZ analyzer data is used in the figure for Days 1 and 2. The data from Day 2 is very different from that recorded on the other days, which may be due to the damaged traffic analyzer. Therefore, the data from Day 2 was eliminated from the data analysis in this study. The figure shows that the speed data for Days 3, 4, 6, and 7 are very similar. The speeds recorded on Day 5 are slightly lower than the other days between approximately midnight and 3:00 a.m.

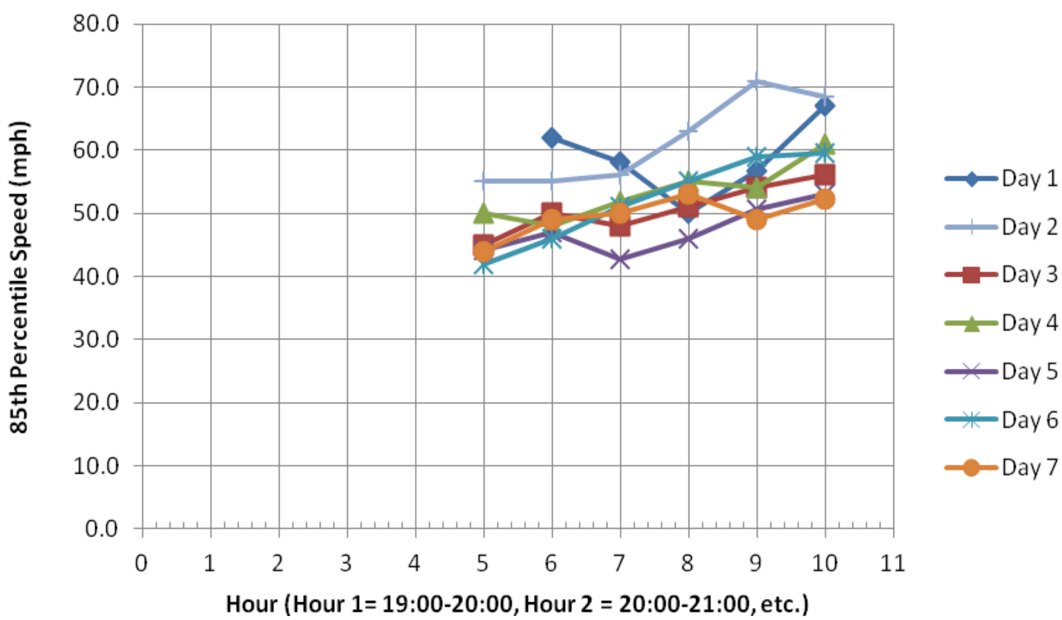

Figure 4.9: Hourly Vehicle Speed (85th Percentile) for All Days of I-5 Project

Figure 4.10 shows the number of vehicles during each hour for all days of the I-5 project. The figure is based on data recorded by the first available traffic analyzer after the beginning point of the paving work. As described above, on some days the first WZ analyzer data was not available, so the second WZ analyzer data is used in the figure below. The traffic counts for Days 1 and 2 are much smaller than the other days, which may be due to the problems with the traffic analyzers and therefore the inaccuracy in the data collected on those two days. The traffic count before midnight on Day 6 is higher than the other days. Day 6 was a Sunday night which may see more vehicles on the roadway due to people returning home from summertime weekend travel. Additionally, on some days the traffic analyzers were either put down or removed in the middle of an hour at the beginning and end of the work period. Therefore, the traffic counts for hour 5 (11:00pm – 12:00am) and hour 10 (4:00am – 5:00am) may not reflect the amount of traffic over an entire hour.

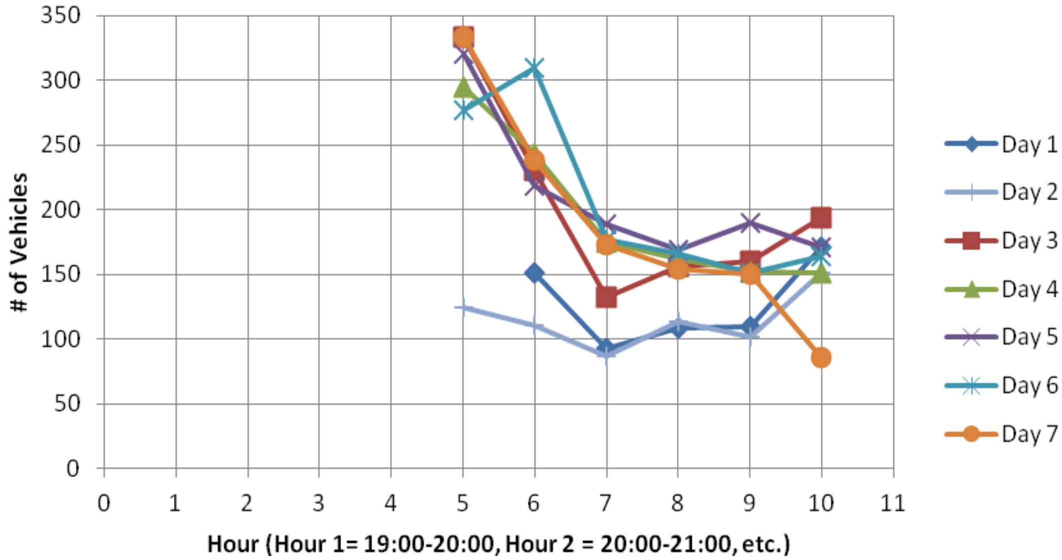

Figure 4.10: Hourly Traffic Volume for All Days for I-5 Project

The speed of the vehicles is impacted in part by the volume of vehicles on the roadway. To understand how this speed-volume relationship varies amongst the different work days, a ratio of the 85th percentile speed to the volume was calculated for each hour on each day. Figure 4.11 shows these ratios. The values in the figure are based on the first WZ traffic analyzer. The values for Days 1 and 2 are likely inaccurate due to difficulties with the traffic analyzers on those days as described above. The figure reveals that generally the ratio of the 85th percentile speed to traffic volume increases from midnight to 5:00am.

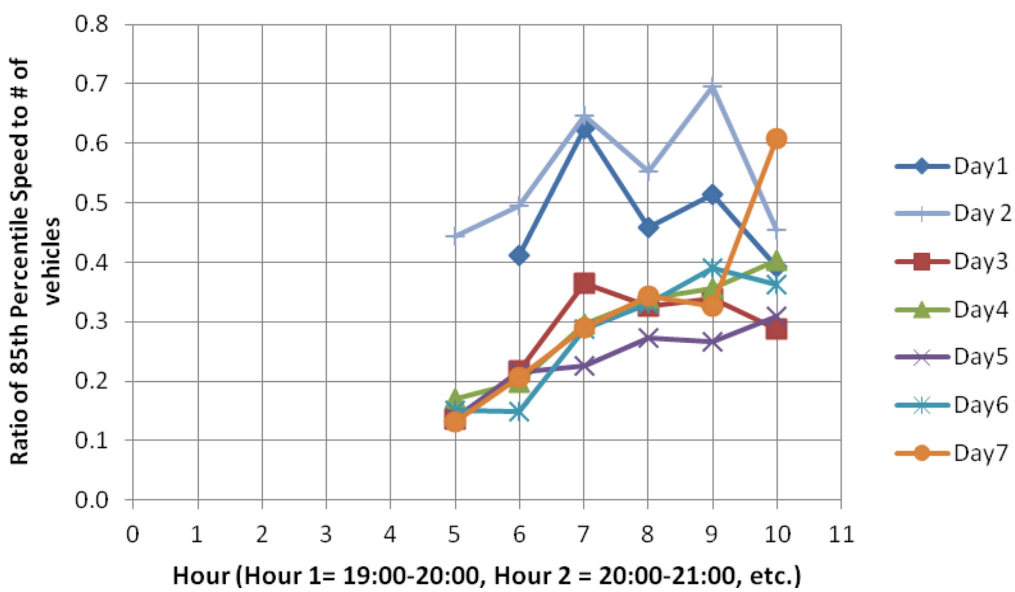

Figure 4.11: Ratio of Hourly Speed (85th Percentile) to Traffic Volume for All Days of I-5 Project

Figure 4.12 shows the 85th percentile speed for different types of vehicles for all days. For this figure, the data is based on all traffic analyzers. The figure shows that the speed for vehicles less than 25 feet in length is similar to vehicles between 25 and 50 feet in length. Also, the speed for vehicles between 50 and 75 feet is similar to the speed for vehicles longer than 75 feet. These trends are different from what was observed on the I-84 case study project.

Figure 4.12 also indicates that the 85th percentile speeds for Day 1 and Day 2 are much higher than the other days. Since Day 1 and Day 2 had no traffic control devices applied but only the initial TCP, it may suggest that the traffic control devices effectively slow down the traffic. However, the data for the first two days is not very reliable due to the significant damage to the portable traffic analyzers. For Day 1, the first and second WZ analyzers were damaged, and only the third WZ analyzer was functioning which was almost at the end of the work zone. The third WZ analyzer is counted as the first WZ analyzer for all of the following analyses using Day 1 data in this report. For Day 2, the end of taper and first WZ analyzers were damaged, so no data was valuable for these two locations. Therefore, there is less confidence in the conclusion that the added traffic control devices slow down the vehicle speeds dramatically as depicted in the figure.

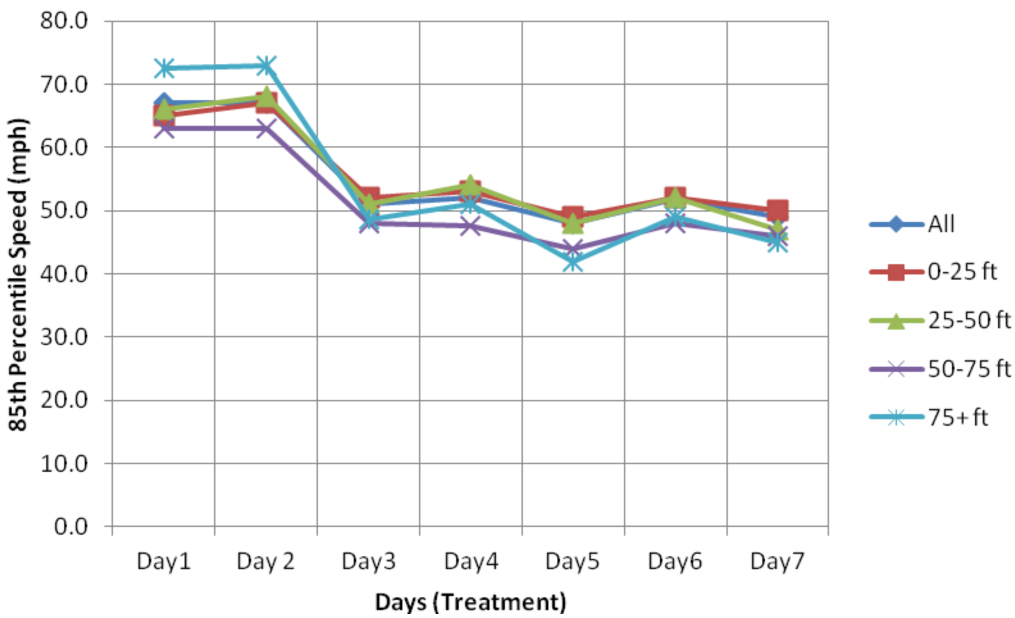

Figure 4.12: Vehicle Speed (85th Percentile) for Different Types of Vehicles for All Days of I-5 Project

Figure 4.13 shows the 85th percentile speed for different locations within the work zone for all days of the I-5 project. The trend in speeds is similar to that observed on the I-84 case study project. The first and second WZ speeds are slower than the end-of-taper speed, and the reference speed (at the Road Work Ahead sign) is the highest. Unlike the I-84 project, on the I-5 project the speed differences between the days are very small. For some days, the speeds are almost identical.

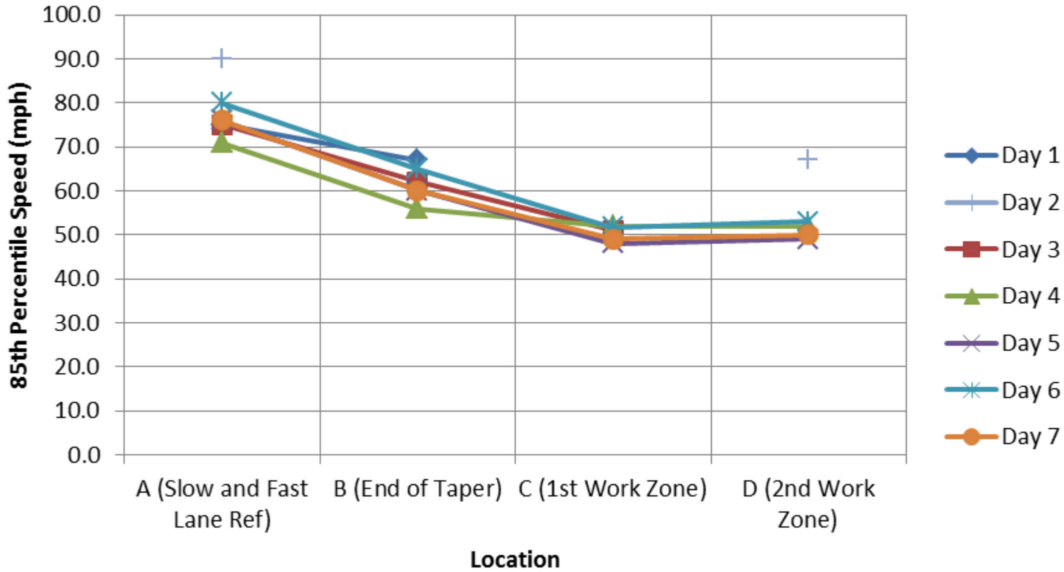

Figure 4.13: Vehicle Speed (85th Percentile) for Different Locations for All Days of I-5 Project

4.3 SURVEY RESULTS OF OTHER DOT PRACTICES REGARDING POLICE ENFORCEMENT DEPLOYMENT

To complement the data collected by the researchers, ODOT Roadway Safety Program Manager Anne Holder conducted a brief e-mail survey through AASHTO about the deployment of police enforcement in construction work zones by other state DOTs. Four questions were asked for the survey as shown below:

1. Does your state deploy police enforcement at work zones? (Yes/No)

2. If yes, which types of enforcement are used (select all that apply):

    (a) Officer(s) actively patrolling the work zone

    (b) Officer(s) parked at the beginning of the work zone

    (c) Officer(s) parked with lights on

    (d) Officer(s) parked at the beginning and end of work zone

    (e) Officer with other type of device (e.g. radar reader board display of traffic's speed)

    (f) All options above are used in our state

3. Provide any other comments about police enforcement.

4. Do you have any research comparing other traffic slowing devices with use of officers in work zones or if one type of police enforcement is more effective than another? (Yes/No)

Responses to the survey were received from seventeen state DOTs. The respondents' answers to Questions 1, 2, and 4 are summarized in Table 4.12. The responses to Question 3 and descriptions of each state's practice of deploying police enforcement are presented and discussed after the summary table.

Table 4.12: Summary of Survey of State Police Enforcement Deployment

State	Q1 (Y/N)	Q2 (a, b, c, d, e, f)	Q4 (Y/N)
Alaska	Y	a, b, c, d	N
Delaware	Y	b, c, e	Y
Hawaii	Y	a, b, c	N
Idaho	Y	a, b, d, e	N
Iowa	Y	a, b, d, e	Y
Kansas	Y	f	N
Minnesota	Y	f	Y
Mississippi	N	N/A	N/A
Missouri	Y	f	N
Nevada	Y	a, b	N
North Dakota	Y	a, b, d, e	N
Pennsylvania	Y	f	N
Rhode Island	Y	f	N
South Dakota	Y	a, b, c, d	N/A
Texas	Y	a, b, c, d	Y
Virginia	Y	a, c	Y
Washington	Y	a	N

Among the seventeen respondents, only one state (Mississippi) does not utilize police enforcement in work zones. All the other states use police enforcement in work zones to some extent. The state of Hawaii requires the deployment of police enforcement in its standard specifications. Five of the responding DOTs (29%) have conducted related research on law enforcement in construction work zones. The DOT responses can be summarized as follows:

- 15 of the 17 DOTs (88%) use active patrolling of the work zones
- 14 (82%) use officers parked at the beginning of the work zone
- 11 (65%) have officers parked with lights on
- 11 (65%) have officers parked at the beginning and the end of work zone
- 9 (53%) have officer presence with other type of devices.

Summary descriptions of the use of police enforcement by each state are provided below:

- In North Dakota, the North Dakota Highway Patrol (NDHP) is the primary enforcement agency that cooperates with North Dakota DOT (NDDOT) to patrol construction work zones. NDDOT provides funding to NDHP to conduct overtime enforcement in addition to their regular patrols. If the construction zone is congested and does not allow for appropriate patrol, the officers will simply park somewhere along the roadway in the construction zone to help slow down traffic. In some cases the DOT has also placed an unmarked DOT service truck in the work zone with an officer inside. The officer uses his radar device in the congested areas, and radios ahead to other officers located at the end of the work zone. NDDOT does not use officers parked with lights on.

- MnDOT (Minnesota) provides a field staff checklist when requesting police enforcement (shown in Appendix H). MnDOT has found that positioning a patrol officer such that the officer is parked with their lights on and directly in front of the workers is the most effective way to reduce speeds of motorists entering the work zone.

- RIDOT (Rhode Island) often requests and pays for law enforcement officers to be present on its projects. RIDOT published guidelines in 2009 (*RIDOT 2009*) to provide guidance on how to use law enforcement in different type of projects. RIDOT has not completed any formal research on this subject, but their experience shows that police officers can have a very positive effect on ensuring safety and mobility in construction work zones.

- WSDOT (Washington) uses active patrolling as the primary enforcement method. WSDOT started using photo enforcement in work zones as of October 1, 2012, and for the first five weeks since that date, 501 citations were issued to motorists on one project. WSDOT is trying to move the photo enforcement to another project location. (Note: As part of a separate research study, the researchers have observed a parked Washington State Patrol (WSP) officer in a work zone. Perhaps the use of parked WSP officers is implemented on an intermittent basis or for special situations only.)

- SDDOT (South Dakota) has South Dakota Highway Patrol on state routes and County Sheriff's officers on local roads. SDDOT also uses part-time or retired law enforcement to patrol work zones. In addition, occupied and unoccupied patrol cars are parked in the work zone with lights on.

- The Nevada DOT indicated that Nevada highway patrol usually increases patrolling in construction work zone areas. For very large urban projects, the DOT may pay for an additional patrol officer specifically for the project.

- The Delaware DOT typically uses a police car parked at the beginning of the work zone with lights on. DelDOT has developed a guideline on how to use the law enforcement officers in work zones (*DelDOT 2008*). DelDOT also conducted a study of work zone speeds in 2009 (*Rummel 2009*), and concluded that police enforcement had no obvious effect on vehicle speeds.

- The state of Hawaii requires the presence of police officers in construction work zones (*Hawaii DOT 2005*). Hawaii uses active patrolling and parked with lights on, depending on the type of work zone and its complexity.

- VDOT (Virginia) has published a guideline to deploy Virginia State Police in work zones (*VDOT 2011*). VDOT has also conducted a research study in 2003 on the effectiveness of law enforcement in work zones in Virginia (*Arnold 2003*).

- The Texas DOT pays the officers to park at the beginning and the end of the work zone with lights on. Sometimes, officers actively conduct cooperative enforcement rather than dedicated/paid enforcement on the project, which is the result of cooperative efforts between TxDOT and local enforcement agencies. TxDOT conducted a research study of controlling speeds in highway work zones in 1980s (*Richards et al. 1984*).

- The Iowa DOT provides a guideline for using law enforcement in construction work zones *(IowaDOT 2010)*. The DOT has also conducted research on this topic *(Kamyab et al. 2003)*.

- MDOT (Mississippi) does not regularly use police enforcement in work zones. However, MDOT used law enforcement several times in the past with large construction projects in very urban areas. The officer is limited to patrolling work zones only while charging MDOT.

5.0 ANALYSIS

This section of the report presents the analysis of the vehicle speed data collected from both case study projects. Section 5.1 addresses the relationship between vehicle speed and the vehicle's distance from the paver when the speed was recorded. Section 5.2 provides a statistical analysis of the speed data.

5.1 SPEED VS. DISTANCE TO PAVER ANALYSIS

5.1.1 Illustration of Speed vs. Distance to Paver Graphs

While on the project sites, the researchers observed that motorists would slow down when they approached the paver and speed up after they passed the paver. This change in speed was also observed when vehicles passed the grinder. Vehicle speed near the paver and grinder are a major concern of this research study given that many workers are on the ground in the vicinity of these pieces of equipment. As a result, knowing how the different traffic control devices affect the vehicle speed around the paver and grinder is very important. (Note: For this analysis, only speeds relative to the paver are presented and analyzed. The change in vehicle speeds relative to the distance to the grinder is assumed to be similar to the change relative to the paver.)

The portable traffic analyzers used to record the speed data were placed on the ground at fixed locations. The paver, on the other hand, is constantly moving as part of the paving operation. As a result, it is difficult to determine the relationship between vehicle speed and distance to paver by direct measurement for each passing vehicle. Therefore, the researchers used an indirect approach. The traffic analyzers recorded vehicle speed, vehicle length, and the time when the vehicle passed the analyzer. As part of the construction operations, a construction worker (ticket taker) is assigned to take asphalt volumes amounts directly from the asphalt truck drivers. The ticket taker also records the time in which the asphalt truck dumps its load in front of the paver and the location of the truck when it dumps its load. Using this information, the researchers know the approximate location of the paver from the ticket taker's forms (a few feet behind the dumping point) and the time in which it was at the location. The location of the traffic analyzer on the roadway is also recorded prior to the start of the paving work. As a result, the distance between the paver and traffic analyzer can be calculated at any time and for each vehicle that passes over the analyzer. Figure 5.1 provides an illustration of the 85th percentile vehicle speeds according to how far the vehicles were from the paver. The figure shows the speed data for the first WZ analyzer on Day 5 of the I-84 case study project. Additional speed versus distance to paver graphs are provided in Appendix I and Appendix J.

On Day 5 of the I-84 project, an OSP officer parked at the end of taper. The first analyzer in the work zone was at a fixed location also. At the beginning of the paving work, the paver was behind the first WZ analyzer (upstream of the analyzer). Hence, the vehicle speed recorded at that time was the speed **after** the vehicle passed the paver. As the paver moved along, it would reach a point when the paver and the first WZ analyzer were at the same location. The speed recorded at that time was the speed when the distance between vehicle and the paver was zero.

The paver then continues up the roadway and away from the first WZ analyzer (downstream of the analyzer), and the speed recorded is the speed **before** the vehicle passes the paver. For the graphs in the figure below and in Appendix I, a negative distance represents the situation when the vehicle has not yet reached the paver; in other words, the paver has already passed the traffic analyzer on the ground. On the other hand, a positive distance means that the vehicle has passed the paver and the paver has not yet reached the analyzer on the ground.

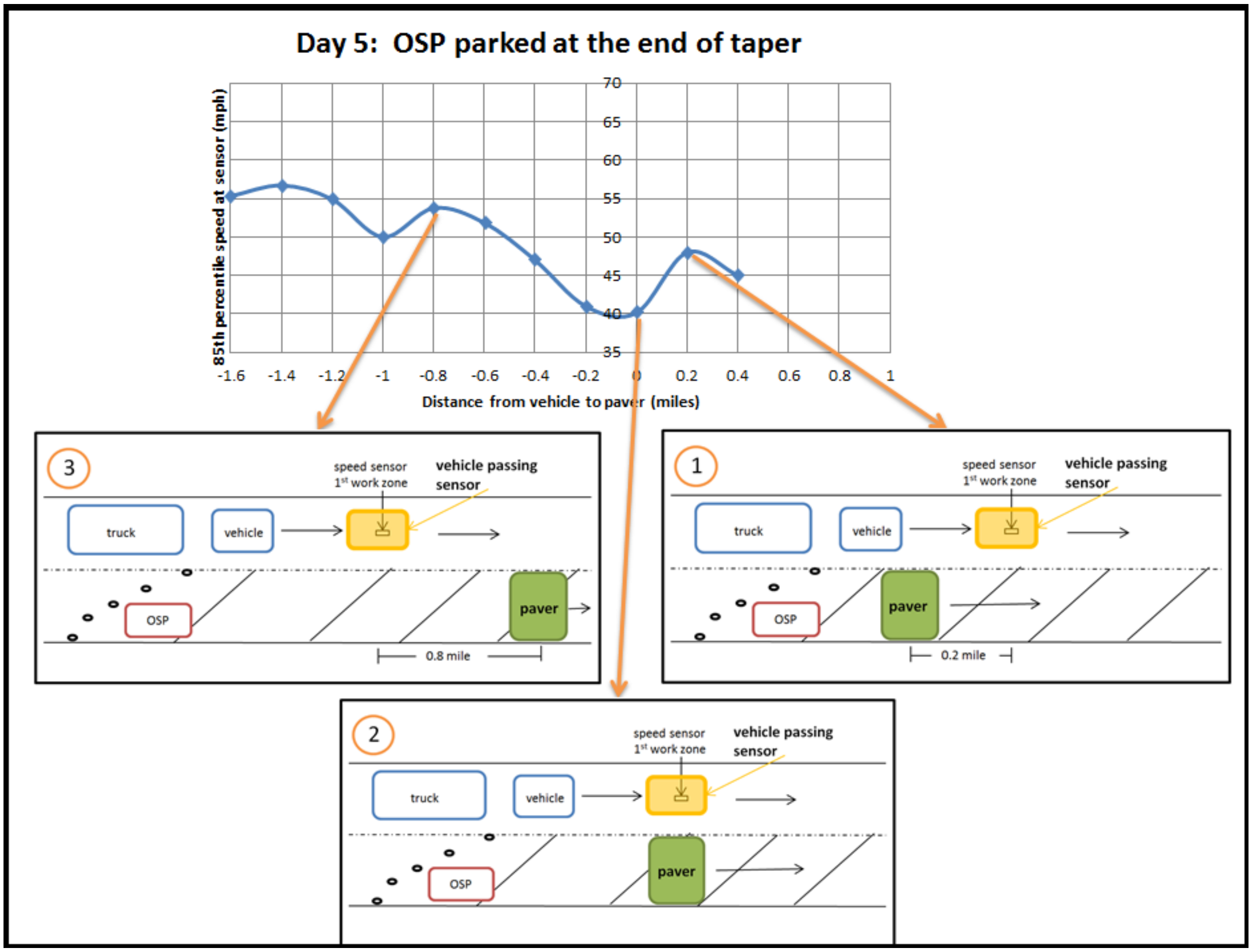

Figure 5.1: Illustration of Distance to Paver Graphs

Given the large volume of traffic, it is unrealistic to calculate the distance to paver for each vehicle speed recorded. Instead, the researchers used an approximate approach. The approach used is illustrated using the speed data from Day 5 of the I-84 project. Table 5.1 shows an example of the data used to draw the distance to paver graphs in Appendix I.

Table 5.1: Data for Distance to Paver Graph for I-84 Project, Day 5

First WZ Analyzer Location	Paver Location	Time the Paver was at Paver Location	Distance from Analyzer to Paver	Time Period	85th Percentile Speed of Vehicles during that Time Period	Average Speed of Vehicles during that Time Period
95.12	94.72	21:45	0.4	21:30-22:00	45.0	38.1
95.12	94.92	22:30	0.2	22:15-22:45	48.0	38.4
95.12	95.12	23:05	0	22:50-23:20	40.2	32.4
95.12	95.32	23:35	-0.2	23:20-23:50	41.0	34.3
95.12	95.52	0:10	-0.4	23:55-0:25	47.0	39.8
95.12	95.72	0:45	-0.6	0:30-1:00	51.9	45.2
95.12	95.92	1:20	-0.8	1:05-1:35	53.8	49.1
95.12	96.12	1:55	-1	1:40-2:10	50.0	43.8
95.12	96.32	2:25	-1.2	2:10-2:40	54.9	47.0
95.12	96.52	2:50	-1.4	2:40-3:10	56.7	51.1
95.12	96.72	3:15	-1.6	3:10-3:40	55.3	51.2

The first column in the table shows the location of the first work zone analyzer, which is stationary at milepoint 95.12. The second and third columns show the location of the paver and the time at that location. The information on the paver in these two columns is taken from the ticket taker's forms. The fourth column is the calculated distance between the paver and analyzer (difference between the first column and second columns). In order to determine the 85th percentile speed for all of the vehicles passing the paver at that location, a time period of ±15 minutes (total 30 minutes) from the time the paver was at that location was chosen based on the speed and length of the paver. All of the vehicles which were recorded by the traffic analyzers within that 30 minute time period were considered to be at the paver at that time. The time period shown in the fifth column ranges from approximately 15 minutes before to 15 minutes after the time in the third column. For the vehicle speeds recorded by the first analyzer in the work zone in that half hour period, the 85th percentile speed is calculated and shown in the sixth column. Similarly, the average speed is shown in the seventh column. Figure 5.2 shows an example of the distance to paver graph using the data in Table 5.1. The figure is based on the speed data recorded by the first WZ analyzer on Day 5. A figure based on the second WZ analyzer will be different. All of the distance to paver graphs are shown in Appendices I and J. In Appendices I and J, the first graph on each page is the figure based on the first WZ analyzer and the second figure shown is based on the second WZ analyzer.

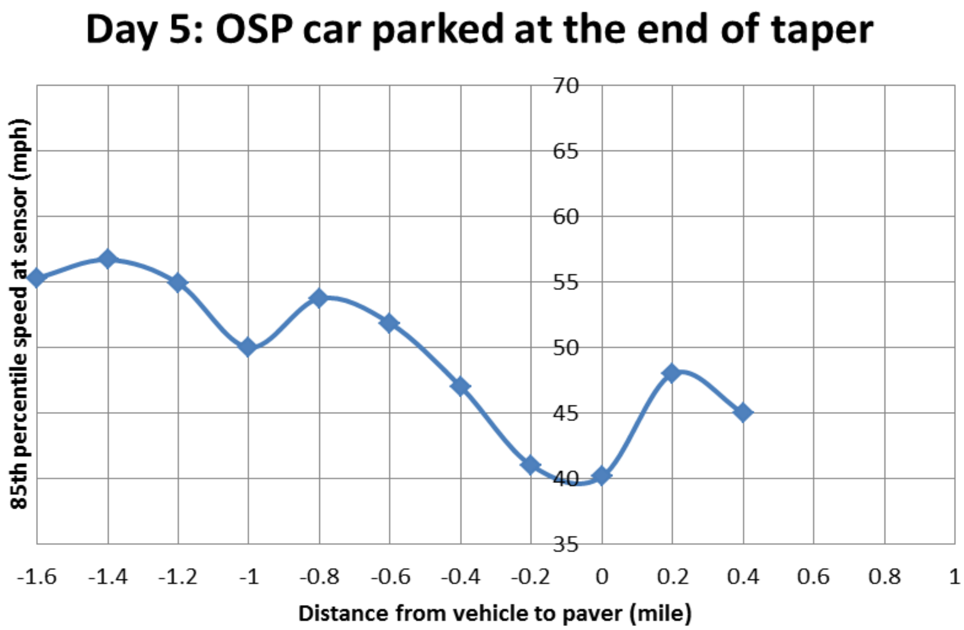

Figure 5.2: Example of Distance to Paver Graphs

Figure 5.3 shows the distance to paver graph for the first day of paving on the I-84 case study project. As seen in the figure, the vehicles slow down to speed that is higher than for Day 5 on the I-84 project (see Figure 5.2), and the rate at which the vehicles slow down before the paver and speed up after passing the paver is sharper. A more gradual change in speed and a lower minimum speed are preferred.

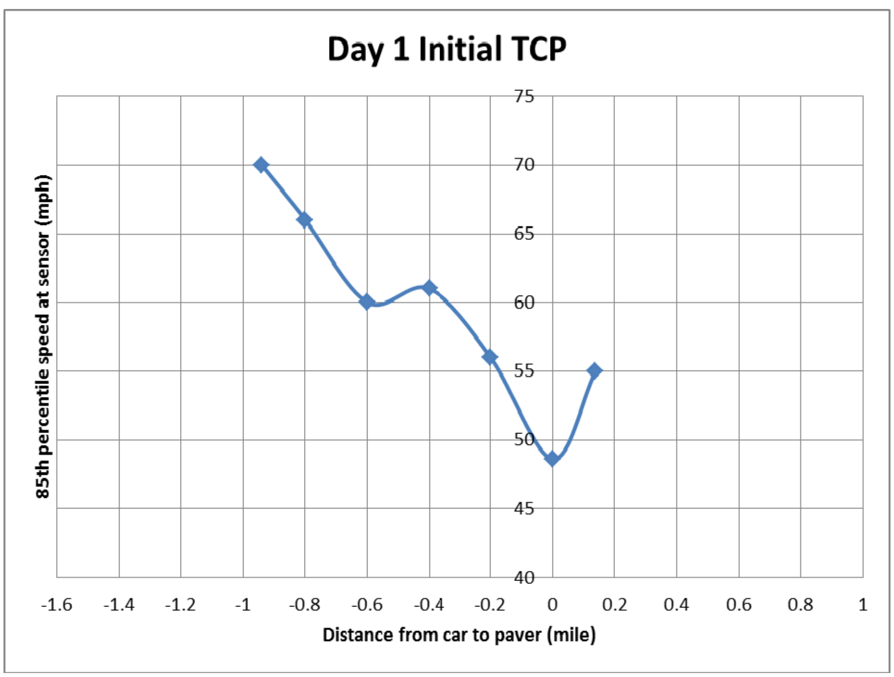

Figure 5.3: Vehicle Speed vs. Distance to Paver - Day 1, I-84 Project

Figure 5.4 presents the distance to paver graph for the I-5 project when the OSP officer parked on site. As seen in the figure, the minimum speed occurs near the paver and is similar to the I-84 project (approximately 40 mph). Additionally, there is a gradual decrease in speed prior to the paver followed by a gradual increase after passing the paver. This figure illustrates a more desirable rate of deceleration and speed at the paver.

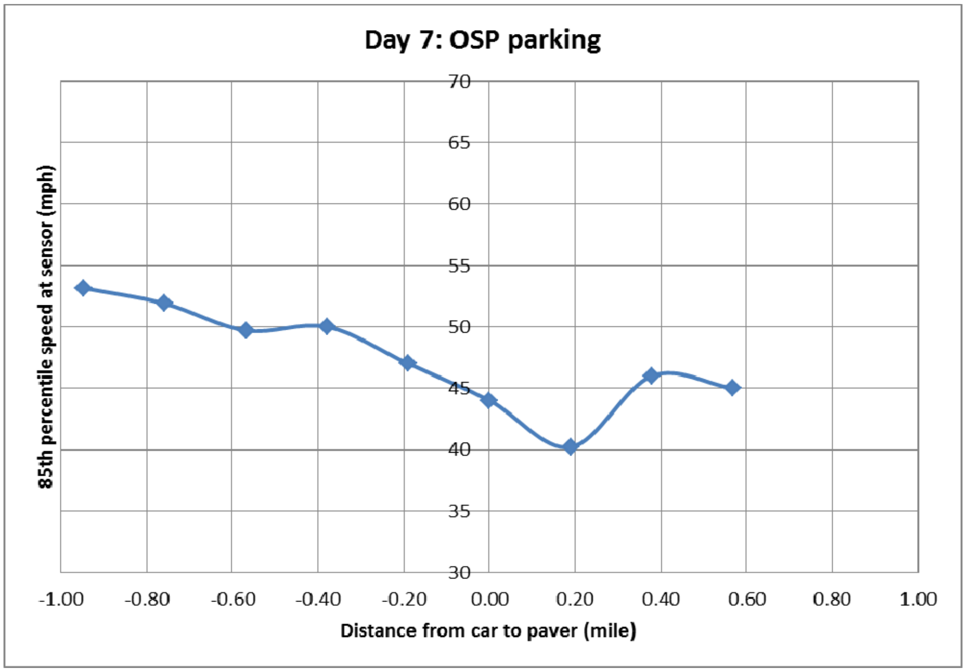

Figure 5.4: Vehicle Speed vs. Distance to Paver - Day 7, I-5 Project

5.1.2 Speed vs. Distance to Paver Analysis for I-84 Project

For the I-84 case study project, summary figures of the vehicle speed relative to the distance to paver for all work days are shown in Figure 5.5 and Figure 5.6. Figure 5.5 is based on the first WZ analyzer, and Figure 5.6 is based on the second WZ analyzer. Both figures show that the vehicle speed tends to decrease when vehicles approach the paver and increase after the vehicles pass the paver.

As mentioned previously, the speed data recorded on Day 10 is noticeably different from the data recorded on the other days. Therefore, the Day 10 data is shown in the figures but is not included as part of the subsequent analyses. Figure 5.5 shows that Day 4 and Day 5 have the lowest near paver speed, which is approximately 40 mph (the 85th percentile speed within the half hour period). The speeds near the paver on Days 1, 2, and 3 are above 45 mph. The speeds change (slow down and then speed up again) smoothly for Days 6 and 9, and sharply for Days 1, 3, 7, and 8. A slow rate of change in speed is preferred to lower the variability in speed and prevent crashes. For some days there is another speed drop at approximately 0.4 miles after vehicles have passed the paver. This second drop in speed could be a result of the vehicles slowing down again as they approach the grinder or other work equipment (e.g., tack truck). It appears that motorists tend to slow down when they see large equipment, bright lights, and lots of activity.

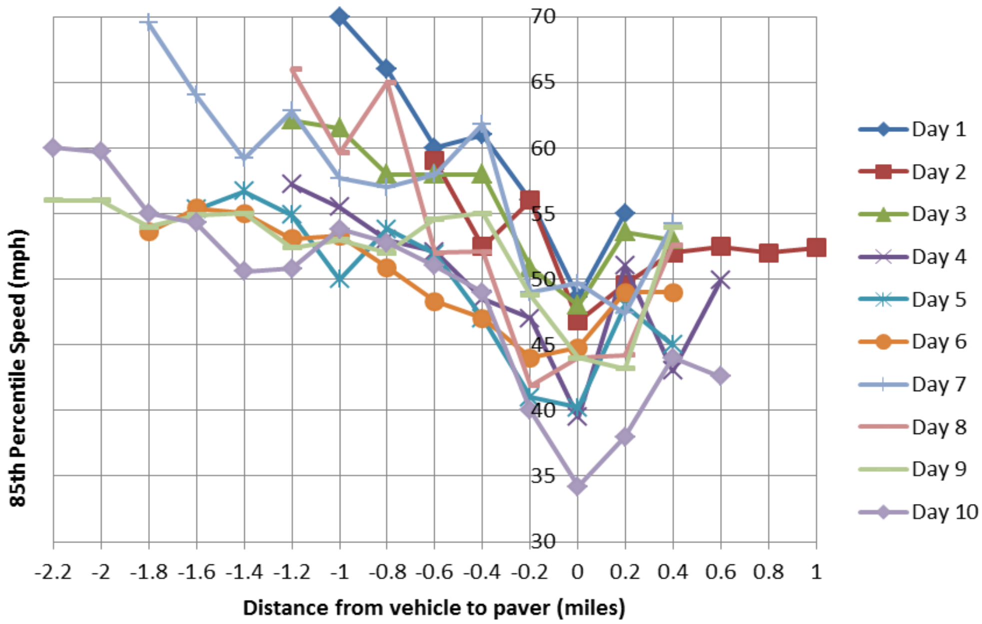

Figure 5.5: 85th Percentile Speed vs. Distance to Paver for All Days Based on First WZ Analyzer for I-84 Project

Figure 5.6, which presents the data from the second WZ analyzer, shows a different pattern than Figure 5.5. Day 7 seems to have the lowest near paver speed, followed by Day 5 and then Day 9. The shapes of the speed diagrams for most of the days are roughly similar. The speed changes sharply for Day 7. The data from Day 2 is not included in the figure due to the placement of the second WZ analyzer on that day (the paving work was prematurely halted and the paver never progressed to the second WZ analyzer location).

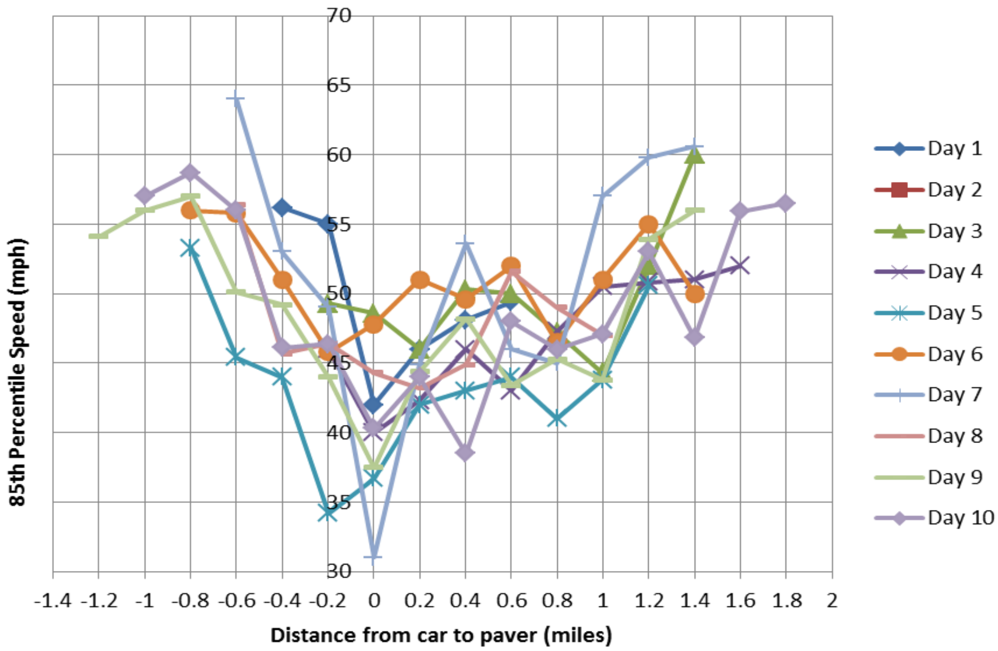

Figure 5.6: 85th Percentile Speed vs. Distance to Paver for All Days Based on Second WZ Analyzer for I-84 Project

5.1.3 Speed vs. Distance to Paver Analysis for I-5 Project

Similar distance to paver graphs are provided in Appendix J for the I-5 case study project. Figure 5.7 shows the summary of the first WZ analyzer's distance to paver data for all days. Figure 5.8 shows the speed relative to the distance to paver for all days based on the second WZ analyzer data. There was no second WZ analyzer data for Days 1, 2 and 3 due to the damage to the analyzers. For the I-5 project, the ticket taker's forms were incomplete for most days. As a result, information about the paver location is only available until 2:00am. Due to the heavy traffic on I-5, the researchers could not place the traffic analyzers on the roadway until 10:00pm or later, so vehicle speed information is only available after 10:00pm. Therefore, for most days, the data used to draw the distance to paver graphs is from 10:00pm to 2:00am.Figure 5.7 reveals that the speeds relative to the paver are similar on Days 5, 6, and 7, and have a near-paver speed of approximately 40 mph. Day 2's near paver speed is low, but the speed changes dramatically. Figure 5.8 provides very little useful information due to the lack of data available to create the graph.

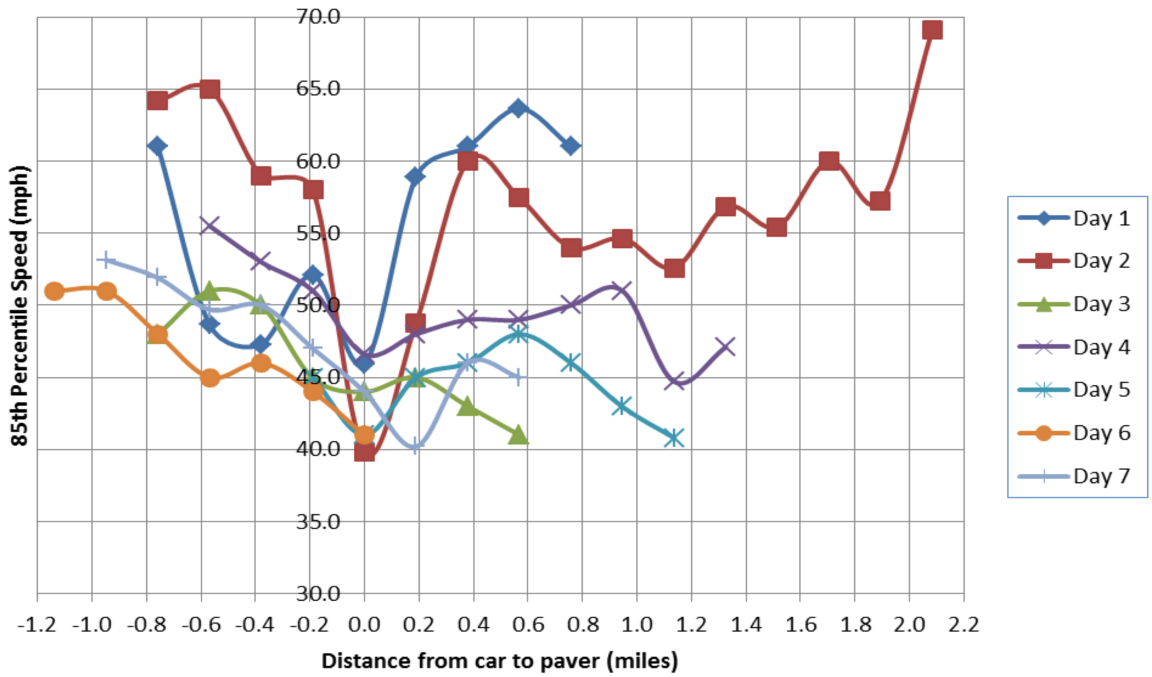

Figure 5.7: 85th Percentile Speed vs. Distance to Paver for All Days Based on First WZ Analyzer for I-5 Project

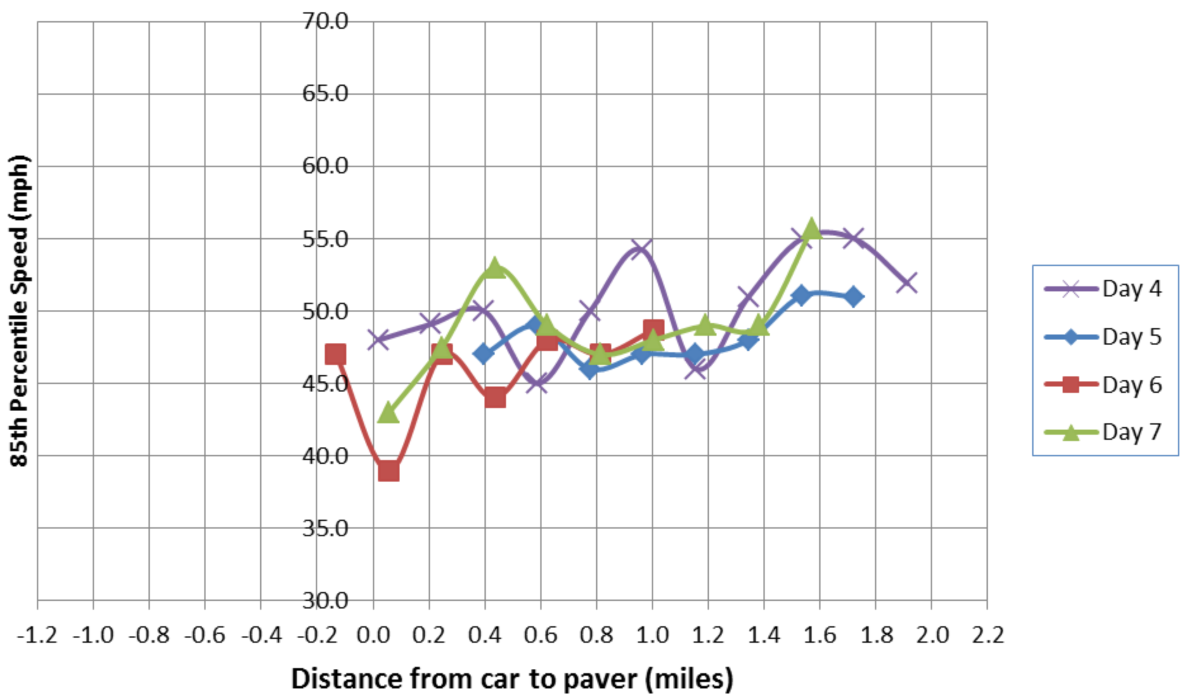

Figure 5.8: 85th Percentile Speed vs. Distance to Paver for All Days Based on Second WZ Analyzer for I-5 Project

5.2 STATISTICAL ANALYSIS

Statistical tools were used to explore the effects of different traffic control devices on traffic speed. Before attributing the speed differences to different traffic control devices implemented each day, it is important to identify confounding factors. After the effects of confounding factors are eliminated, a determination can be made as to whether the traffic control devices lead to a difference in traffic speed or not. A multiple regression analysis can help to achieve this goal.

The researchers created a comprehensive spreadsheet containing all of the valid speed data points for both case study projects. The data from Day10 on the I-84 project was omitted due to the unique factors of that work day. The final spreadsheet included 74,892 speed data points.

For each data point, the following information was available and included in the spreadsheet:

- time when the data point was recorded,
- location of where the data was recorded,
- length of the vehicle,
- speed of the vehicle,
- case study project on which it was recorded,
- traffic control devices used for that day,
- traffic volume during that hour, and
- distance between the vehicle and the paver at the time when the speed was recorded.

Since the relationship between vehicle speed and distance to paver is not linear, the absolute value of distance to paver is used in the analysis. Statistical analysis software programs “R” and SPSS were used to assist with the analysis.

5.2.1 Comparing Reference Speeds for All Days on Both Case Study Projects

A multiple regression model is fitted to compare reference speeds for all days, including both I-84 and I-5 study projects. An output summary of the regression model is provided in Appendix K. In this model, the speeds from the reference analyzers for Day 1 on the I-84 project are compared to all the other days’ reference analyzer speeds. The speeds recorded during the period from 12:00am to 4:00am are used in the analysis because all of the days have valid reference speed data during this time period.

The results show that Days 3, 4, 5, 6, and 8 of the I-84 project, and Days 1 and 4 of the I-5 project have similar reference speeds to Day 1 of I-84 project (the p-values for those days are larger than 0.1). The mean reference speed for Day 2 of the I-84 project is 3.57 mph lower than for Day 1 of the I-84 project (p-value = $4.15e^{-6}$). The mean reference speed for Day 7 on the I-84 project is 2.48 mph lower than for Day 1 on the I-84 project (p-value = 0.0038). The mean reference speed for Day 9 on the I-84 project is 3.49 mph lower than for Day 1 (p-value = $2.5e^{-5}$).

The mean reference speed for Day 2 on the I-5 project is 17.5 mph higher than the mean reference speed for Day 1 on the I-84 project (p-value < $2e^{-16}$). This difference is significant and likely due to the location of reference traffic analyzers. For both projects the reference location traffic analyzers were placed at the "Road Work Ahead" signs for the work conducted on Day 1. On the I-5 project, the analyzers were left on the road for two days, and at this location, the analyzers were located about 3.8 miles ahead of the beginning of the paving work for Day 2. Therefore, for Day 2 on the I-5 project, the reference speeds are likely recorded before the drivers see the "Road Work Ahead" signs, and thus do not reflect any slowdown of the vehicles when the drivers pass by the "Road Work Ahead" signs.

The mean reference speed for Day 3 on the I-5 project is 4.08 mph higher than on Day 1 on the I-84 project (p-value = $6.52e^{-9}$). The mean reference speeds for the following days on the I-5 project compared to Day 1 on the I-84 project were as follows: Day 5 is 3.41 mph higher (p-value = $6.93e^{-7}$); Day 6 is 6.86 mph higher (p-value<$2e^{-16}$); and Day 7 is 4.25 mph higher (p-value = $1.85e^{-9}$).

Based on the comparison of reference speeds of each day described above, the traffic speeds for the I-84 and I-5 projects are different. Five days of the I-84 project have similar reference speeds to Day 1's reference speed, and the other three days' speeds are lower than Day 1's speed. Two days of the I-5 project have similar reference speeds to Day 1 of the I-84 project, while the other five days have higher speeds. Therefore, because of the difference in reference speeds between the case study projects, the researchers decided to analyze the speed data from each case study project separately.

5.2.2 Multiple Regression Models for I-84 Project

Since the vehicle speeds at the end of taper are very different from the speeds in the work zone, the speed for different traffic analyzer locations were analyzed separately. The first WZ analyzer and second WZ analyzer speeds are combined to form a common WZ speed. As indicated previously, Day 10's data is excluded in all analyses. Also, only speeds from 12:00am – 4:00am of each day are analyzed.

End of Taper Speeds

The end of taper analyzer for Day 6 was malfunctioning, so only eight days of end of taper speeds are analyzed. A regression model (speed vs. traffic volume + absolute value of distance to paver + vehicle types + different days) was fitted, and the regression output is provided in Appendix K.

The results of the multiple regression analysis show that traffic volume (p-value = 0.09) and the absolute value of distance to paver (p-value = 0.51) have no effect on traffic speeds at the end of taper. However, vehicle type has a great effect on speed. Compared to small vehicles (less than 25 feet in length), vehicles that are 26-50 feet long have a lower mean speed by 4.02 mph. Similarly, the mean speed of vehicles that are 51-75 feet long is 6.76 mph lower, and long trucks (more than 75 feet in length) are 3.36 mph slower on average than small vehicles.

After accounting for different vehicle types, it is clear that Day 2 and Day 3 have higher speeds than Day 1. Day 4's end of taper mean speed is the lowest, 5.82 mph lower than on Day 1. Day 5's mean speed is 4.47 mph lower than Day 1. Day 7 and 9's end of taper speeds are the same as Day 1's speed. There is also suggestive evidence that Day 8's end of taper mean speed is 1.93 mph lower than Day 1.

The speed variance for Day 2 is the largest, followed by Day 8 and Day 9. The speed variance for Day 4 is the smallest.

Work Zone Speeds

A regression model (work zone speed vs. traffic volume + absolute value of distance to paver + vehicle types + different days) was fitted, and the regression output is listed in Appendix K.

The results show that traffic volume and the absolute value of distance to paver have some effect on traffic speeds in the work zone. With traffic volume increasing by 100 count, the mean speed in the work zone will increase by 2.77 mph (p-value = 0.0137). The absolute value of distance to paver has a large effect on vehicle speed in the work zone. With the distance to paver increasing by 1 mile, the mean speed increases by 9.89 mph (p-value < $2e^{-16}$).

Vehicle type has a smaller effect on traffic speeds in the work zone compared to the effects on traffic speeds at the end of taper. Vehicles that are 26-50 feet long have a similar mean speed (p-value = 0.08) as small vehicles less than 25 feet in length. Vehicles that are 51-75 feet long have speeds that are 3.75 mph lower, and long trucks (more than 75 feet in length) are 0.95 mph slower than small vehicles.

After accounting for different vehicle types, it is clear that all days, except for Day 3, have lower work zone mean speeds than Day 1. Day 3's work zone speed is identical to Day 1's speed. Day 5 has the lowest work zone mean speed, which is 7.98 mph lower than Day 1 (p-value < $2e^{-16}$), followed by Day 9's speed which is 7.58 mph lower, and Day 4's speed which is 6.64 mph lower. The speed variance for Day 2 is still the largest. The speed variances for all other days are similar.

Summary for I-84 Project

Table 5.2 summarizes the treatment effect at different locations, after accounting for the effect of vehicle type on traffic speed. For each treatment, the table shows the difference in mean speed compared to the typical TCP treatment (Day 1). The traffic control devices should have no effect on traffic speed at the reference location (at "Road Work Ahead" signs). However, it is good to know the difference between each day's reference speed; therefore, the reference speed information is also included in the table below.

Table 5.2: Summary of Treatment Effects on Mean Speed at Different Locations for I-84 Project

Day	Treatment	Reference (mph)	End of Taper (mph)	Work Zone (mph)
1	Typical TCP	--	--	--
2	50 mph signs	-3.57	+6.00	-3.23
3	PCMS signs on rollers and 50 mph signs	0	+2.45	0
4	OSP patrolling, PCMS signs on rollers, and 50 mph signs	0	-5.82	-6.64
5	OSP parked, PCMS signs on rollers, and 50 mph signs	0	-4.47	-7.98
6	Radar speed monitoring display and 50 mph signs	0	--	-4.73
7	Tubular markers on both sides, PCMS signs on rollers, and 50 mph signs	-2.48	0	-5.80
8	Drums on both sides, PCMS signs on rollers, and 50 mph signs	0	-1.93	-6.04
9	PCMS signs on rollers, radar speed monitoring display, and 50 mph signs	-3.49	0	-7.58

However, there are limitations in the comparisons shown above that need to be considered when drawing conclusions from the results. On Days 4 and 5, the police officers left the site at 12:00am. The speed data used in the comparisons is from 12:00am to 4:00am. Therefore, unless there are latent effects of the officer's presence on the site, the speed reductions for Day 4 and Day 5 cannot be due to the presence of law enforcement. Regression models using speed data from 8:00pm – 12:00am are fitted for 9 days of the I-84 project, and this regression model output is provided in Appendix K. The results from this analysis are as follows:

- For the end of taper vehicle speed regression model, the results show that traffic volume and distance to paver do not affect traffic speed. However, after accounting for vehicle type, Day 5's end of taper mean speed is 10.98 mph lower than on Day 1, and Day 4 is 9.81 mph lower than on Day 1.

- For the WZ speed, the regression output shows that all days have higher work zone speeds than Day 1 except Day 5. Day 5 has similar work zone speed to Day 1. This result appears inconsistent with the treatments applied and researcher observations. However, if the paving operation for Day 1 and the locations of the two WZ analyzers are considered, there is more confidence in the results. The two WZ analyzers for Day 1 were placed very close to each other (only 0.5 mile apart). For the other days, the analyzers were about 1 mile apart. Moreover, only 1 mile was paved on Day 1, so both WZ analyzers were relatively close to the paver at the same time. This may result in lower second WZ analyzer speeds, and make the overall work zone speed lower than the other days.

5.2.3 Multiple Regression Models for I-5 Project

For the I-5 case study project, as mentioned previously, due to the unique characteristics of Day 2's data, the researchers decided to exclude Day 2's data from all following statistical analysis. Speed data recorded from 12:00am – 4:00am on the other days is included in the analysis.

End of Taper Speeds
Similar to the analysis for the I-84 project, a regression model (speed vs. traffic volume + absolute value of distance to paver + vehicle types + different days) was fitted, and the regression output is listed in Appendix K.

The results show that the distance to paver has no effect on mean traffic speed at the end of taper. With traffic count increasing by 100, the mean speed will drop 1.06 mph (p-value = 0.008). At this case study location, vehicle type greatly affects the mean traffic speed. Compared to small vehicles less than 25 feet in length, vehicles that are 26-50 feet long have a lower mean speed by 4.92 mph. Similarly, vehicles that are 51-75 feet long traveled at speeds that were on average 6.85 mph lower, and long trucks (more than 75 feet in length) were 4.26 mph slower on average than small vehicles.

After accounting for different vehicle types, it is clear that all days except Day 6 have lower speeds than Day 1 of the I-5 project. Day 3's mean speed at the end of taper is 3.81 mph lower than Day 1. For the remaining days, the difference is as follows: Day 4 is 8.58 mph lower; Day 5 is 6.21 mph lower; and Day 7 is 4.17 mph lower. The speed variances for all days at this location are very similar.

Work Zone Speeds
The results of a regression model for work zone speeds are also provided in Appendix K. The results reveal that the distance to paver has a small effect on mean speed in the work zone. The difference in speed is 0.91 mph higher for each mile increase in distance from the paver. With the traffic volume increasing by 100 vehicle counts, the speed will drop 0.7 mph. Vehicle type affects the mean traffic the same way as on the I-84 project. Compared to small vehicles less than 25 feet in length, vehicles that are 26-50 feet long have a lower mean speed by 0.93 mph; 51-75 feet long vehicles are 5.18 mph lower, and long trucks (more than 75 feet in length) are 1.36 mph lower than small vehicles.

After accounting for different vehicle types and other factors, it is clear that all days have lower mean work zone speed than Day 1 of the I-5 project. Day 3's mean speed is 1.62 mph lower than Day 1; Day 4 is 5.22 mph lower; Day 5 is 8.04 mph lower; Day 6 is 6.38 mph lower; Day 7 is 6.30 mph lower. The speed variances for all days at this location are very similar.

Summary for I-5 Project

Table 5.3 summarizes the treatment effect at different locations, after accounting for the effect of vehicle type on traffic speed. For each treatment, the table shows the difference in mean speed compared to the typical TCP treatment (Day 1).

Table 5.3: Summary of Treatment Effects on Mean Speed at Different Locations for I-5 Project

Day	Treatment	Reference (mph)	End of Taper (mph)	Work Zone (mph)
1	Typical TCP	0	--	--
3	Temporary 50 mph signs	+4.08	-3.81	-1.62
4	PCMS signs on trailers and 50 mph signs	0	-8.58	-5.22
5	Radar speed monitoring display, PCMS signs on trailers, and 50 mph signs	+3.42	-6.21	-8.04
6	Radar speed monitoring display, PCMS signs on trailers, and 50 mph signs	+6.86	0	-6.38
7	OSP parked on site and 50 mph signs	+4.25	-4.17	-6.30

The OSP officer who parked on the site on Day 7 left the site at 1:00am. Therefore, it is inconsistent to use the data from 12:00am – 4:00am to analyze the effect of the police officer parked at the end of taper. Since speed data is only available from 12:00am – 4:00am on Day 1, the speed data for one hour from 12:00am – 1:00am can be used to analyze the effect of the police presence. The regression output for this comparison is provided in Appendix K. The results are similar to those using the 12:00am – 4:00am speed data as response.

6.0 CONCLUSIONS

This section of the report summarizes the conclusions that can be drawn from the implementation of the traffic control devices in this research study. The first part of this section presents the positives and negatives of each traffic control device based on input provided to the research team by field personnel (ODOT and contractor) and based on the researchers' personal observations. The second part of this section presents conclusions about the effectiveness of each traffic control devices based on the results and statistical analysis of the speed data.

6.1 EVALUATION OF TRAFFIC CONTROL DEVICE IMPLEMENTATION AND FEASIBILITY

Table 6.1 provides a summary of positives and negatives for each traffic control device. The information in the table is based on the interview results and researcher observations.

Table 6.1: Pros and Cons of Traffic Control Devices

No.	Traffic control device	Positive Attributes	Negative Attributes
1	50 mph signs	• May slow down the traffic. • Necessary if using law enforcement or a radar speed monitoring display. • Relatively cheap.	• Limited effect without law enforcement: if people don't care without the speed reduction, they still don't care with the speed reduction. • Need to cover existing speed signs. • Need special permission/approval to reduce the speed. • If using TSS (temporary sign support) to support the signs, it is very hard to move them. The TSS needs to be protected by Type III barricades and doesn't work well on uneven ground.
2	Contractor asphalt trucks driving at 45 mph through the work zone	• Slows down the traffic.	• May cause long queues. • Takes longer for asphalt trucks to arrive at the work zone and return to the plant.
3	PCMS signs on rollers	• Highly visible. • Make drivers aware of workers on the road. • Slows down traffic before the drivers see the paver. • After initial installation and programming, require just a few minutes to implement every night.	• Initial cost is high. • Vibration of rollers may damage PCMS signs. • Does not benefit workers on the roadway who may be far away from the rollers (e.g., QA/QC personnel).
4	PCMS signs on trailers	• May slow down the traffic. • Make drivers aware of construction workers ahead. • Very large and visible. • When located at the beginning of the work zone, will benefit everyone in the work zone, not only the workers who are located around the paver.	• If too many signs at the beginning of the work zone, drivers are distracted. • Require a lot of space (need a big shoulder or median) • Need to be protected from vehicles using a barricade. • Not easy to move. • Initial cost is high.
5	Radar speed monitoring display	• Slows down the traffic. • Make drivers think that maybe OSP officer is somewhere close by. • Rental cost is relatively low. • Light and easy to move and set up. • Small and do not take up a lot of space.	• People tend to slow down before it and then speed up afterwards; works better along with police enforcement. • Need to implement together with 50 mph signs. • May not be big or bright enough; not very visible depending on location.
6	Tubular markers on	• Slows down the traffic.	• Hit by cars a lot; require more time/personnel to maintain upright and in

No.	Traffic control device	Positive Attributes	Negative Attributes
	both sides of the traveling lane to narrow down the lane width	• Clearly mark the lane, help to direct traffic, provide guidance when there is no fog line. • Raise drivers' attention to the work zone.	proper location. • Not as visible as drums. • May shift cars closer to the worker. • Need more time and extra labor to put down and pick up. • May not be applicable if travel lane is already at minimum allowed width. • More tubular markers required for the project.
7	Drums on both sides of the traveling lane to narrow down the lane width	• Slows down the traffic. • Highly visible. • Clearly mark the lane, help to direct traffic, provide guidance when there is no fog line. • Raise drivers' attention to the work zone. • Provide a clear path through the work zone.	• Take a long time and three extra laborers to put them out and even more time to pick them up. • When picking them up, no lane closure and no protection for workers. • Cost is high; more drums needed for the project. • Very shiny; may make drivers confused. • When big trucks hit the drums and send them flying, they become a hazard. • Asphalt truck drivers feel the spacing is often too narrow to pull into the work area. • May shift cars closer to the workers.
8	OSP officer patrolling around the work zone	• Slows down the traffic. • Especially effective for truck drivers because they know there are police offices in the work zone through communication over the radio. • Especially effective for truck drivers because tickets will affect their jobs.	• Cost is high; overtime for OSP officers. • Need enough officers to cover extended paving operations. • Need extra time to coordinate with OSP office. • If officers pull over cars in the work zone, may force oncoming vehicles to go into the closed lane.
9	OSP parked at the beginning of the work zone with red/blue lights flashing	• Slows down the traffic and wake up the drivers. • Highly visible. • Causes drivers to slow down at the beginning of the work zone, benefiting every worker. • Especially effective for truck drivers because tickets will affect their jobs. • After drivers see OSP, they will lower their temper and tend to hit tubular markers less frequently, lightening the burden on TCS to maintain the markers.	• Cost is high. • Need enough officers so that someone can take this job.

As can be seen from the table above, each type of traffic control measure has both positive and negative aspects. The PCMS signs on trailers and rollers provide a relatively low cost means for traffic control and gaining the driver's attention. PCMS signs on trailers can be placed at the beginning of the work area to alert drivers of not only the work at the paver and grinder, but also alert drivers of the personnel on the ground and the entering/exiting vehicles throughout the work zone. Placing PCMS signs on the rollers provides an additional benefit of the signs staying close to the paver as the paver moves up the roadway. The PCMS signs are relatively easy to implement, readily available, and commonly recognized by motorists.

The radar speed monitoring display also provides a relatively low cost means for traffic control and gaining the driver's attention. The mobile nature of the display makes it easy to locate. Placing radar speed displays at the beginning of the work zone and perhaps once or twice within the work zone help to slow down drivers initially and remind them to keep their speeds lower.

Use of the tubular markers and drums on both sides of the travel lane appears to create additional problems and concerns for the passing motorists, asphalt truck drivers, and contractor. The extra cost, especially for a long line of drums, is also an inhibitor to their use. The additional time and effort required to place the second line of markers or drums impacts the contractor's efficiency. These traffic control measures are therefore not suggested for typical work zones in practice.

The presence of an OSP officer is appreciated by all of those involved in the paving project, and is seen as a benefit to the paving operation. OSP presence is relatively easy to implement, and requires prior communication and coordination between ODOT, the contractor, and OSP. No additional contractor resources are required. The additional cost and availability of OSP officers may inhibit their use.

6.2 EFFECTIVENESS OF TRAFFIC CONTROL DEVICES

The effectiveness of each traffic control measure can be evaluated by the reduction in mean vehicle speed (at the end of taper and in the work zone) after the traffic control measure is implemented. This provides a comparison of the vehicle speed within the work zone to the reference speed before the drivers are aware of and enter the work zone. Traffic control devices which lead to larger speed reductions are considered more effective. Another measurement used to determine the effectiveness of traffic control devices is the variance of traffic speed. Those traffic control measures which lead to lower variance in speed between vehicles at each location throughout the work zone are considered more effective.

Table 6.2 and Table 6.3 summarize the effectiveness of the traffic control devices implemented on the I-84 project and I-5 project, respectively. Vehicle speed variability is measured by the standard error calculated as part of the statistical analysis. A larger standard error indicates greater variability in the speeds of the vehicles. Since it is difficult to separate the effects of each traffic control device when multiple traffic control devices were used together, the effectiveness is based on the combination of traffic control devices for the days that multiple traffic control devices were implemented.

The descriptions of the columns in the tables are as follows:

- **Treatment**: The combination of traffic control devices used each day.
- **Mean speed**: The mean speed (mph) from the end of taper sensor and the two work zone (WZ) sensors.
- **% change in mean speed compared to typical TCP:** The percent change in the mean speed for the treatment compared to the mean speed for the typical TCP. A positive value indicates an increase in speed, and a negative value indicates a decrease in speed.
- **Rank based on lowest mean speed**: The numerical ranking starting with 1 for the treatment with the lowest mean speed. A lower number indicates a higher ranking.
- **Standard Error**: The standard error associated with the mean speed, showing the variance in the speeds recorded. A higher value indicates greater variance.
- **Rank based on lowest Standard Error**: The numerical ranking starting with 1 for the treatment with the lowest Standard Error. A lower number indicates a higher ranking.
- **% change in mean speed compared to OSP**: The percent change in the mean speed for the treatment compared to the mean speed for the OSP parked treatment. A positive value indicates an increase in speed, and a negative value indicates a decrease in speed.
- **Additional cost per day beyond typical TCP**: Added cost for all the additional traffic control devices used for each night, not including typical TCP cost (10 days for I-84, 8 days for I-5).
- **Ratio of WZ speed to reference speed**: Speed of WZ sensors divided by the average speed of the reference sensors located prior to the WZ at the Road Work Ahead signs (shown as a percentage). This value is used to reduce the unexplainable day-to-day differences of traffic speeds.

Table 6.2: Comparing Effectiveness of Traffic Control Devices for I-84 Project

Treatment	Mean speed (end of taper and in WZ)	% change in mean speed compared to typical TCP	Rank based on lowest mean speed	Standard Error	Rank based on lowest Standard Error	% change in mean speed compared to OSP parked and PCMS	Additional cost per day beyond typical TCP	Ratio of WZ speed to reference speed (%)
Typical TCP	49.07	0%	5	0.178	6	10.9%	$0	72.6%
50 mph signs	54.55	11.2%	9	0.201	8	23.3%	$1,190	84.7%
PCMS signs on rollers	50.56	3.0%	8	0.172	4	14.3%	$2,265	75.4%
OSP patrolling and PCMS	47.19	-3.8%	2	0.175	5	6.7%	$2,581	71.8%
OSP parked and PCMS signs	44.24	-9.8%	1	0.171	3	0%	$2,581	67.5%
Speed monitor only	49.07	0%	5	0.212	9	10.9%	$1,240	73.7%
Tubular markers on both sides and PCMS signs	50.41	2.7%	7	0.183	7	13.9%	$2,715	74.1%
Drums on both sides and PCMS signs	49.03	-0.08%	4	0.167	2	10.8%	$2,865	70.1%
PCMS signs and speed monitoring display	48.30	-1.6%	3	0.155	1	9.2%	$2,315	74.2%

Table 6.3: Comparing Effectiveness of Traffic Control Devices for I-5 Project

Treatment	Mean speed (end of taper and in WZ)	% change in mean speed compared to typical TCP	Rank based on lowest mean speed	Standard Error	Rank based on lowest Standard Error	% change in mean speed compared to OSP parked	Additional cost per day beyond typical TCP	Ratio of WZ speed to reference speed (%)
Typical TCP	47.40	0%	5	0.301	5	5.9%	$0	79.9%
50 mph signs	46.03	-2.9%	4	0.186	4	2.8%	$2,538.50	64.5%
PCMS signs on trailer	44.30	-6.5%	1	0.145	1	-1.0%	$2,888.50	70.7%
PCMS signs and speed monitoring display	44.39	-6.4%	2	0.168	3	-0.08%	$2,951	61.0%
OSP parked only	44.77	-5.6%	3	0.154	2	0%	$2,818.50	63.7%

The conclusions drawn from the two projects are different. For the I-84 project, using reduction in mean speed as the measurement, the most effective treatment is the combination of OSP parked on site and PCMS signs on rollers (Day 5). This are followed in effectiveness by OSP patrolling and PCMS signs on rollers (Day 4), and then PCMS signs on rollers and radar speed monitoring display (Day 9). When using speed variance as the measurement, the most effective treatment is PCMS signs on rollers and speed monitoring display (Day 9). Other treatments that are effective in reducing speed variance are drums on both sides and PCMS signs on rollers (Day 8), and OSP parked on site and PCMS signs on rollers (Day 5).

For the I-5 project, using reduction in mean speed as the measurement, the most effective treatment is PCMS signs on trailer, followed by the combination of PCMS signs on trailer and radar speed monitoring display. Having an OSP officer parked on the site is also very effective. Using speed variance as the measurement, the most effective treatment is still PCMS signs on trailer. This is followed in effectiveness by an OSP officer parked on the site, and then by the combination of PCMS signs on trailer and radar speed monitoring display.

When considering all of the performance criteria and both case study projects, those traffic control measures which performed well were the OSP officer parked on the site, PCMS signs on trailers and rollers, and the radar speed monitoring display. Each of these traffic control measures performed well when considering ease of implementation, cost, and impact on construction worker productivity. Additionally, when each of these measures was used, the traffic speeds were reduced the greatest amount. While vehicle speed at all locations within the work zone was not significantly below the posted 50 mph when each measure was present, the speed at the paver reduced to approximately 40-45 mph. However, lowering vehicle speed throughout the work zone is important, especially for the many workers who are on the ground and not in the immediate vicinity of the paver or grinder. Producing a lower speed throughout the work zone would require additional measures, most likely in combination with a greater reduction in the posted speed limit (e.g., down to 35 mph). The pilot study was successful in demonstrating that the 85th percentile speeds can be reduced to approximately 35 mph using a two-step reduction and three OSP officers. The researchers believe that similar results could have been achieved on the two case study projects within the present study if a two-step reduction to 35 mph and one or more OSP officers were used.

It is important to remember that there is no traffic control device that is a “silver bullet” for work zone safety. The decision regarding whether to use a certain traffic control device or not should be based on the effectiveness of the traffic control device in slowing and controlling traffic, along with consideration of the positives and negatives related to cost, availability, ease of use, application to the particular site, and impact on the work progress. In most cases, a combination of multiple traffic control measures is needed. In all cases, worker and motorist safety should be given highest priority.

7.0 RECOMMENDATIONS

The research study provides an opportunity to recommend, based on objective site data and statistical analyses, traffic control measures to use on highway paving projects. It should be noted that the limitations and confounding factors present in the data collection and research methods of this study will affect the study results. Further study is needed to gain repeatability in the findings and improve confidence in the overall recommendations for practice.

7.1 RECOMMENDED TRAFFIC CONTROL MEASURES

After considering the effectiveness of the treatments in reducing vehicle speed and speed variation, along with the positive and negative aspects of implementing the traffic control devices in practice, several traffic control measures were found to perform better than others. Those that perform well are: OSP officer parked on the site, radar speed monitoring display, and PCMS signs on both trailers and rollers. The implementation of a combination of these traffic control measures along with a posted speed reduction is recommended for typical highway preservation projects. Further recommendations related to each of these measures are provided below:

- *OSP Officer*: The use of one or more OSP officers during the work period is recommended if available and feasible. Police officer presence was found to be effective in this research study, on the pilot study, and in prior studies described in published literature. Police presence is also currently employed by all but one of the 17 states surveyed. If only one officer is available, the officer should park his/her vehicle on the site for the duration of the work period. While an OSP officer patrolling the site was also found to be effective, the patrolling officer's presence in the work zone is intermittent when cycling into and out of the work zone. The parked OSP officer and vehicle should be located in the closed lane, shoulder, or median at the beginning of the work area (near the end of the taper) so that the vehicle is clearly visible to oncoming traffic. The vehicle should have its red/blue flashing lights turned on to make it as visible as possible and stand out from the construction work. The officer may relocate and park at other locations as the paving operation moves up the roadway if sufficient space is available to park. However, the vehicle should remain upstream of all construction work activity, including the activities that take place after the rollers. If more than one officer is available, one officer should park on the site as described above, and the other officer(s) should either patrol the site and/or park downstream of the taper at various locations spread throughout the work zone.

- *Radar Speed Monitoring Display*: A radar speed monitoring display is relatively easy to set up, inexpensive, and catches the attention of drivers, and was found to help lower vehicle speed. Including one or more radar speed monitoring display in the work zone is recommended in practice. When the displays are used on a project, the speed limit posted on the display must match that posted for the work zone. One radar speed monitoring display should be placed at the beginning of the work zone in the buffer area after the end of taper and before the work starting point. If possible based on the space available on the site, an additional display should be located at the mid-point of the work zone as a reminder to the drivers. If the work zone is very long, additional displays can be located periodically throughout the work zone. All of the radar speed displays should be located such that they are clearly visible to the passing motorists, and not where there are already multiple permanent or temporary traffic control signs present (i.e., ensure sufficient spacing between signs to allow for motorist comprehension of the signs).

- *PCMS Signs on Trailers and Rollers*: Use of PCMS signs is recommended to alert the drivers of upcoming hazards, provide additional requests to slow down, and remind them to watch for workers on the roadway. The PCMS signs may be supported on trailers or rollers. A combination of both PCMS signs on trailers and on rollers is especially beneficial. One PCMS sign on a trailer can be placed at the beginning of the work zone (in the buffer area after the end of taper and before the work starting point) to alert the drivers of all of the work in the work zone. An additional PCMS sign on a trailer can be located near the mid-point of the work zone as an additional reminder to the drivers. One or more PCMS signs on rollers can be used to alert motorists again to further protect those working around the paver. The benefit of PCMS signs on the rollers is that they stay up with the paver as the operation moves up the roadway. Utilizing a combination of both PCMS signs on trailers and on rollers is especially effective and recommended.

  It is important to remember to provide enough distance between the PCMS signs on trailers and the radar speed monitoring displays to eliminate driver confusion. Many signs, pieces of equipment, lights and other work zone features at the beginning of the work zone may be overwhelming for motorists, especially when the drivers are trying to merge lanes. The messages on the PCMS signs should clearly alert the motorists of the workers on the roadway and instruct the drivers to slow down. The following are suggested messages: “Slow for Workers”, “Workers on Roadway”, and “Narrow Lane”.

- *Temporary Speed Limit Signs*: To reduce vehicle speeds throughout the work zone, temporary speed limit signs should be used along with the traffic control measures recommended above. The research study revealed that with temporary 50mph speed signs, the traffic control measures enable speed reductions from 65mph to 50mph and less. Further reduction in speeds can be attained as was found on the pilot study. If lower speeds are desired, such as reducing speed to 35mph, lower temporary speed limit signs should be used with multiple levels of speed reduction (e.g., two steps).

  The speed limit signs should be mounted on portable stands which are easy to set up, relocate, and transport. The signs should be placed on both sides of the travel lane. One set of the temporary lower speed limit signs should be placed after the merge. Additional sets of speed limit signs should be placed periodically approximately 1 mile apart along the work zone. After the work zone, a set of regular speed limit signs (e.g., 65 mph) need to be placed. While the temporary signs are in place, any permanent speed limit signs in the work zone need to be covered.

Additionally, incorporating all of the planned traffic control measures within the TCP in the contract documents is beneficial to ensure that the measures will all be implemented as part of the TCP and to allow for efficient implementation at the start of the work period. It is important to have all of the traffic control measures in place as early in the work period as possible and ideally before any construction work begins.

7.2 LIMITATIONS AND RESEARCH RELATED ISSUES

A large amount of data was collected on the case study projects as part of the research. However, the researchers believe that there are limitations in generalizing the research results and further case studies are needed to confidently suggest recommended practice and to enable continual improvement of TCP design and construction practices. On each case study project, confounding factors such as intermittent progress of the work, extreme weather, inconsistent application of the traffic control devices, and differences in the traffic control measures from one project to the other, limited the ability to control the research efforts. Due to confounding factors, both related to the case study projects and the research methods and obstacles, additional speed data is needed to provide a high level of confidence in the statistical comparisons. The researchers prepared research plans before the start of each case study project, but the plans had to change several times during the course of each project to account for the paving progress and availability of police officers. Additionally, the implementation of traffic control devices and the placement of traffic analyzers went well on some days, but were unsuccessful or marginally effective on other days. All of these factors can make the data collected from each day unique and difficult to compare amongst the other days.

Furthermore, the placement of the traffic analyzers and the weather-sensitive tape to secure the analyzers weakened the reliability of the speed data. On future studies, it may be helpful to use another type of equipment to collect speed data, or to use another type of equipment as a second source of speed data along with the traffic analyzers for comparison.

Other recommendations related to research methods are listed below:

- The measurements used to evaluate the effectiveness of the traffic control devices in this research are speed reduction and speed variance. It may be helpful to use other measurements as well, such as the speed reduction for free-flowing vehicles, the percentage of vehicles exceeding the posted speed limit, and the length of traffic queue upstream of the work zone.

- Besides conducting field studies of traffic control measures, consider augmenting the research with other research tools that can provide additional guidance and validate the research results. For example, the use of a driving simulator is an efficient and safe way of evaluating driver behavior relative to specific driving environments and traffic control measures.

- Randomly selecting traffic control devices to implement on each day will help avoid problems associated with daily traffic differences.

- Consider placing the reference traffic analyzers further upstream of the work zone to eliminate any affects on the reference speeds related to queuing and the initial presence of the "Road Work Ahead" signs.

- Communication between the research team, ODOT, and contractor is essential to successfully implement the research plan. Ensure that pre-construction meetings take place with the contractor to clearly describe the research efforts, roles, and expectations.

- Vehicles used by the researchers to enter and exit the work area should have flashing lights on top to make the vehicles stand out while on the site and help keep other vehicles from unknowingly following them into the closed work area.

Change orders were implemented on the case study projects to cover the cost of the additional traffic control measures and compensate the contractor for the additional efforts required of the contractor to assist with the research. The change order costs were significant for both the I-84 and I-5 case study projects. A major portion of the extra cost was an additional TCS to help the research team place the traffic analyzers and conduct data collection. This added cost will not be part of the cost of implementing the traffic control measures when used on future projects. Additionally, the cost for implementation of the suggested traffic control measures may be lower if the traffic control measures are included in the contracted scope of work before bidding.

7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

In the most recent Technical Advisory Committee (TAC) meeting for the research study, the TAC members suggested conducting additional case study projects. The purpose of the additional research is to collect additional data and address the following issues and needs:

- More accurately determine the effectiveness of each traffic control measure and improve confidence in moving forward with recommendations.

- Collect additional speed data needed to better identify the advantages of one traffic control measure over another.

- Record speeds further upstream of "Road Work Ahead" signs to determine if speeds are being reduced simply due to the presence of the work zone.

- Conduct additional case study projects to allow for eliminating confounding factors due to project-specific conditions and data collection limitations

The additional research should comprise augmenting the present research study with at least two additional case study projects.

The two additional case studies should be on paving projects similar to the projects evaluated in the present study, and focus on adding the following specific traffic control measures to the original TCP:

- “SPEED 50” signs
- PCMS signs on a roller(s) or a stationary trailer(s)
- Radar speed reader trailers

The tasks to be undertaken are similar to those on the present study, and are as follows:

- *Task 1*: Select case study projects. The projects should be similar in size, scope, and site conditions to the I-84 and I-5 projects on the present study (i.e., high-speed freeways in rural areas with two lanes in each direction). If possible, the projects should be selected such that the timing allows for the added traffic control measures to be included in the construction bid package so that a representative cost of the measures can also be obtained.
- *Task 2*: Implement the proposed traffic control measures identified above (“SPEED 50” signs, PCMS, and radar trailers) on each case study project. Measure the traffic volume, speed, and speed variability throughout the projects. Record other impacts to the projects (cost, time, productivity, safety, etc.) based on each measure. Along with the original TCP, the research plan should include implementing each additional measure for a period of several days to minimize daily impacts.
- *Task 3*: Analyze the speed and other data collected to determine the impacts of each traffic control measure on the project.
- *Task 4*: Prepare a research report that describes the case studies, presents the findings of the research, and provides recommendations to ODOT for implementation in practice.

The research is expected to enhance the data collected from the present study, and provide guidance and support to ODOT. It is ODOT’s responsibility to provide a safe environment for highway workers and the driving public, and the recommended research will take an additional step toward further improvement.

7.4 ADDITIONAL RECOMMENDATIONS FOR WORK OPERATIONS

During the course of the study, the researchers observed additional site conditions and work practices that should be addressed and/or researched. The following recommendations relate to the conditions and practices separate from the traffic control plan which would greatly help to improve safety in the work zone:

- The amount of light provided in the work areas is important. The bright lights around the paver and grinder help to illuminate the work area and workers, draw the motorists’ attention, and indicate to the motorists the importance of the lighted area. The work areas should be illuminated as much as possible. However, the lights must not be too bright or be oriented such that they create disabling glare for the passing motorists. Minimizing glare is important given that the drivers are trying to negotiate through an active, variable, and unfamiliar work zone. In addition, if possible, temporary portable lights (battery powered) could help illuminate the workers on the ground who are not in the immediate vicinity of the paver or grinder. Also, Class 3 reflective apparel is suggested for all workers on the site. The apparel should be regularly maintained so that it is clean and reflective.

- All asphalt trucks should have back-up alarms and signs on the back warning trailing vehicles not to follow the trucks into the closed work area. It would help if the signs were lit up or highlighted only when the trucks began entering the closed work area. The signs are not needed (and possibly confusing to drivers) when the trucks are traveling in the open lane through the work zone.

- In some cases work is conducted during the daytime to service on-site equipment, prepare the site, plan the work, and conduct other miscellaneous activities. Protection of the workers during these hours is essential as well. Consideration should be given to also placing traffic control measures in the work zone (e.g., PCMS signs on trailers) during the non-paving hours.

- If OSP officers are utilized with active enforcement throughout the work zone (i.e., patrolling the work zone), care should be taken by the officers to not disrupt the work operations or distract drivers when stopping a vehicle. Officers should pull over vehicles a good distance downstream of the paving operation so that it does not distract the drivers passing through the work zone or disrupt the work.

- The presence of existing site conditions in addition to temporary control measures should be considered. For example, after repaving the B lane (slow lane) there is often a construction joint in the pavement between the lane and shoulder. If the shoulder is not newly paved, the shoulder pavement may also be a different color and texture than the new asphalt and there may be debris on the shoulder. In any situation, driver tendency is to not want to drive on the shoulder because of the unknown pavement condition and debris that might exist. Therefore, when paving the A lane (fast lane) and before the fog line is in place on the B lane, drivers traveling in the B lane use the construction joint as a guiding line on where to drive and where they would prefer not to drive. If the distance between the construction joint and the line of tubular markers on the opposite side of the travel lane is not great, drivers will tend to drive close to the line of tubular markers and hence close to the worker area. This situation should be avoided if possible in order to increase the distance between the passing vehicles and workers.

- Communicating with the contractor to maintain safe worker activities is important. A significant portion of the risk to worker safety can be mitigated through safe work operations. Continued monitoring of contractor work operations and enforcement of safe work practices is needed.

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APPENDICES

The appendices are provided in the file titled "High Speed Reduction Report – Appendices.docx".