SAFE AND EFFECTIVE SPEED REDUCTIONS FOR FREEWAY WORK ZONES PHASE 2

Final Report

SPR 769

Oregon Department of Transportation

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16. Abstract: Freeway preservation projects typically require construction workers to conduct their work in close proximity to ongoing traffic and often reduce traffic flow to a single lane while work is undertaken in an adjacent lane. Due to the short-term nature of these work zones, temporary traffic control measures typically consist of a line of cones, blocker vehicles, and impact attenuators. Work zones place both the workers and passing motorists at risk of injury. The Oregon Department of Transportation conducted a research study to investigate the impact of selected traffic control devices on vehicle speeds within highway paving project work zones. The research study, which follows a similar study conducted a year earlier, centered around two case studies on multi-lane paving projects in Oregon. On each case study, the researchers implemented combinations of multiple traffic control devices ("Speed 50" signs, PCMS signs, and radar speed displays) and evaluated their impact on vehicle speed. The research findings suggest using a combination of reduced speed limit signs, radar speed monitoring displays, and PCMS signs on either trailers or rollers. The results of the present study complement those of the prior study and, combined with the prior study, provide ODOT with guidance on the selection of traffic control measures for freeway preservation projects.

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ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
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ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
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gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
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yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
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lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
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*SI is the symbol for the International System of Measurement

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DEDICATION

The research efforts and outcomes of this study are dedicated to those workers and motorists who have been injured or lost their lives in highway construction work zones, especially Kathleen Wilson of Trail, OR, who was hit and killed while working to clear a traffic control device in the work zone on one of the case study projects. Our work is dedicated to their lives and to preventing additional worker and motorist injuries and fatalities in the future.

DISCLAIMER

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1.0 INTRODUCTION

1.1 BACKGROUND

Freeway 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 and often 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. Areas of limited protection create considerable safety risk for both the workers and passing motorists. Inattentive or speeding drivers, careless workers, misplaced cones, and hazardous roadway conditions can lead to crashes and ultimately work zone injuries and fatalities. The severity of a crash intensifies as the speed of traffic increases (*Aarts and Schagen 2006*). 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 vehicle-related crashes on roadways *(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, reducing traffic speeds a large amount would likely enhance the safety of the workers and traveling public. However, reducing speed for example from 65 mph to 35 mph is a large reduction, and evaluation of the impacts of this differential in speed on interstate highways has been limited. 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*). To help minimize the potential for crashes in such cases, FHWA recommends staging an additional advanced warning and speed transition area if the speed reduction is greater than 20 mph *(FHWA 2009)*. 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 further complicate the jobsite conditions, be difficult to implement, and may increase risks to worker and motorist safety. Lastly, when an accident occurs in a work zone, additional costs and delays accrue. From a cost and delay standpoint, it is better to slow the traffic and avoid an accident altogether.

Research on controlling and reducing speeds on high-speed roadways, and on significant speed reductions, has been conducted. 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, although no quantified impact of each independent traffic control measure was provided (*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.

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 project safety enhancements. Preservation projects are short-term projects that involve rehabilitation of the roadway (e.g., pavement overlays, "chip seal" operations, and guardrail repair/replacement). For such projects, the work zone is typically not static (i.e., the work zone is relocated frequently as the work progresses along the roadway). Preservation projects were selected as the focus of the study given their increasing prevalence within the ODOT roadway construction program, presence of workers close to the travel lane, and the difficulties in providing positive protection for short-term work zones. 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 on highway preservation projects. 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 is recommended by FHWA *(FHWA 2009)* and 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).

To augment the pilot study, ODOT began a research study (SPR-751) in FY2013 to look for ways to safely reduce speeds through work zones on preservation projects taking place on high-speed freeways. The recently completed study included two paving projects, one on I-84 near The Dalles and one on I-5 just north of the McKenzie River Bridge. On each project, different traffic control measures (TCMs) were implemented and speed data was collected both prior to and within the work zone. The TCMs, which were implemented after one treatment with the original traffic control plan (TCP), were:

- "SPEED 50" regulatory signs throughout the work zone
- PCMS signs on pavement rollers or stationary trailers
- Radar speed reader trailers

- Oregon State Police (OSP) patrolling work zone
- OSP parked at end of lane closure taper
- Tubular markers placed on both sides of the live travel lane
- Plastic drums placed on both sides of the live travel lane

Using the speed data recorded, the reduction in speed from the beginning reference point – "Road Work Ahead" (RWA) signs – to locations within the work zone was calculated along with the speed relative to the distance to the paver. Statistical analyses of the data show that each TCM helps to reduce the mean speed. The data also suggests a difference in the relative effectiveness of each TCM. However, confounding factors in the study and data collected limit confidence in this result. The SPR-751 study report was published in February 2013. The final report for the SPR-751 report can be found at the following website: http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2013/SPR751_SpeedReductions.pdf; and report appendices at: http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/2013/SPR-751_SpeedReduction-Appendices.pdf).

Based on the results of SPR-751, the Technical Advisory Committee (TAC) members for the study suggested conducting additional case study projects to collect supplementary data and address the following issues and needs:

- More accurately determine the effectiveness of each TCM and improve confidence in moving forward with recommendations
- Collect additional speed data to better identify the advantages of one TCM over another
- Record speeds further upstream of RWA 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 present study is designed to supplement the initial SPR-751 study and address the concerns and recommendations of the TAC.

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. The research includes conducting two additional case studies on paving projects similar to those studied in the SPR-751 study. In addition, as recommended in the SPR-751 final report, the research includes fewer treatments. The TCMs chosen as the focus of the study are: “SPEED 50” signs, PCMS signs on a roller(s) or a stationary trailer(s), and radar speed reader trailers. The research is expected to enhance the data already collected on specific treatments from the SPR-751 study, and provide guidance to ODOT on how to design traffic control plans for work zones. The research will take an additional step toward further improvement in safety for highway workers and the driving public with the support of FHWA and the AGC. The specific objectives established for this research study are to:

1. Identify potential case study projects and select two projects to study as part of the research.
2. Implement the selected traffic control measures (“SPEED 50” signs, PCMS signs, and radar speed readers) on the case study projects.
3. Compare the performance of the implemented treatments based on their ability to lower speeds a significant amount, ability to minimize speed variability, ease of use, and implementation cost.
4. Develop guidance for ODOT and construction contractors to reference when planning and implementing traffic control measures on highway preservation projects.

The research will focus on effective means to reduce actual speeds in work zones. This includes methods to safely reduce legal posted speeds as well as find measures that reduce actual speed without relying on a posted speed reduction. Research products (outputs) include recommendations for traffic control plans and guidelines for OSP activities under these conditions.

All of the resources and tools necessary for data collection and analysis are already available from the SPR-751 study. The researchers were able to utilize their experience and knowledge learned from the prior study to efficiently and effectively conduct the additional case studies.

1.3 BENEFIT

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. The research is expected to enhance the data collected from the SPR-751 study, and provide guidance and support to ODOT for improving work zone safety. Importantly, the research will benefit construction workers and motorists by leading to safer work zones. Additionally, the research is expected to reveal how to promote efficient treatments for travel through work zones, and ultimately maintain a high level of mobility throughout the state. Lastly, successful completion of the research and implementation of the research results is expected to strengthen the partnerships between ODOT and the AGC Oregon-Columbia Chapter and the Oregon Trucking Association.

1.4 IMPLEMENTATION

The research results will be combined with those from the SPR-751 study and used by the Traffic/Roadway Section through procedures outlined to the Region Tech Centers, and implemented through the State Traffic/Roadway Engineer. The results will be used by the Statewide Construction Office for these types of projects and implemented through communication and education of the Construction Project Managers statewide, as approved by the Statewide Construction and Materials Engineer. The results will also 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

Research studies have been conducted regarding the effectiveness of traffic control measures in work zones. Standards and practical guidelines for controlling traffic through work zones and providing a safe environment for both workers and motorists have also been developed. The researchers conducted a literature review as part of the research activities for the initial high speed reduction study (SPR-751), which is provided in the SPR-751 final report. The literature relevant to SPR-751 is also relevant to this Phase II study, and therefore is provided again in this section of the report. A discussion of additional literature and updates to the documents described that are especially relevant to the Phase II study has been added at the end of this section.

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.

2.1.1.1 Traffic Control Plan:

The principal function of a TCP is to enable 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*).

2.1.1.2 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. It should be noted that for pavement preservation projects like those included in the present research study, the activity area may be up to several miles long or more.

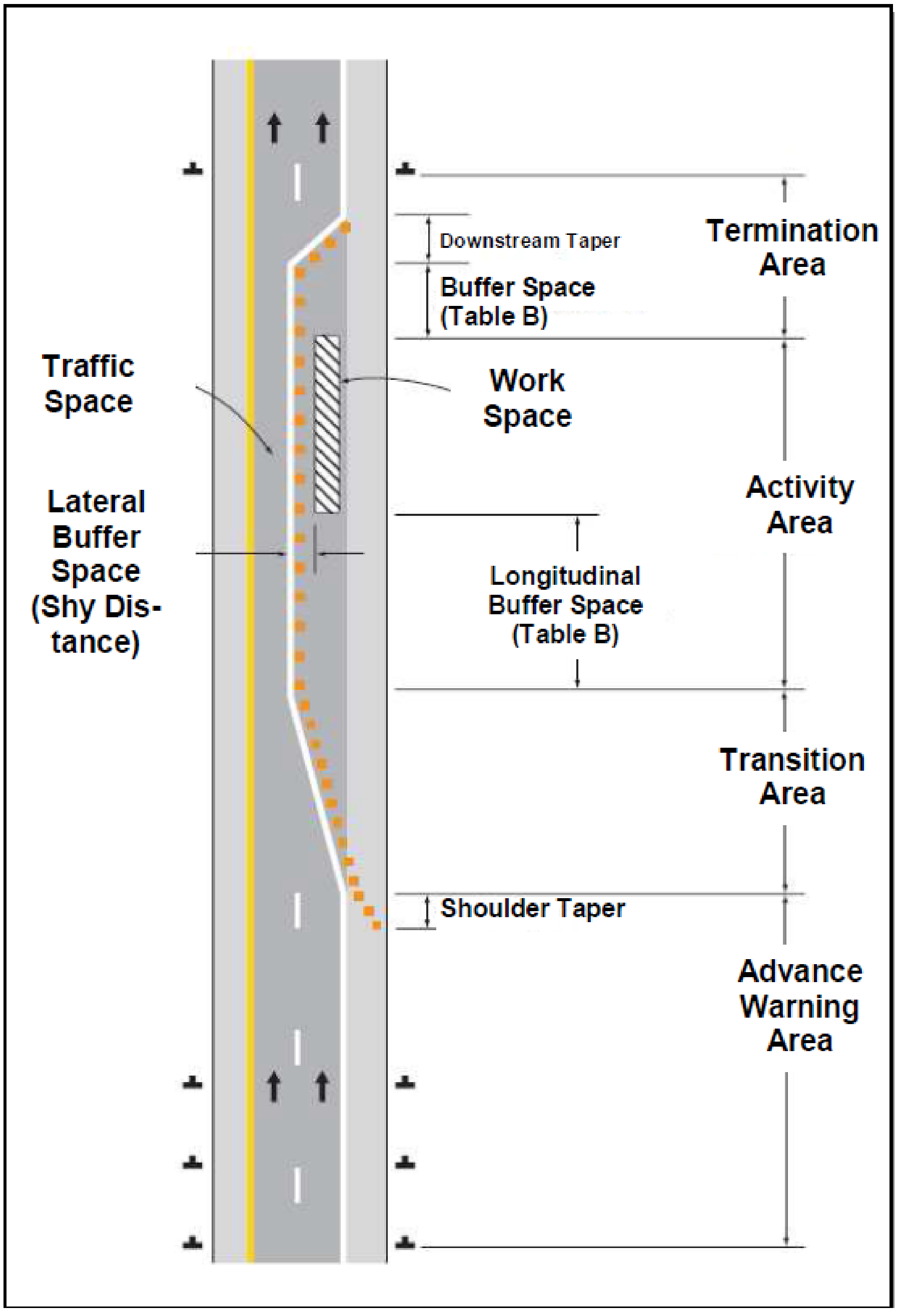


Figure 2.1: Four Areas in a Work Zone (*ODOT 2011*)

2.1.1.3 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 speed-dependent. Spacing dimensions, ‘A’, ‘B’ and ‘C’ are defined in Table 2.1, where dimension A represents the distance between the beginning of taper and the 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

2.1.1.4 Traffic Control Devices:

Traffic control devices (TCDs) 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 the I-84 case study project as part of SPR-751.

Figure 2.2: Tubular Markers on Roadway

Temporary Plastic Drums – Plastic drums (barrels) are the largest, most visible deformable channelization devices. Plastic drums are usually used to delineate travel lanes, identify work areas, construct lane closure tapers, and delineate portable changeable message sign (PCMS) and temporary traffic signal installations (*ODOT 2011*). Figure 2.3 shows plastic drums in use on the I-84 case study project as part of SPR-751.

While designed primarily for channelization, both tubular markers and drums may also be employed for vehicle speed reduction. Channeling the traffic in a certain direction or location may cause reduction in speeds. In addition, and as tested as part of this research study, tubular markers and drums can be located to narrow down a lane, giving the impression of a tighter driving lane and thus promoting slower speeds.

Figure 2.3: Plastic Drums on Roadway

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

Figure 2.4: Type III Barricade (ODOT 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 PSS 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 barriers 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 barriers or other fixed objects. Figure 2.8 shows an example of a TMA attached to the rear of a truck.

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 2.8 above shows an example of a sequential arrow board mounted on top of a truck.

Portable Changeable Message Sign (PCMS) – PCMS's are large lighted signs used to display programmable, dynamic messages that reflect 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. A 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. Examples of the responsibilities included in this role are: inspecting and maintaining the temporary traffic control devices, replacing damaged devices, monitoring traffic flows through the work zone or the effectiveness of a detour, and making recommendations to ODOT and the contractor to improve upon the TCP (*ODOT 2011*). The TCS must be certified and carry a valid certificate verifying their certification. The person assigned to the TCS role must not be the project superintendent. TCS involvement is typically measured and paid for on a work shift basis. One payment is made for a TCS regardless of length of the work shift.

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

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

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

1. General plans or guidelines should be developed to provide safety for motorists, bicyclists, pedestrians, workers, enforcement/emergency officials, and equipment.
2. Road user movement should be inhibited as little as practical.
3. Motorists, bicyclists, and pedestrians should be guided in a clear and positive manner while approaching and traversing TTC zones and incident sites.
4. To provide acceptable levels of operations, routine day and night inspections of TTC elements should be performed.
5. Attention should be given to the maintenance of roadside safety during the life of the TTC.
6. Each person whose actions affect TTC zone safety, from the upper-level management through the field workers, should receive training appropriate to the job decisions each individual is required to make. Only those individuals who are trained in proper

TTC practices and have a basic understanding of the principles (established by applicable standards and guidelines, including those of this Manual) should supervise the selection, placement, and maintenance of TTC devices used for TTC zones and for incident management.

7. Good public relations should be maintained.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

- *6C.01-12*: Reduced speed limits should be used only in the specific portion of the TTC zone where conditions or restrictive features are present. However, frequent changes in the speed limit should be avoided. A TTC plan should be designed so that vehicles can travel through the TTC zone with a speed limit reduction of no more than 10 mph.

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

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

- Support: *6C.01-15*: Research has demonstrated that large reductions in the speed limit, such as a 30 mph reduction, increase speed variance and the potential for crashes. Smaller reductions in the speed limit of up to 10 mph cause smaller changes

> in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 10 mph from the normal speed limit has been shown to be more effective.

The present study aims to reduce vehicle speeds as much as possible and also minimize speed variability. The nighttime paving operations targeted in the study put workers immediately adjacent to on-going traffic without positive protection. This condition represents a very restrictive feature from a safety management standpoint, and therefore qualifies under Section 6C.01-13 for higher speed reduction. To address the issue of large reductions in speed, additional notification of slower speeds is provided in the form of the additional traffic control devices deployed in the research.

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 roadways with 50 mph regulatory speed 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)*

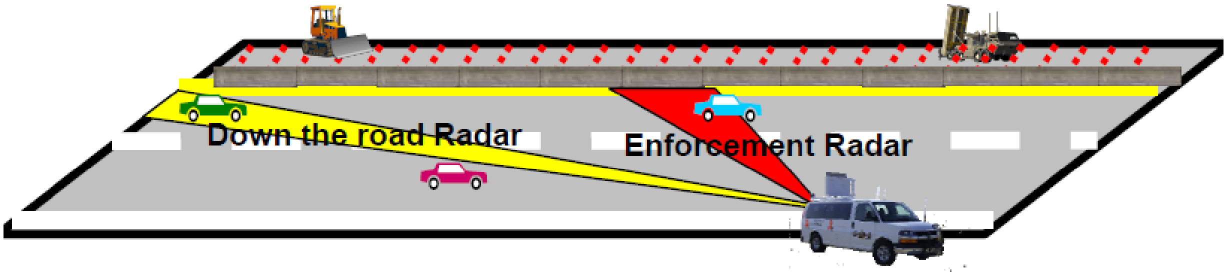


Figure 2.13: Operation of the Photo Enforcement *(Benekohal et al. 2010)*

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 where the regulatory speed was 50 mph. The percentage of free-flowing vehicles (with headways greater than 4 seconds) exceeding the speed limit at the treatment location was reduced drastically (*Tobias 2011*). The presence of the SPE system also reduced the speeds of vehicles 1.5 miles downstream of the van location by 2 to 5 mph.

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. One exception, for example is the state of Washington, which has a large state patrol force and frequently employs police presence in work zones, both parked as a visible deterrent and patrolling. Replacing police enforcement by photo-radar enforcement machines may be more practical and cost-effective for those states with fewer police resources available.

One activity within the research study involved conducting a survey of the state transportation agencies in all 50 states plus 13 non-DOT transportation agencies (e.g., state turnpike commissions) about the practices which the agencies implement to reduce work zone speeds. Based on the 39 responses received, the researchers concluded that the most effective speed reduction method involved some combination of traffic control devices. [Note: As part of ODOT’s SPR-751 study, the researchers conducted a survey of other DOT practices regarding police enforcement deployment. The results of the survey are provided in the SPR-751 final report.]

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 (Maze et al. 2000). 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. Maze et al. cite a study (*Ullman et al. 1991*) which evaluated the effectiveness of drone radar at work zones on suburban and rural divided highways and on suburban interstates. Ullman et al. analyzed the data to determine whether the fastest motorists were indeed the most likely to be affected by drone radar. The average speed reduction of vehicles traveling faster than 65 mph was compared with the average speed reduction of all vehicles. The average speed of the speeding group was determined to be 0.2-2.6 mph greater than the average speed reduction for all of the vehicles (*Ullman et al. 1991; as cited in Maze et al. 2000*).

Removable rumble strips are a type of rumble strips that can be temporarily placed and removed from the roadway. This type of rumble strips is available is various configurations and designs. One type has polymeric tape treated with pre-applied adhesive to secure it to the roadway, and can be applied on both asphalt and concrete road surfaces. Another type relies on its own weight and friction between the rumble strip and pavement to keep it in place. 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, and to help slow down the traffic. The research done by Maze et al. *(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 *(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 *(Elghamrawy et al. 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.

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

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.

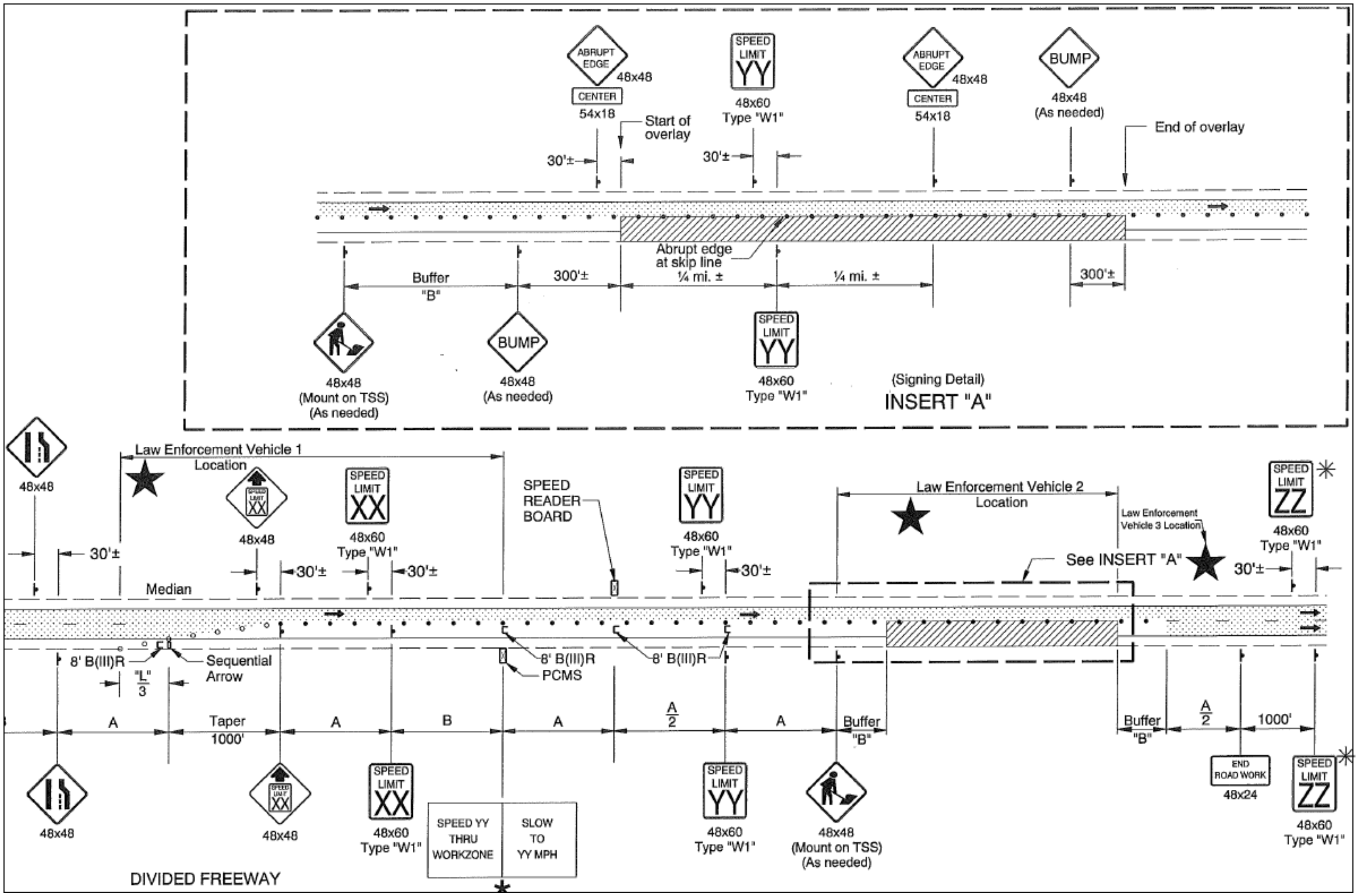


Figure 2.15: Pilot Study Traffic Control Plan Using Two Stage Speed Reduction

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. Figure 2.16 shows the data summary for passenger vehicles, and Figure 2.17 shows the data summary for commercial trucks.

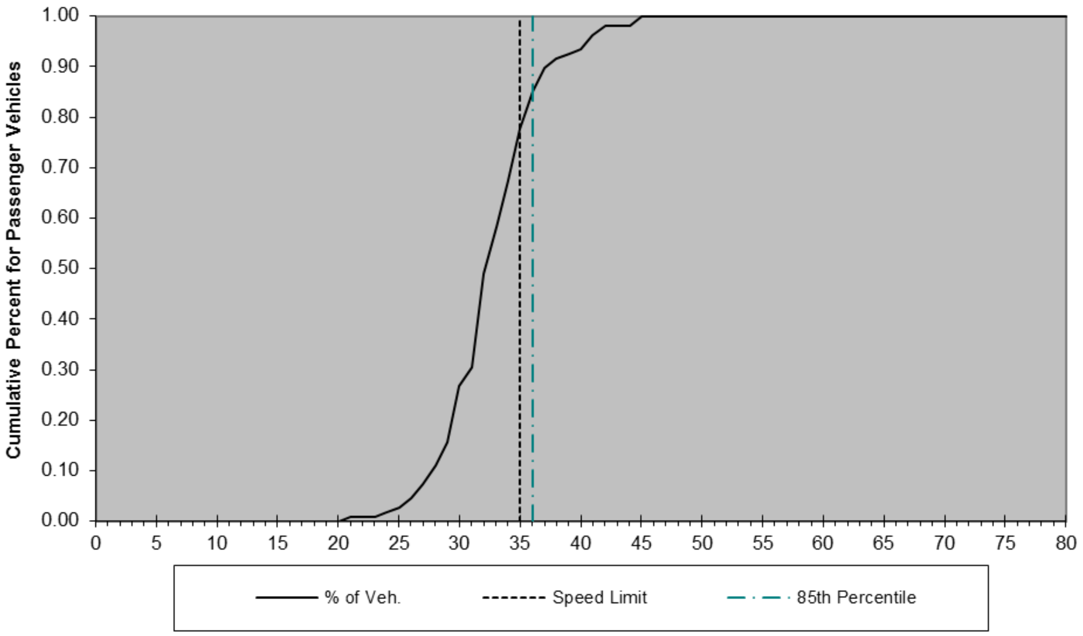


Figure 2.16: Pilot Study Speed Data Summary for Passenger Vehicles

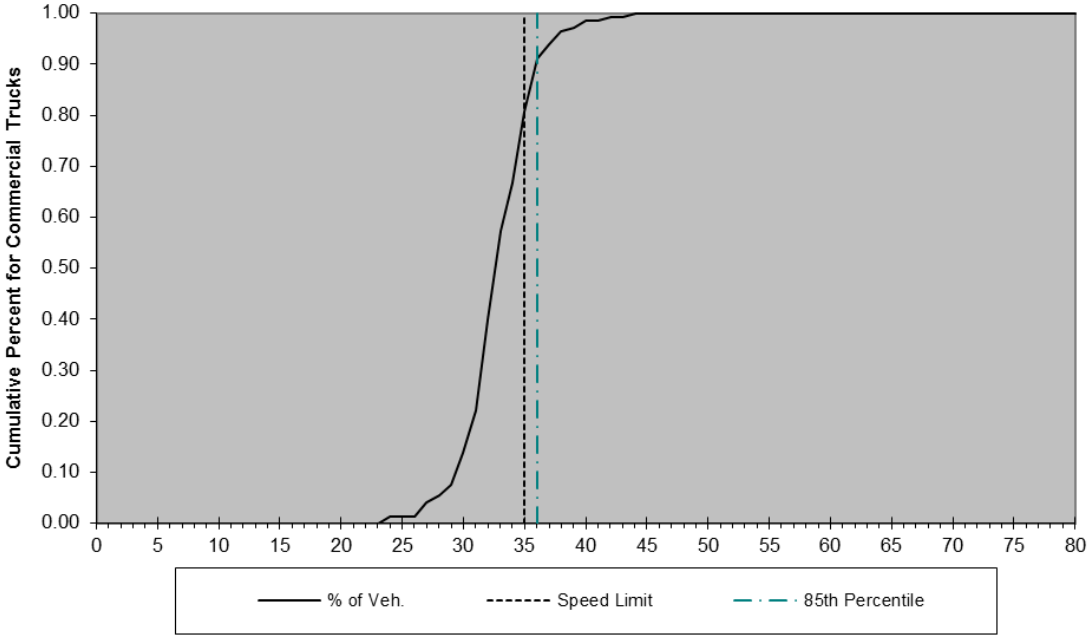


Figure 2.17: Pilot Study Speed Data Summary for Commercial Trucks

The speeds for a total of 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 present 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.

2.5 ADDITIONAL RELEVANT LITERATURE

As mentioned previously, the literature discussed above was presented in the report for the initial high speed reduction study (SPR-751). While not part of the stated work plan, the researchers searched for additional literature which may have been published since the SPR-751 final report and which is relevant to the present study. Below is a discussion of the additional literature found.

2.5.1 ODOT 2013 PCMS Handbook

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

2.5.2 ODOT Temporary Traffic Control Handbook

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

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

2.5.3 New Research

Since the completion of the prior study (SPR-751), additional research on the topic of work zone traffic control has been conducted and presented at the recent Transportation Research Board (TRB) 93rd Annual Meeting in Washington, DC, in January 2014. One study used quantile regression to evaluate speed data instead of traditional methods *(Chen and Tarko 2014)*. The study was conducted in work zones where the posted speed limit was 45 mph. The researchers concluded that the flexibility of quantile regression allowed for investigating the effects of each traffic control measure on each driver group (slow, average, and fast drivers). The results of the study show that, while a large percentage of all vehicles travelled at greater than the posted 45 mph, police enforcement has more impact on fast drivers than on slow and average drivers. The analyses of the data collected for the present study employed commonly-used statistical analysis techniques that did not include quantile regression.

A second study focused on driver behavior of cars and trucks in six-lane (three lanes in each direction) highway work zones *(Jun et al. 2014)*. The study shows that temporary reduced speed limits in advanced warning areas cause very small or no speed reduction of vehicle speed. The speed of vehicles dropped to the minimal speed recorded when the vehicles reach the activity area. In addition, the study found that trucks and cars behave differently in the work zone. The researchers developed a model to predict vehicle speed based on the distance to the activity area. Further research on this topic would be of value to ODOT. While not included in the current or previous ODOT studies, expected vehicle composition could be used as an input in determining the types or configuration of traffic control devices to use. Helpful outputs from the research would be guidelines on when to change the traffic control measures based on the number and/or percentage of trucks in the traffic mix and, when a change is needed, how to change the type, number, size, location, etc. of the traffic control measures.

3.0 CASE STUDIES

The present research study (SPR-769) is designed to collect supplementary data on the performance of selected traffic control measures in order to eliminate confounding factors present in the prior study (SPR-751). The additional data is intended to provide more confidence in the research conclusions and recommendations for implementation in practice. Speed data is collected by the portable traffic analyzers as in the previous study. In addition, two additional research methods are used to collect traffic speed data. Since the traffic control measurements are the same as last year, no additional interviews of site personnel were conducted.

Collecting vehicle speed data in work zones is commonly performed as part of transportation and construction research. However, the research conducted in the present study (SPR-769) and in the prior study (SPR-751) is unique in several ways. Both studies focus on preservation projects on high-speed roadways in which the location of the work area changes from one day to the next. The traffic control measures or treatments are also varied to measure not only their impact individually but also in combination. In addition, the portable traffic analyzers are located at multiple locations prior to and within the work zone to measure the impact of the traffic control devices at different locations and with respect to specific pieces of construction equipment (paver) during the course of the work shift. These qualities of the research make it different from prior studies.

3.1 PROJECT IDENTIFICATION

The first task in the study was to identify and select paving projects to include in the study. In order to supplement the data collected in SPR-751, the case study projects selected needed to be similar to the two previously selected case study projects. Using upcoming project information provided on the ODOT website, along with input from ODOT Project Managers, the researchers created a list of potential case study projects (see Table 3.1). The list included those projects which were planned to be under construction in the 2013-2014 timeframe, and which included paving within the scope of work.

Table 3.1: List of Potential Case Study Projects

No.	Title	Milepoints	Key #	Contract #	County	Region
1	I-5: Rock Point – Seven Oaks	36.6 – 43.1	18146	14567	Jackson	3
2	FFO – I-84: Kamela Interchange – 2nd Street Undercrossing (La Grande)	246 – 260.3	17989	14555	Union	5
3	I-5: Glendale-Hugo Paving and Sexton Climbing Lane	66.7-81.4	16763	14526	Douglas	3
4	FFO – US-97: OR-58 Jct. – Chemult Passing Lanes	194.6 – 200	17548	14569	Klamath	4
5	FFO – US-26: Mill Creek – Warm Springs Grade	92.75 – 97.1	16198	14560	Wasco	4
6	OR-42: Jct. Hwy. 242 – Remote (MP 23.65-38.35)	23.7 to 38.4	17869	14550	Coos	3
7	OR-140: Lakeshore Drive – Klamath County Boat Marina	57 – 61.7	18148	14570	Klamath	4
8	OR-39: 6th Street (Austin Ave.) – Merrill/Lakeview Jct.	2.6 – 5.7	17936		Klamath	4

The list of potential projects was presented to the Technical Advisory Committee (TAC) for the study. The TAC identified two projects from the list to include in the study: (1) I-5: Glendale – Hugo, and (2) I-5: Rock Point – Seven Oaks. Both projects are on rural/suburban freeways with two lanes in each direction, similar to the two case study projects from SPR-751.

3.2 DATA COLLECTION

The data to be collected from the two case study projects is mainly vehicle data (vehicle type, speed, length, time of day, etc.). To collect the data, a variety of different pieces of equipment, tools, and resources were used by the researchers, including traffic control analyzers, a speed gun, and a video camera. Each of these pieces of research equipment is described below.

3.2.1 Traffic Control Analyzer and Placement

NC-200 portable traffic analyzers manufactured by Vaisala were used to collect vehicle data on the roadway. Figure 3.1 shows an example of the traffic analyzer and a cover used to protect it on the roadway.

Figure 3.1: Portable Traffic Analyzer NC-200 (*Vaisala 2012*)

The traffic analyzer is designed to provide accurate traffic counts, speed, and classification (vehicle length) data. The analyzer is placed directly in the traffic lane to measure and record the passing traffic. The sensor utilizes Vehicle Magnetic Imaging technology to count the number of passing vehicles and detect vehicle speed and length (*Vaisala 2012*). Table 3.2 shows the technical specifications of the NC-200 portable traffic analyzer.

Table 3.2: 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 traffic analyzer manufacturer suggests that the analyzer be nailed down to the pavement through nail holes on the cover as shown in Figure 3.2. 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 3.3 shows an example of how adhesive tape is used to keep the analyzer at the desired location.

Figure 3.2: Placement of Portable Traffic Analyzer by Nails (Vaisala 2012)

Figure 3.3: Placement of Portable Traffic Analyzer using Adhesive Tape

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

To fully understand motorist behavior and vehicle speed through a long paving construction work zone, ten portable traffic analyzers were placed on the roadway for each work period (night of paving). The first two analyzers were placed approximately 1 mile upstream of the "Road Work Ahead" sign to capture vehicle speeds before the vehicles become aware of or enter the work zone. Two analyzers were placed near the "Road Work Ahead" sign, which is typically approximately one mile upstream of the actual work area. Two analyzers were placed at the beginning of the taper, and one analyzer was placed at the end of taper. Three analyzers were placed in the travelling lane at different points in the working area. The actual location and spacing of the last three analyzers in the work zone was dependent on the amount and location of work being performed on the given night. Figure 3.4 shows an example of a plan view of the portable traffic analyzer placement for a typical night. The locations of the portable traffic analyzers are indicated with rectangles in the figure.

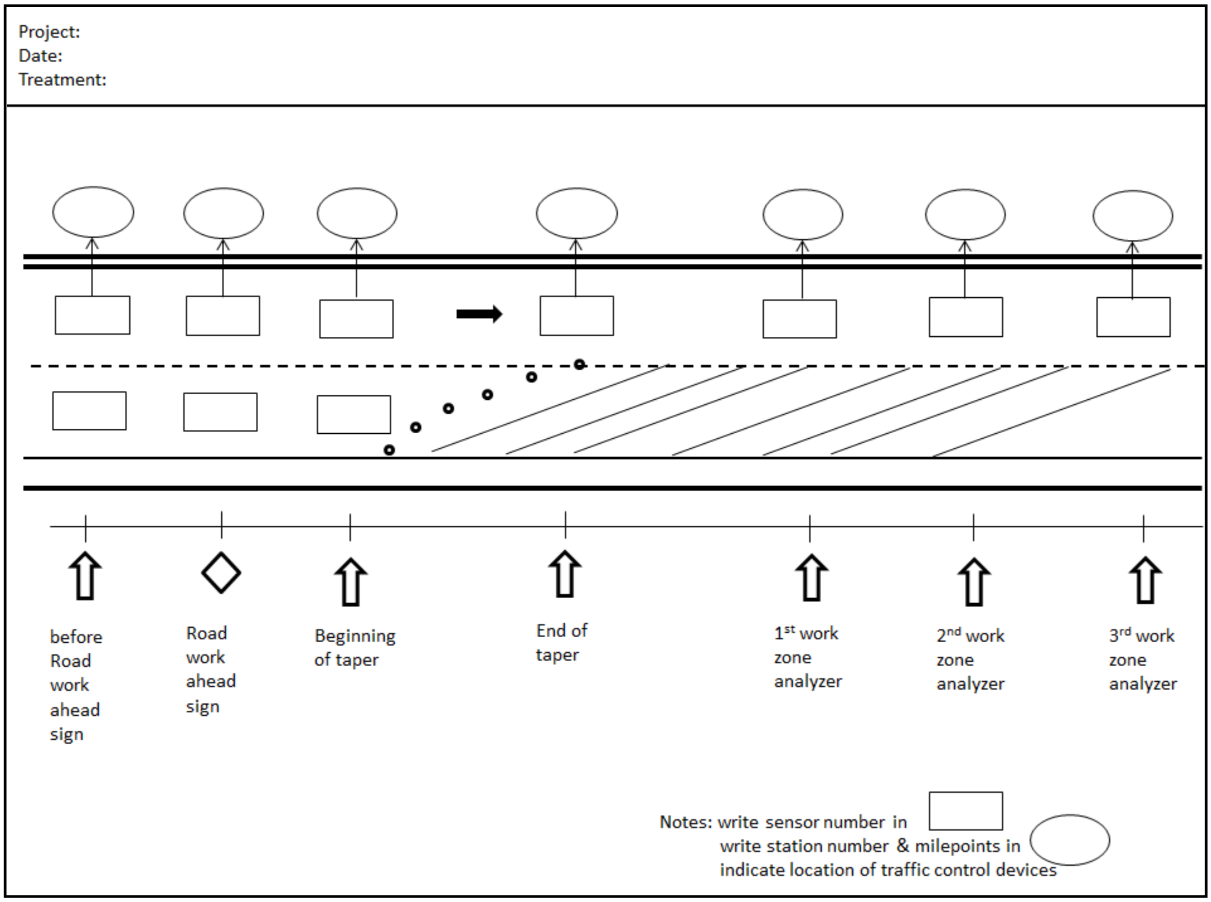


Figure 3.4: Placement of Traffic Control Analyzers (Sensors)

3.2.2 Radar Speed Gun

A radar speed gun was also used to measure vehicle speeds at specific locations in the work zone. The researchers selected several locations within the work zone to monitor traffic speeds. The researchers held the speed gun for a 5-minute period of time and recorded free flow traffic speeds. Using the speed gun is an auxiliary method to provide supplementary data for further analysis and verification of the speeds recorded by the portable traffic analyzers. Figure 3.5 shows a speed gun used in the research. The accuracy of the speed gun is +/- 1 mph and the speed range is 10-200 mph. Prior to using the speed gun, the researchers received a brief training session and demonstration from an OSP officer on how to best use the speed gun.

Figure 3.5: Radar Speed Gun

3.2.3 Video Camera

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

3.3 CASE STUDY #1: I-5 GLENDALE – HUGO PROJECT

The I-5 Glendale – Hugo case study project was located in Douglas County approximately 50 miles south of Roseburg and 20 miles north of Grants Pass. The limits of the project were between milepoints 66.7 and 81.4, including both southbound and northbound lanes. Figure 3.6 shows the location of the project. The overall scope of the project contained many pieces of work, including the construction of a climbing lane in the northbound direction. Only the paving of the roadway as included within the research study.

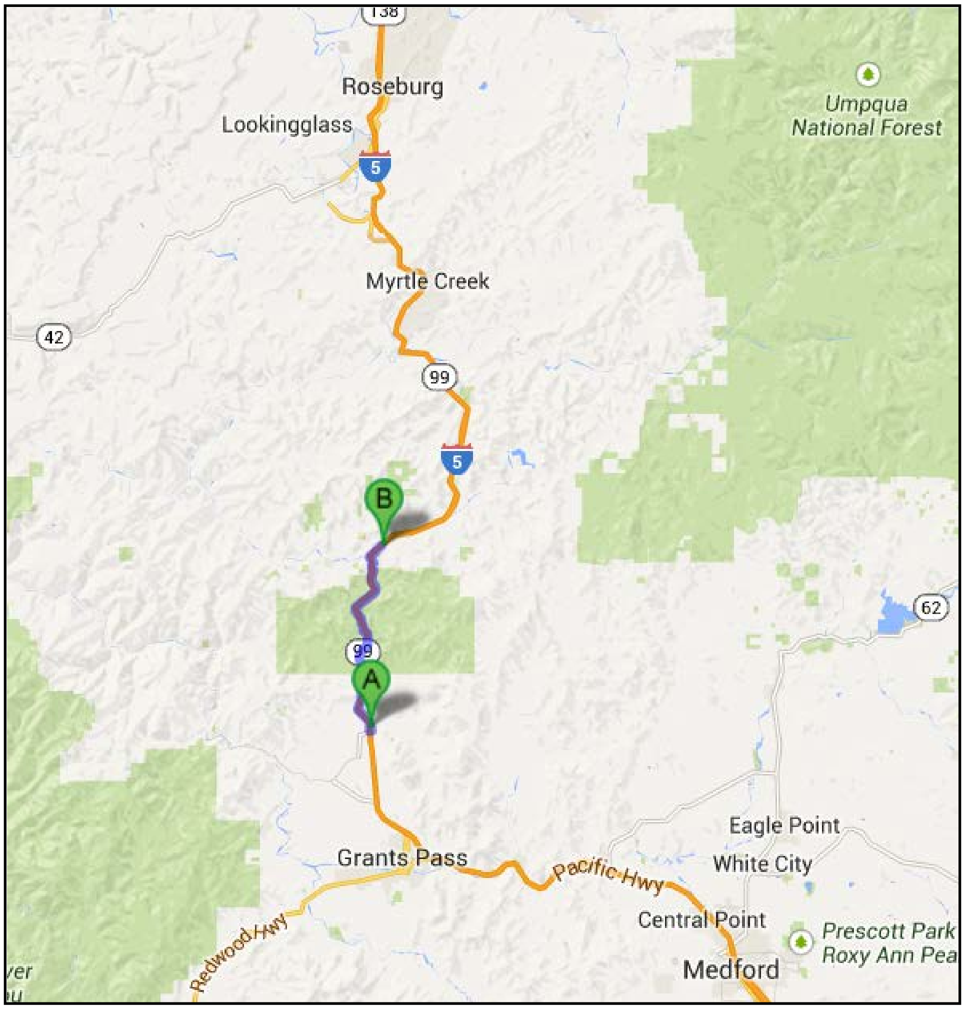


Figure 3.6: Location of I-5 Glendale – Hugo Project (Case Study #1)

At this location the roadway is four lanes (two lanes in each direction plus shoulders), with paving work conducted in both the northbound and southbound directions. The project consisted of paving the base course and wearing course separately. The project location is a mountainous area with sharp curves and steep grades, which presented a challenge to both the paving operation and the research data collection. Figure 3.7 shows the approximate roadway elevation (in feet) along the length of the work zone. The figure shows the milepoint and elevation at various locations within the work zone. (Note: The vertical and horizontal scales in the figure are not the same.)

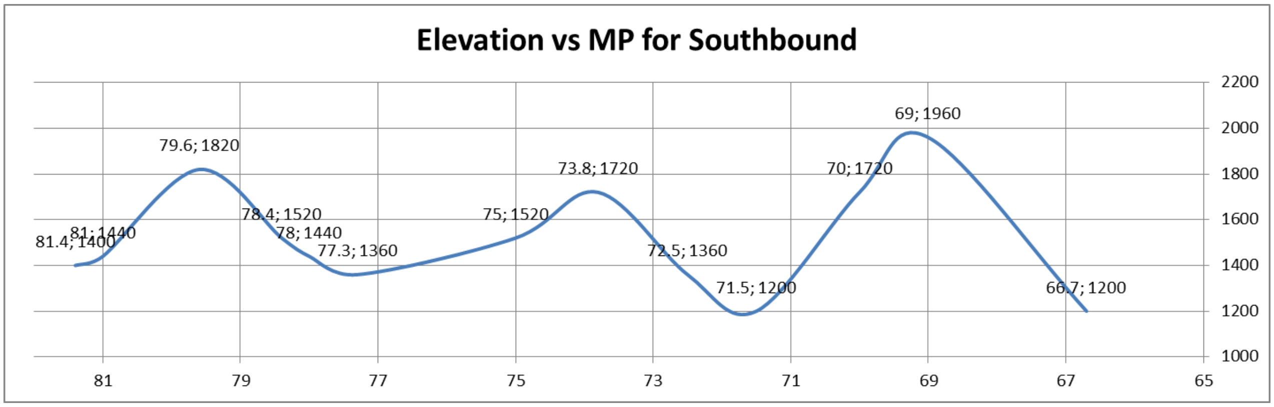


Figure 3.7: Roadway Elevation for I-5 Glendale – Hugo Project (Case Study #1)

The work on this project included the construction of a new climbing lane for trucks on northbound I-5 near the Hugo area. On some of the nights, the contractor conducted blasting operations before the paving operation started. The contractor used a rolling slowdown to control the traffic while blasting. The researchers took advantage of the slowdown and put out the portable traffic analyzers (sensors) on road during the slowdown. If there was no blast operation taking place, the contractor conducted a rolling slowdown for the research team to help put down the sensors. In the morning at the end of the paving work shift, the traffic was very light. The researchers waited for a gap in the traffic to pick up the sensors.

The paving work was conducted at nighttime, requiring the use of reflective clothing and lights. The workers typically wore reflective vests/jackets and hard hats. In some cases the workers also wore reflective pants and carried personal lights. In addition, the lighting provided at the paver and grinder locations was consistent with that seen on other paving projects (balloon lights attached to paver and grinder).

The traffic volume on this section of I-5 area is generally light compared to other sections, but contains many long haul trucks. Due to the steep roadway grades and sharp horizontal curves at some locations within the work zone, the researchers noticed that the trucks often travelled as slow as 30 mph or less while climbing uphill. This low speed slowed down all of the traffic on the roadway when the vehicles traveled in a single lane. Therefore, on some of the test days, the slow speeds recorded may not be the result of the traffic control treatments employed for the research. The slow speeds may be solely due to the grade, roadway curves, and presence of slow trucks.

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. An initial research plan was presented to the contractor to plan and conduct the research. During the course of the study, the contractor changed the construction schedule periodically due to various reasons and, as a result, the research plan was updated several times. Table 3.3 shows the final research plan for the I-5 Glendale – Hugo case study project.

Table 3.3: Final Research Plan for I-5 Glendale – Hugo Project (Case Study #1)

Day	Paving lane (FL, SL, SD) and paving layer	Milepoints	Date	Treatments			
				A	B	C	D
				50 mph speed signs	PCMS on trailers	PCMS on rollers	Radar speed display
Day 1	FL – Wearing	81.4 - 78.4	6/30 – Sunday	●			
Day 2	SL – Wearing	81.4 - 78.4	7/1 – Monday	●	●		
Day 3	SD – Wearing	81.4 - 78.4	7/2 – Tuesday	●	●		●
Day 4	FL – Base	78.4 - 77	7/15 – Monday	●			
Day 5	SL – Base	78.4 - 77	7/16 – Tuesday	●	●	●	
Day 6	FL – Base	77 - 75	7/17 – Wednesday	●		●	
Day 7	SL – Base	77 - 75	7/18 – Thursday	●		●	●
Day 8	SD – Base	78.4 - 75	7/21 – Sunday	●			●
Day 9	FL – Base	75 - 73	7/22 – Monday	●		●	●
Day 10	FL – Base	73 - 71	7/23 – Tuesday	●	●	●	●
Day 11	SL – Base	75 - 69.5	7/25 – Thursday	●			●
Day 12	SD – Base	75 - 71.5	7/28 – Sunday	●	●		

The intent of the present study (SPR-769) is to collect additional work zone data in order to allow for more concrete conclusions regarding specific traffic control measures. To do so, the researchers planned to implement each treatment on at least two days of testing. This would allow for multiple days of data to be used in the analysis for each treatment and help to eliminate some of the confounding factors. However, an accident occurred during the course of the study in which a worker was struck and killed during a daytime work shift. (The incident was not related to the research study). As a result of the accident, in order to enhance safety through the work zone, the contractor decided to implement all of the treatments available, plus temporary rumble strips and OSP presence, for all nights during the remainder of the project. These additional treatments were not planned as part of the researcher study. Therefore, following the accident, further data collection on the I-5 Glendale – Hugo project was not conducted. As a result, two days of data could not be obtained for some of the treatments. The treatments for which data was collected on only one day were those on days 3, 5, 6, and 10 as indicated in Table 3.3 above.

3.4 CASE STUDY #2: I-5 ROCK POINT – SEVEN OAKS PROJECT

The I-5 Rock Point – Seven Oaks project was located on I-5 from milepoints 37 to 43, between Grants Pass and Medford. The project location is shown in Figure 3.8. At this location the roadway is four lanes (two-lanes in each direction plus shoulders). The roadway in this section of I-5 is predominantly straight and almost flat with no grade or horizontal curve impacts on vehicle speed. The contractor on this project was different than on the I-5 Glendale – Hugo project.

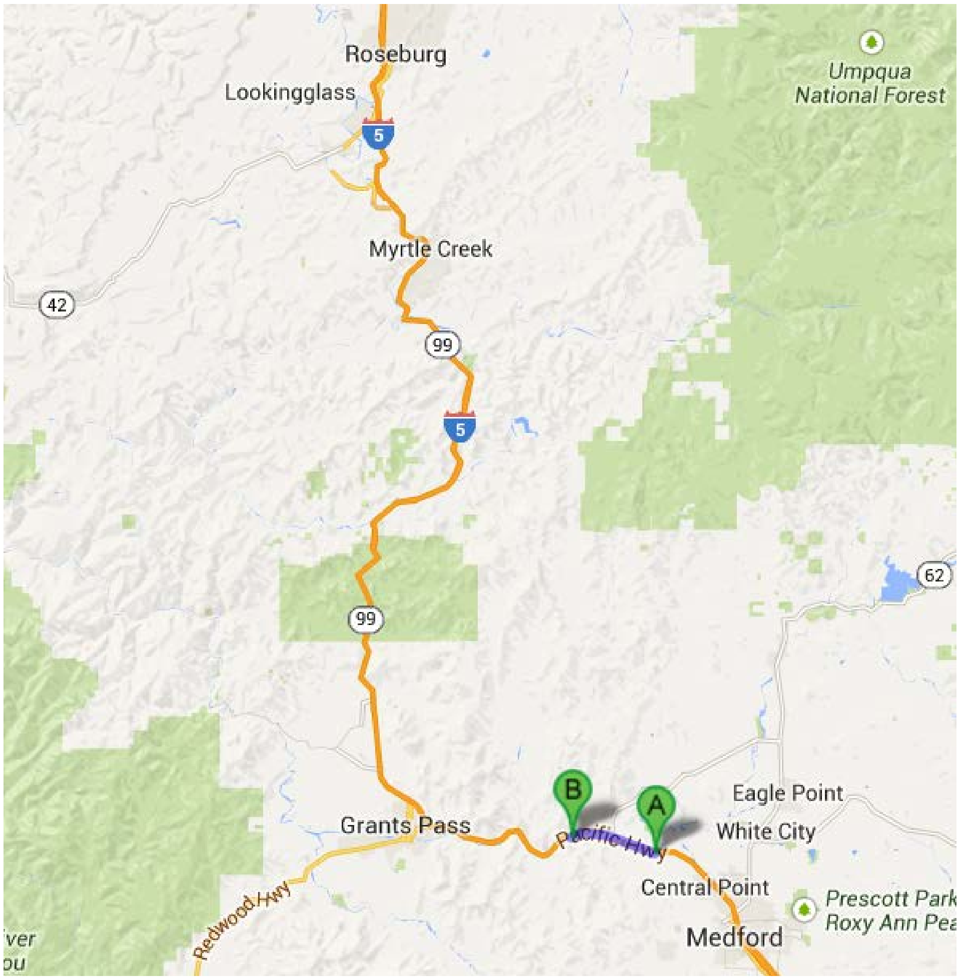


Figure 3.8: Location of I-5 Rock Point – Seven Oaks Project (Case Study #2)

For this case study project, paving work was conducted in both the fast lane and slow lane. No paving was done on the shoulders. Only wearing course paving was conducted. Traffic volumes were typically greater than on the I-5 Glendale – Hugo project. Rolling slowdowns were required in order to allow the researchers to both put down and pick up the speed sensors during the course of the research.

Similar to the I-5 Hugo project, the paving work was conducted at night. In addition, the personal protective equipment and clothing used by the workers on this project, and the work area lighting, were similar to that employed on the I-5 Hugo project as described above.

Only three treatments are used in this project: 50 mph speed signs, PCMS on trailers, and radar speed display. The contractor did not have rollers available with PCMS signs. The researchers managed to implement the same treatments or the combination of treatments on two paving days for all of the treatments in order to get the desired replication. Table 3.4 shows the final research plan for the I-5 Rock Point – Seven Oaks case study project.

Table 3.4: Research Plan for I-5 Rock Point – Seven Oaks Project (Case Study #2)

Day	Direction (NB, SB)	Paving Lane	Milepoints	Date	Treatments		
					A	B	C
					50 mph speed signs	PCMS on trailers	Radar speed display
Day 1	NB	FL	37 - 39	8/18 – Sunday	●		
Day 2	NB	FL	39 - 41	8/19 – Monday	●	●	
Day 3	NB	FL	41 - 43	8/20 – Tuesday	●		●
Day 4	NB	SL	37 - 39	8/21 – Wednesday	●	●	●
Day 5	NB	SL	41 - 43	8/26 – Monday	●		
Day 6	SB	FL	43 - 41	8/27 – Tuesday	●		●
Day 7	SB	FL	41 - 39	8/28 – Wednesday	●	●	●
Day 8	SB	SL	39 - 37	9/6 – Friday	●	●	

4.0 RESULTS

Data collection on both case study projects was conducted on the dates shown in Table 3.3 and Table 3.4 above. On each day, the researchers contacted the contractor to plan and place the portable traffic analyzers on the roadway. After the analyzers were placed, the researchers collected additional speed data at various locations using the radar speed gun, and followed videotape vehicles driving through the work zone. The researchers also documented the equipment used for the paving operation. At the end of the work shift after paving was complete, the researchers picked up the traffic analyzers from the roadway, downloaded the vehicle data from the analyzers, and recharged and reprogrammed the analyzers for use during the following work shift.

Three portable traffic analyzers were placed in the work area where the paving was planned to take place. The specific locations of the three traffic analyzers in the work area were selected to record traffic speeds at multiple locations within the section of roadway that was to be paved that night, and approximately every 0.5 – 1 mile apart. The actual spacing depended on the planned length of paving for the night. In some cases, where the paving work did not progress to the planned milepoint, the last traffic analyzer was downstream of the end of the paving. In addition, on the I-5 Glendale – Hugo project, the analyzer locations were selected giving consideration to the roadway grade and curves in order to collect free-flow speeds.

4.1 DATA ADJUSTMENT

The data collected from the portable traffic analyzers was downloaded for analysis. Initial analysis of the data showed odd results. The traffic speeds recorded by some of the sensors were very high, and much higher than expected. The researchers identified several sensors which consistently recorded very high speeds. Therefore, the researchers decided to test the accuracy of the traffic analyzers. Tests of the accuracy of the traffic analyzers were conducted on two different occasions as described below. The goal of the tests was to determine how far off the speeds recorded by the sensors were from the actual vehicle speeds. Having this information would then allow for adjusting the speeds actually recorded on the case study projects. As shown in Table 3.2 above, the accuracy of speed measurements stated by the manufacturer is +/- 4 mph, 90% of the time.

4.1.1 First Day of Sensor Testing

The first day of sensor testing was conducted on November 7 on a long, straight stretch of two-lane road adjacent the airport near Corvallis, OR. The 14 sensors used for the data collection on the two case study projects were placed on the roadway in the center of the lane approximately 3 feet apart in a straight line. Figure 4.1 shows the layout of the sensors and the weather conditions.

Figure 4.1: Sensor Layout on First Day of Sensor Testing

The researchers drove over the sensors multiple times at different speeds. In addition, the researchers recorded the vehicle speed at the sensor location using the radar speed gun in order to verify the actual speed of the vehicle. The researchers drove over the sensors twice at each of the following speeds: 10 mph, 20 mph, 30 mph, 35 mph, 40 mph, 45 mph, 50 mph, 55 mph, and 60 mph. Figure 4.2 shows the results from the first day of testing. The figure shows the actual speeds recorded at each of the test speeds are shown for each sensor (identified by the sensor number).

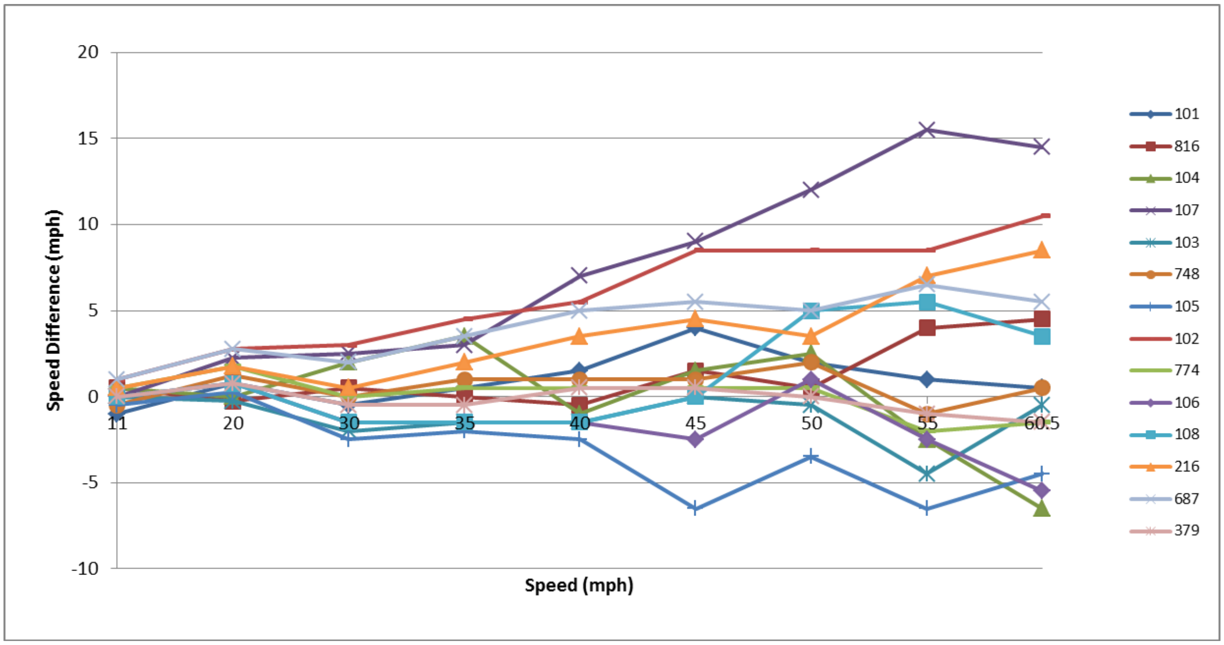


Figure 4.2: First Day of Sensor Testing – Results

In Figure 4.2, the y-axis shows the difference between the speed recorded by the sensor and the actual speed of the vehicle. The x-axis represents the actual vehicle speed. Each line represents data from one sensor. The last three digits of the sensor serial number are used here to identify the different sensors. As seen in the figure, for some sensors, the difference in speed becomes larger as the vehicle speed increases. Two of the sensors (#102 and #107) produced significantly more inaccurate results than the other 12 sensors. For this test, only two data points were recorded at each speed. Based on the test data, the researchers did not feel confident that the data could be used to adjust the actual case study data with accuracy. Therefore, a second day of sensor testing was conducted to collect more data.

4.1.2 Second Day of Sensor Testing

The second day of sensor testing was conducted on November 28 at the same location. The sensor layout was similar to that on the first day of testing and is shown in Figure 4.3.

Figure 4.3: Sensor Layout on Second Day of Sensor Testing

On the second day of testing, the researchers drove over the sensors five times at speeds from 30 mph to 75 mph in intervals of 5mph. The full set of results is provided in Appendix A. The results for Sensor #774 are shown below as an example. The difference between the speed recorded by the sensor and the actual vehicle speed at each test speed is shown in Figure 4.4. Figure 4.5 shows the percentage difference at each speed, and the average of the five passes at each test speed is shown in Figure 4.6. In Figure 4.6, the x-axis shows the actual speed and the y-axis shows the average of the five speeds recorded by the sensors.

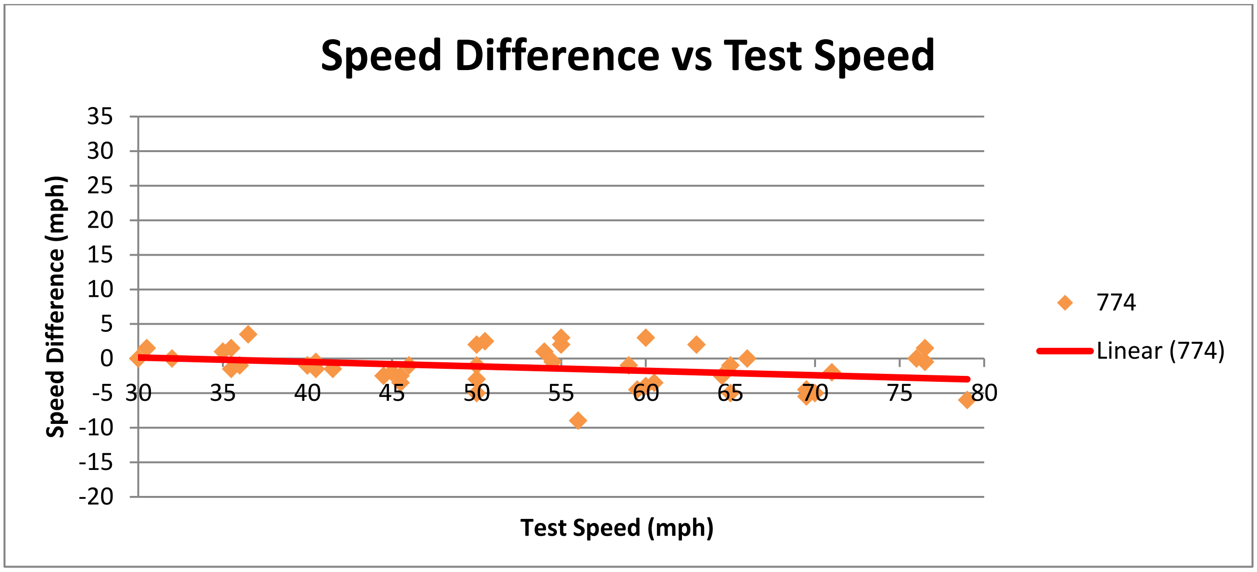


Figure 4.4: Difference between Recorded and Actual Speed vs. Test Speed for Sensor #774

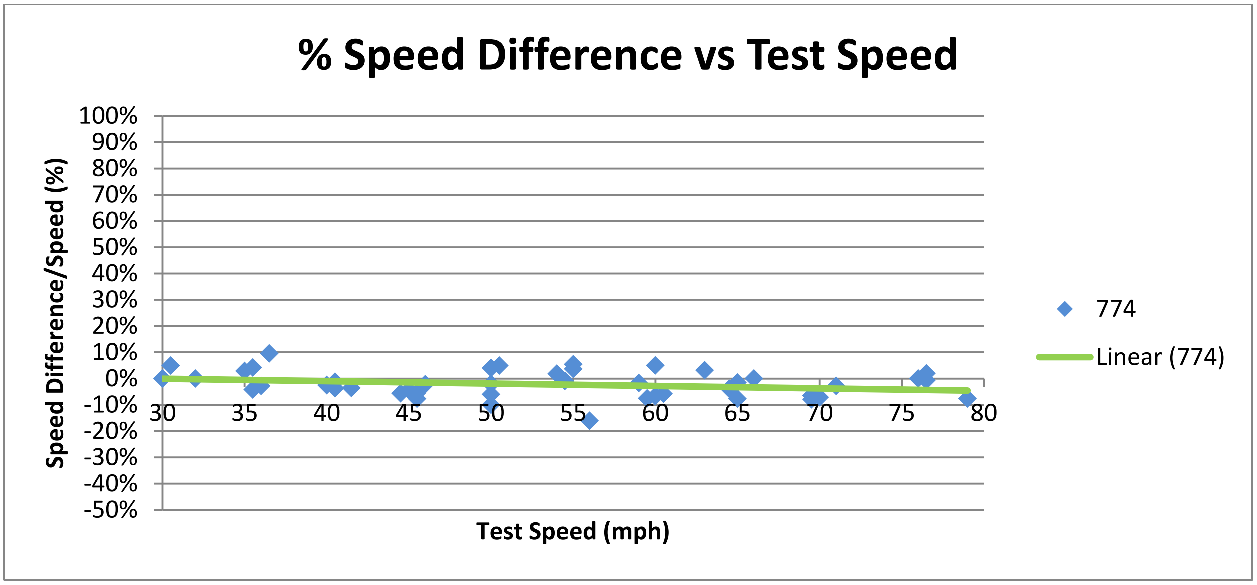


Figure 4.5: % Difference between Recorded and Actual Speed vs. Test Speed for Sensor #774

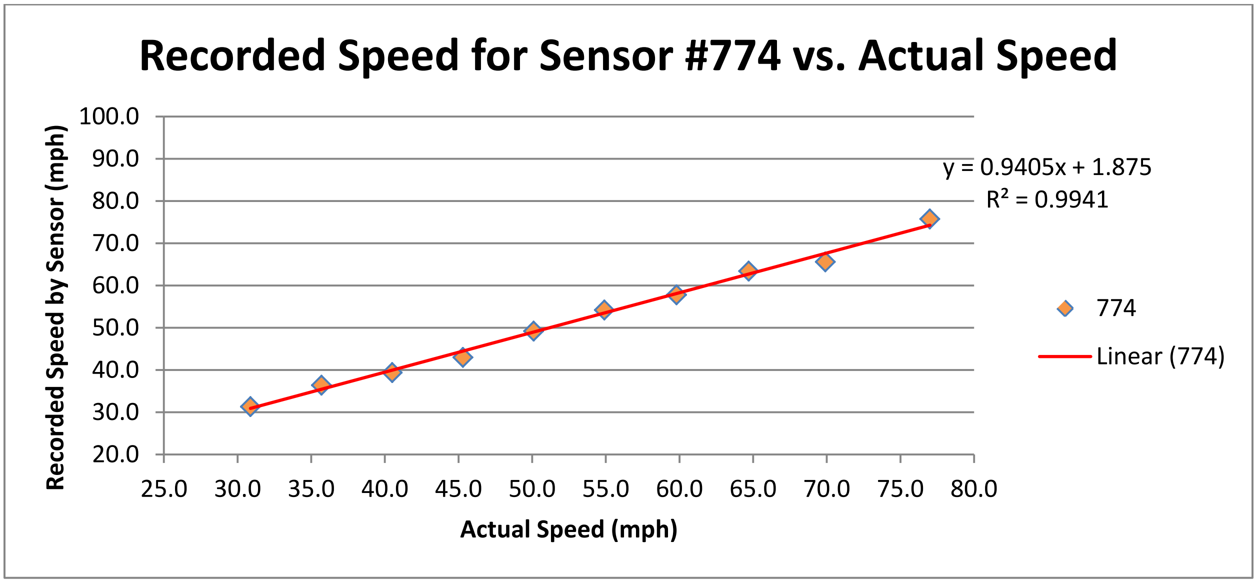


Figure 4.6: Average Recorded Speed vs. Actual Speed for Sensor #774

The final adjustment for each sensor is based on the regression lines from the average recorded speed vs. actual speed (Figure 4.6). The equations used for final adjustment are presented in Table 4.1. In the table, the variable *x* represents the speed recorded by the sensor, and the variable *y* is the adjusted speed to use in the analysis.

Table 4.1: Data Adjustment Equations

Sensor ID	Adjustment Equation
101	Adjustment not needed
102	y = 1.3454x – 4.6868
103	y = 0.7690x + 6.5026
104	y = 0.9494x + 1.6036
105	y = 0.8734x + 0.8160
106	y = 0.8790x + 3.8569
107	y = 1.2358x – 0.7095
108	y = 0.8399x + 6.3645
216	y = 1.1218x – 1.3706
379	y = 0.8744x + 5.2341
687	y = 1.0848x + 0.3837
748	Adjustment not needed
774	y = 0.9405x + 1.8750
816	y = 1.0676x – 2.0680

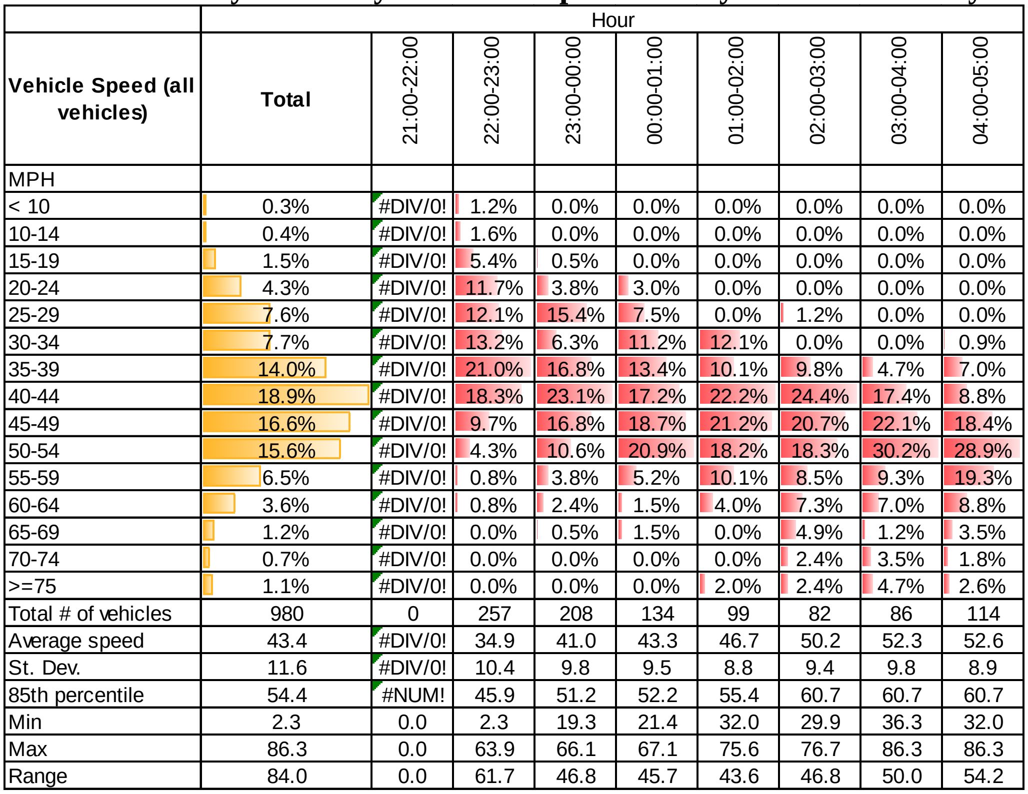
Where: x = speed recorded by speed sensor, and y = adjusted speed to use in analysis

4.2 RESULTS FOR I-5 GLENDALE – HUGO PROJECT (CASE STUDY #1)

A total of twelve days of speed data were recorded on the I-5 Glendale – Hugo project. For each day, ten sensors were used to record traffic speeds at seven locations. For each sensor location on each day, the researchers created tables and figures showing the hourly summary of vehicle speeds and vehicle length. As a result, there are a great number of tables and figures for this project alone. These tables and figures are provided in Appendix B. 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 B are similar to the following presented for Day 1.

Table 4.2 shows the hourly summary of vehicle speeds for the first work zone (WZ) traffic analyzer on Day 1. The data was recorded from 10:00pm to 5:00am on Day 1. 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 in the table 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 40-44 mph. The red bars indicate that the speed distribution changes from hour-to-hour, with a trend of increasing speeds from 10:00pm to 5:00am.

Table 4.2: Hourly Summary of Vehicle Speed for Day 1 First WZ Analyzer (Case Study #1)



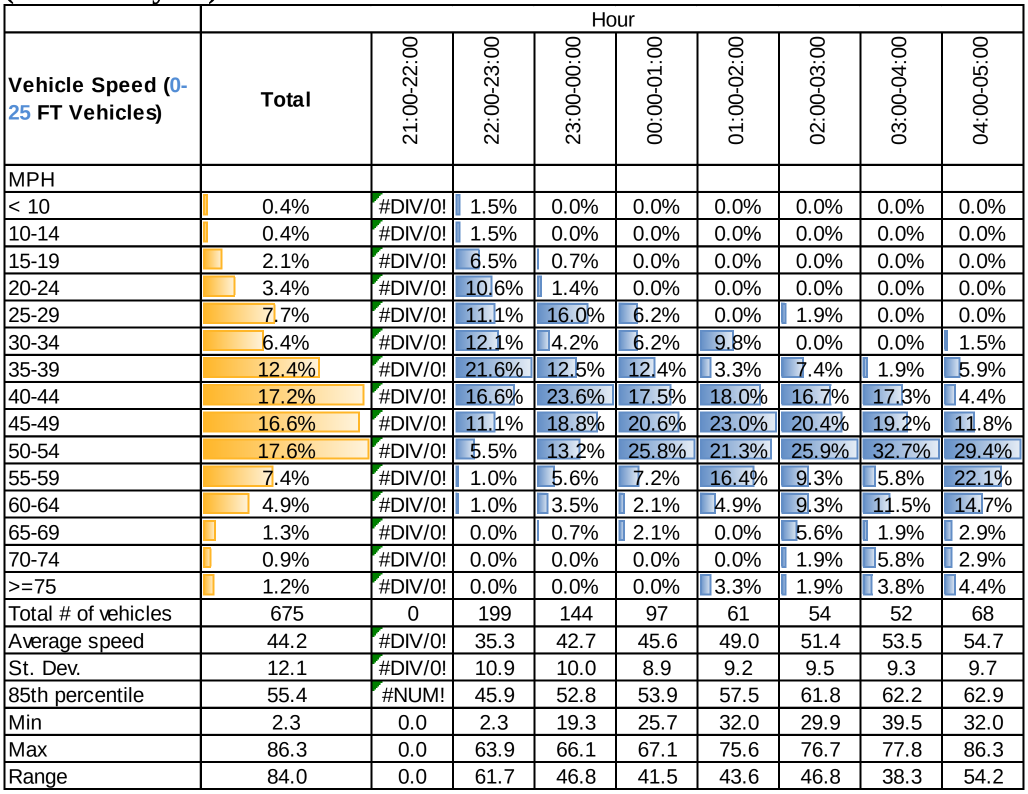
		Hour							
Vehicle Speed (all vehicles)	**Total**	21:00-22:00	22:00-23:00	23:00-00:00	00:00-01:00	01:00-02:00	02:00-03:00	03:00-04:00	04:00-05:00
MPH									
< 10	0.3%	#DIV/0!	1.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.4%	#DIV/0!	1.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	1.5%	#DIV/0!	5.4%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	4.3%	#DIV/0!	11.7%	3.8%	3.0%	0.0%	0.0%	0.0%	0.0%
25-29	7.6%	#DIV/0!	12.1%	15.4%	7.5%	0.0%	1.2%	0.0%	0.0%
30-34	7.7%	#DIV/0!	13.2%	6.3%	11.2%	12.1%	0.0%	0.0%	0.9%
35-39	14.0%	#DIV/0!	21.0%	16.8%	13.4%	10.1%	9.8%	4.7%	7.0%
40-44	18.9%	#DIV/0!	18.3%	23.1%	17.2%	22.2%	24.4%	17.4%	8.8%
45-49	16.6%	#DIV/0!	9.7%	16.8%	18.7%	21.2%	20.7%	22.1%	18.4%
50-54	15.6%	#DIV/0!	4.3%	10.6%	20.9%	18.2%	18.3%	30.2%	28.9%
55-59	6.5%	#DIV/0!	0.8%	3.8%	5.2%	10.1%	8.5%	9.3%	19.3%
60-64	3.6%	#DIV/0!	0.8%	2.4%	1.5%	4.0%	7.3%	7.0%	8.8%
65-69	1.2%	#DIV/0!	0.0%	0.5%	1.5%	0.0%	4.9%	1.2%	3.5%
70-74	0.7%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	2.4%	3.5%	1.8%
>=75	1.1%	#DIV/0!	0.0%	0.0%	0.0%	2.0%	2.4%	4.7%	2.6%
Total # of vehicles	980	0	257	208	134	99	82	86	114
Average speed	43.4	#DIV/0!	34.9	41.0	43.3	46.7	50.2	52.3	52.6
St. Dev.	11.6	#DIV/0!	10.4	9.8	9.5	8.8	9.4	9.8	8.9
85th percentile	54.4	#NUM!	45.9	51.2	52.2	55.4	60.7	60.7	60.7
Min	2.3	0.0	2.3	19.3	21.4	32.0	29.9	36.3	32.0
Max	86.3	0.0	63.9	66.1	67.1	75.6	76.7	86.3	86.3
Range	84.0	0.0	61.7	46.8	45.7	43.6	46.8	50.0	54.2

The total number of vehicles row shows the traffic volume for that day during the time period in which the data was recorded. The traffic count for each hour shows the hourly traffic volume. 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 4.3, Table 4.4, Table 4.5, and Table 4.6 show similar information to that shown Table 4.2, for a specific vehicle type based on the length of the vehicle. The vehicles are categorized into four types depending on their length. Table 4.3 shows the speed information for vehicles less than 25 feet long, which are normal passenger cars and small pick-ups without a trailer. Table 4.4 shows speeds for vehicles between 25 and 49 feet long, which are mostly long vans, one trailer pick-ups, and small trucks. Table 4.5 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 this category. Table 4.6 shows the speeds for vehicles longer than or equal to 75 feet, which are long trucks.

For each of these tables, what does the “desired” distribution of speeds look like? Taking both safety and mobility into consideration, the average (mean) speed would be below the posted, regulatory speed. The highest speed recorded would also be below the posted, regulatory speed. In addition, the distribution of speeds from the slowest speed to the fastest speed would be small so that there is as little differential in speed between adjacent vehicles as possible. Lastly, this distribution should hold true regardless of the volume of traffic, type of vehicle, and time of day.

Table 4.3: Hourly Summary of Vehicle (0-25 ft long) Speeds for Day 1 First WZ Analyzer (Case Study #1)



		Hour							
Vehicle Speed (0-25 FT Vehicles)	**Total**	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	0.4%	#DIV/0!	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.4%	#DIV/0!	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	2.1%	#DIV/0!	6.5%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	3.4%	#DIV/0!	10.6%	1.4%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	7.7%	#DIV/0!	11.1%	16.0%	6.2%	0.0%	1.9%	0.0%	0.0%
30-34	6.4%	#DIV/0!	12.1%	4.2%	6.2%	9.8%	0.0%	0.0%	1.5%
35-39	12.4%	#DIV/0!	21.6%	12.5%	12.4%	3.3%	7.4%	1.9%	5.9%
40-44	17.2%	#DIV/0!	16.6%	23.6%	17.5%	18.0%	16.7%	17.3%	4.4%
45-49	16.6%	#DIV/0!	11.1%	18.8%	20.6%	23.0%	20.4%	19.2%	11.8%
50-54	17.6%	#DIV/0!	5.5%	13.2%	25.8%	21.3%	25.9%	32.7%	29.4%
55-59	7.4%	#DIV/0!	1.0%	5.6%	7.2%	16.4%	9.3%	5.8%	22.1%
60-64	4.9%	#DIV/0!	1.0%	3.5%	2.1%	4.9%	9.3%	11.5%	14.7%
65-69	1.3%	#DIV/0!	0.0%	0.7%	2.1%	0.0%	5.6%	1.9%	2.9%
70-74	0.9%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	1.9%	5.8%	2.9%
>=75	1.2%	#DIV/0!	0.0%	0.0%	0.0%	3.3%	1.9%	3.8%	4.4%
Total # of vehicles	675	0	199	144	97	61	54	52	68
Average speed	44.2	#DIV/0!	35.3	42.7	45.6	49.0	51.4	53.5	54.7
St. Dev.	12.1	#DIV/0!	10.9	10.0	8.9	9.2	9.5	9.3	9.7
85th percentile	55.4	#NUM!	45.9	52.8	53.9	57.5	61.8	62.2	62.9
Min	2.3	0.0	2.3	19.3	25.7	32.0	29.9	39.5	32.0
Max	86.3	0.0	63.9	66.1	67.1	75.6	76.7	77.8	86.3
Range	84.0	0.0	61.7	46.8	41.5	43.6	46.8	38.3	54.2

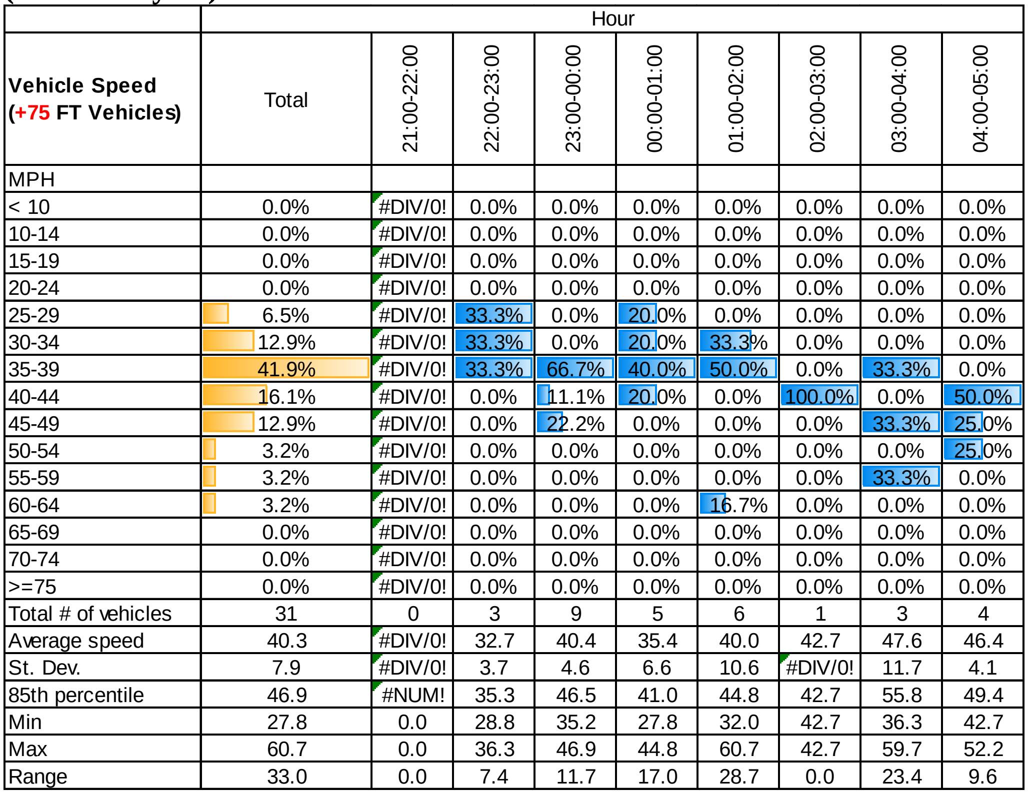
Table 4.4: Hourly Summary of Vehicle (25-50 ft long) Speeds for Day 1 First WZ Analyzer (Case Study #1)

	Hour								
Vehicle Speed (25-50 FT Vehicles)	Total	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%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.6%	#DIV/0!	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	5.7%	#DIV/0!	14.6%	6.3%	12.5%	0.0%	0.0%	0.0%	0.0%
25-29	4.6%	#DIV/0!	7.3%	12.5%	6.3%	0.0%	0.0%	0.0%	0.0%
30-34	8.0%	#DIV/0!	19.5%	3.1%	12.5%	17.6%	0.0%	0.0%	0.0%
35-39	12.6%	#DIV/0!	17.1%	15.6%	18.8%	5.9%	11.1%	5.0%	9.7%
40-44	26.9%	#DIV/0!	31.7%	34.4%	18.8%	29.4%	33.3%	20.0%	16.1%
45-49	19.4%	#DIV/0!	7.3%	18.8%	18.8%	29.4%	27.8%	25.0%	22.6%
50-54	13.7%	#DIV/0!	0.0%	9.4%	12.5%	17.6%	0.0%	30.0%	32.3%
55-59	5.1%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	11.1%	10.0%	16.1%
60-64	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
65-69	1.1%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	5.6%	0.0%	3.2%
70-74	0.6%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	5.6%	0.0%	0.0%
>=75	1.7%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	5.6%	10.0%	0.0%
Total # of vehicles	175	0	41	32	16	17	18	20	31
Average speed	43.1	#DIV/0!	35.2	39.9	38.7	44.2	49.0	51.9	49.6
St. Dev.	10.5	#DIV/0!	8.6	8.0	8.9	6.8	9.7	12.3	6.6
85th percentile	51.2	#NUM!	43.7	46.9	46.7	50.3	57.8	55.9	55.4
Min	10.8	0.0	10.8	21.4	21.4	33.1	38.4	38.4	35.2
Max	86.3	0.0	46.9	52.2	50.1	54.4	74.6	86.3	66.1
Range	75.5	0.0	36.2	30.8	28.7	21.3	36.2	47.8	30.8

Table 4.5: Hourly Summary of Vehicle (50-75 ft long) Speeds for Day 1 First WZ Analyzer (Case Study #1)

	Hour								
Vehicle Speed (50-75 FT Vehicles)	Total	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%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	1.0%	#DIV/0!	7.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	9.1%	#DIV/0!	21.4%	17.4%	12.5%	0.0%	0.0%	0.0%	0.0%
25-29	12.1%	#DIV/0!	35.7%	21.7%	12.5%	0.0%	0.0%	0.0%	0.0%
30-34	14.1%	#DIV/0!	7.1%	26.1%	37.5%	6.7%	0.0%	0.0%	0.0%
35-39	18.2%	#DIV/0!	21.4%	26.1%	6.3%	26.7%	22.2%	9.1%	9.1%
40-44	17.2%	#DIV/0!	7.1%	8.7%	12.5%	40.0%	44.4%	18.2%	0.0%
45-49	13.1%	#DIV/0!	0.0%	0.0%	12.5%	13.3%	11.1%	27.3%	45.5%
50-54	9.1%	#DIV/0!	0.0%	0.0%	6.3%	13.3%	11.1%	27.3%	18.2%
55-59	4.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	18.2%	18.2%
60-64	1.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	11.1%	0.0%	0.0%
65-69	1.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	9.1%
70-74	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicles	99	0	14	23	16	15	9	11	11
Average speed	39.2	#DIV/0!	29.7	31.9	36.0	42.9	46.1	48.9	50.7
St. Dev.	10.1	#DIV/0!	6.5	6.1	8.6	5.2	7.3	5.6	7.6
85th percentile	49.4	#NUM!	36.3	38.8	45.3	47.8	51.4	54.4	56.5
Min	17.1	0.0	17.1	21.4	23.5	34.2	37.3	37.3	35.2
Max	66.1	0.0	41.6	42.7	52.2	52.2	61.8	56.5	66.1
Range	48.9	0.0	24.5	21.3	28.7	18.1	24.5	19.1	30.8

Table 4.6: Hourly Summary of Vehicle (75+ ft long) Speeds for Day 1 First WZ Analyzer (Case Study #1)



	Hour								
Vehicle Speed (+75 FT Vehicles)	Total	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%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
10-14	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
15-19	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20-24	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
25-29	6.5%	#DIV/0!	33.3%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%
30-34	12.9%	#DIV/0!	33.3%	0.0%	20.0%	33.3%	0.0%	0.0%	0.0%
35-39	41.9%	#DIV/0!	33.3%	66.7%	40.0%	50.0%	0.0%	33.3%	0.0%
40-44	16.1%	#DIV/0!	0.0%	11.1%	20.0%	0.0%	100.0%	0.0%	50.0%
45-49	12.9%	#DIV/0!	0.0%	22.2%	0.0%	0.0%	0.0%	33.3%	25.0%
50-54	3.2%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	25.0%
55-59	3.2%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	33.3%	0.0%
60-64	3.2%	#DIV/0!	0.0%	0.0%	0.0%	16.7%	0.0%	0.0%	0.0%
65-69	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
70-74	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
>=75	0.0%	#DIV/0!	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total # of vehicles	31	0	3	9	5	6	1	3	4
Average speed	40.3	#DIV/0!	32.7	40.4	35.4	40.0	42.7	47.6	46.4
St. Dev.	7.9	#DIV/0!	3.7	4.6	6.6	10.6	#DIV/0!	11.7	4.1
85th percentile	46.9	#NUM!	35.3	46.5	41.0	44.8	42.7	55.8	49.4
Min	27.8	0.0	28.8	35.2	27.8	32.0	42.7	36.3	42.7
Max	60.7	0.0	36.3	46.9	44.8	60.7	42.7	59.7	52.2
Range	33.0	0.0	7.4	11.7	17.0	28.7	0.0	23.4	9.6

The above tables and interpretation show an example of how to understand the additional tables in Appendix B. For the I-5 Rock Point – Seven Oaks case study project, similar tables are provided in Appendix C.

Examining the tables above reveals some important characteristics about the passing traffic. In some cases there is a wide distribution of speeds within the hour. In other cases, the distribution is small. Prior research, as described previously, indicates that a smaller distribution is desired. The tables also reveal that in some cases there are gaps in speeds, meaning that the speed of one or more vehicles is much different than the rest. These gaps in speed are also not desired. They are an indication of the traffic control measures affecting the behavior of drivers differently. For safety, a smooth, rather than abrupt, distribution is preferred.

It also should be remembered that the vehicle speeds recorded are those of both the public vehicles passing through the work zone and those of the construction vehicles. Construction vehicles, such as asphalt trucks and traffic control vehicles, may travel at a slower speed than public vehicles. For example, for trucks greater than 75 feet in length (Table 4.6), between 1:00 and 2:00am, one of the six trucks recorded was travelling at a much higher rate of speed than the other five trucks. The five slower trucks may have been asphalt trucks while the faster truck may have been a public vehicle. However, in many cases the construction vehicles likely have an impact on the speeds of the public vehicles. This impact depends on the traffic volume and concentration of construction vehicles on the roadway. No measures were taken in the research study to separate out the speeds of the construction vehicles from the public vehicles.

Vehicle speed data at some PTA locations was not available on some days due to various reasons. On Day 9, an asphalt truck accidently dumped asphalt on the travelling lane prior to and through the taper. As a result, the researchers had to pick up a few speed sensors to allow the contractor to clean the roadway. One of the sensors was picked up by contractor and not put back, so the data at that location (beginning of taper) was missing for that day. On Day 11, the speed sensors at two locations (before RWA sign and at RWA sign) were located in the closed area due to some guardrail work at those locations. No vehicle data was collected at these locations on Day 11.

Figure 4.7 shows a summary of the 85th percentile speed in each hour for all twelve days of testing on the I-5 Glendale – Hugo project. The figure presents the data recorded from the first work zone traffic analyzer. The impact of the asphalt truck accidently dumping asphalt on the travelling lane on Day 9 can be seen in the lower speeds recorded on that day.

In this figure it can be seen that the later hours of data typically show an increase in speed relative to the earlier hours. This may be due to the time of day in which the speeds are recorded (faster speed with less traffic early in the morning). Also, early in the work shift the work takes place near the first work zone sensor, but later in the work shift the work has passed the first work zone sensor at a time when there is no workers and equipment present. In the previous SPR-751 study, the vehicles were found to typically slow down when driving past the workers and equipment. Therefore, this may also be a reason for higher speeds recorded later in the work shift at the first work zone sensor location than the speeds recorded earlier in the work shift at the same location. Additionally, the increase in the last hour 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 speed over the entire hour.

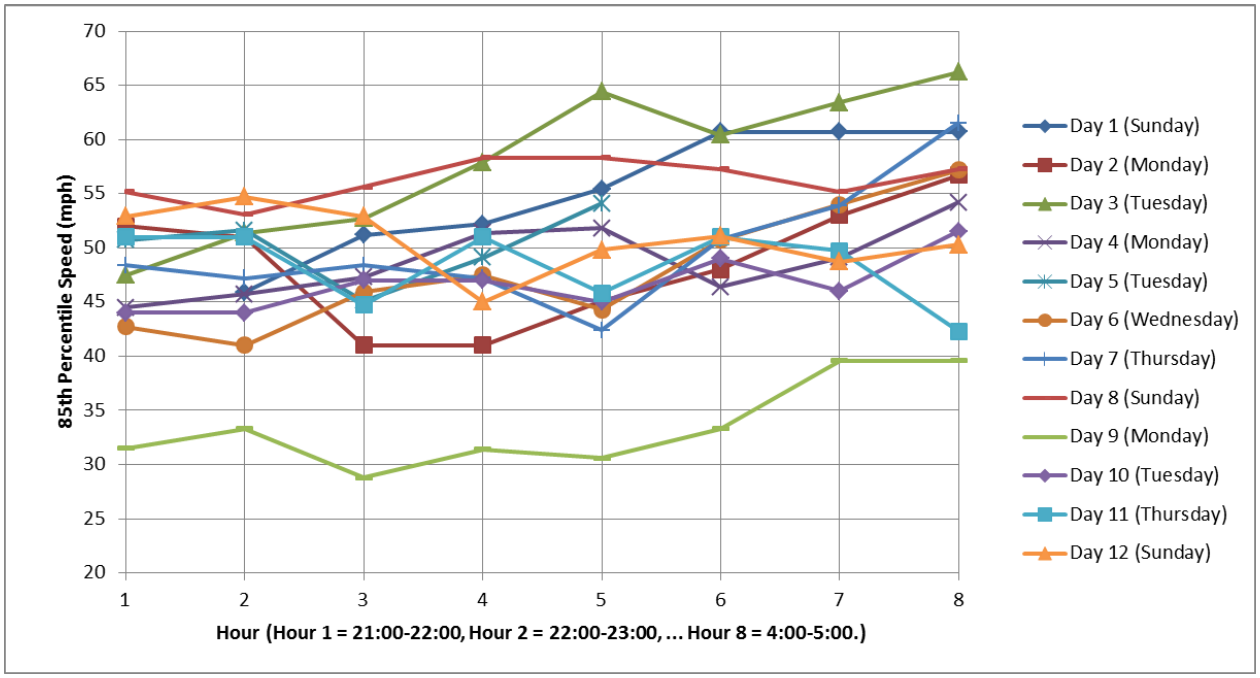


Figure 4.7: Hourly Vehicle Speed (85% percentile) at First WZ Sensor for All Days (Case Study #1)

Figure 4.7 provides a clear view of each hour's speed for all days. However, it is inappropriate to compare the same hour's speed among days because the paver passed the first WZ traffic analyzer at different times on different days. 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 during 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 of this report.

Moreover, the roadway elevation at different locations in this project was a significant factor affecting vehicle speed and cannot be dismissed in the analysis. The impact of roadway grade is a contributor to the speed differences on each day that can be seen in Figure 4.7.

Figure 4.8 shows the number of vehicles for each hour for all days of this project. The data used for this figure comes from the first WZ sensor. Looking at the historical data prior to the study, the traffic volumes are similar to those previously recorded by ODOT near this location. There is a clear trend for all days that the traffic volume drops gradually from 9:00pm to 3:00am, and slightly increases after that time period. The traffic volumes for the same hour for different days are similar except for Day 10 and the first hour of Day 12. There is slight variation in the volumes based on day of the week. The typical traffic volume on each day of the week during the period of time in the day when the testing was conducted was not available from ODOT records. It is assumed that the level of traffic on each day of the week during the period of time when the testing was conducted was not abnormal.

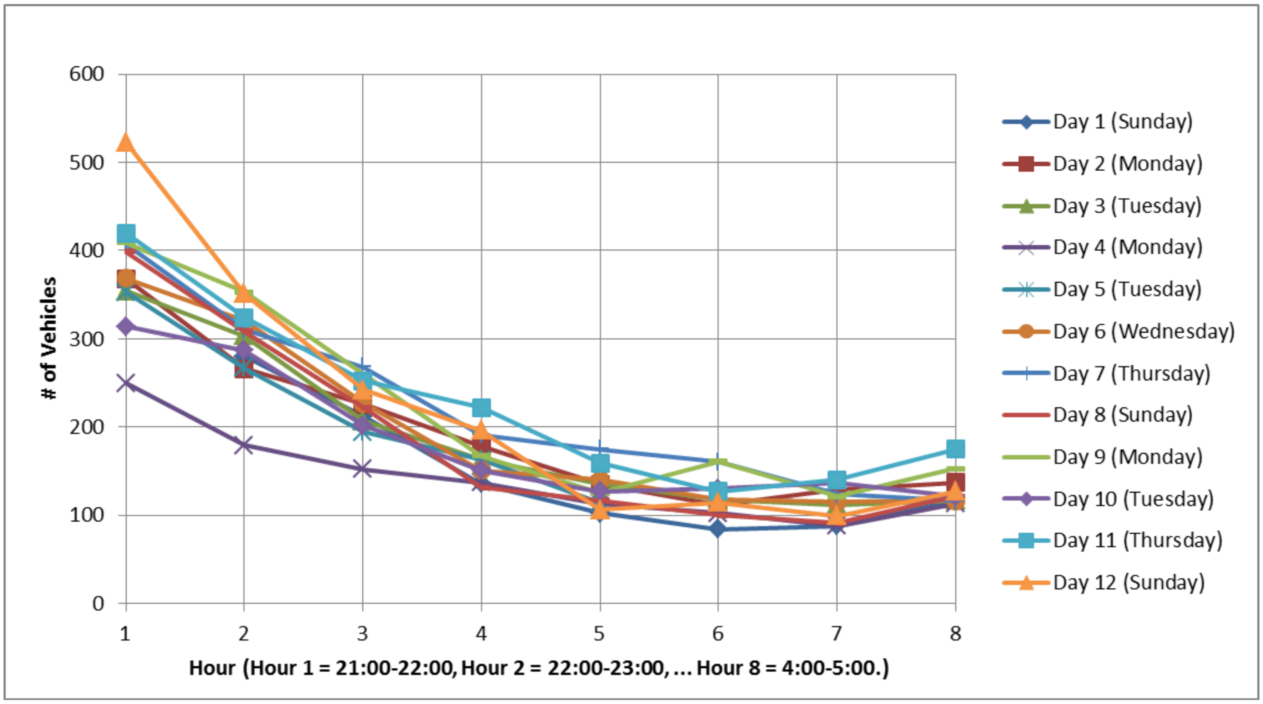


Figure 4.8: Hourly Traffic Volume at First WZ Sensor for All Days (Case Study #1)

Figure 4.9 shows the ratio of the 85th percentile speed of each hour to the number of vehicles for each hour, based on the first WZ sensor. The trends for all days are similar. The ratio increases until approximately 3:00am or 4:00am, then decreases after that time. It is not clear from the data whether the difference in ratios is due to the different in traffic volume or the difference in recorded speeds. For example, the ratio may increase if the traffic volume decreases or if the 85th percentile speed increases. Further research on the extent of impact of traffic volume on vehicle speed in the work zone is needed.

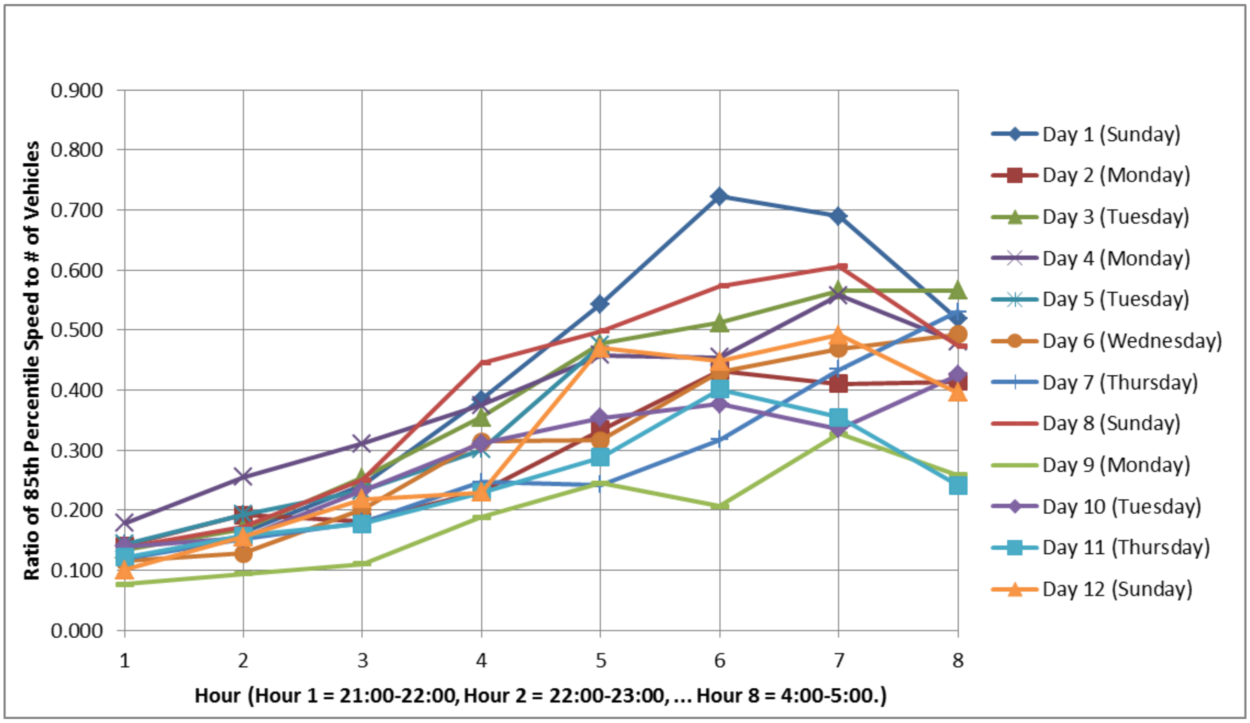


Figure 4.9: Ratio of Hourly Speed (85th Percentile) at First WZ Sensor to Traffic Volume for All Days (Case Study #1)

Figure 4.10 shows the 85th percentile speed for different locations before and within the work zone for all days. At the location before the Road Work Ahead signs, the speeds for all days are similar, between 70 and 80mph. At the Road Work Ahead signs location, the speed for Days 4, 5, and 8 are approximately 10mph lower than the speeds for the other days. According to the work plan and researcher notes, the work on Days 4, 5 and 8 occurred on the same section of the roadway. The Road Work Ahead signs locations for those days were the same, which was at the uphill section near the Glendale overpass (MP 79.6). The before RWA sign locations for these days were at the beginning of the uphill section.

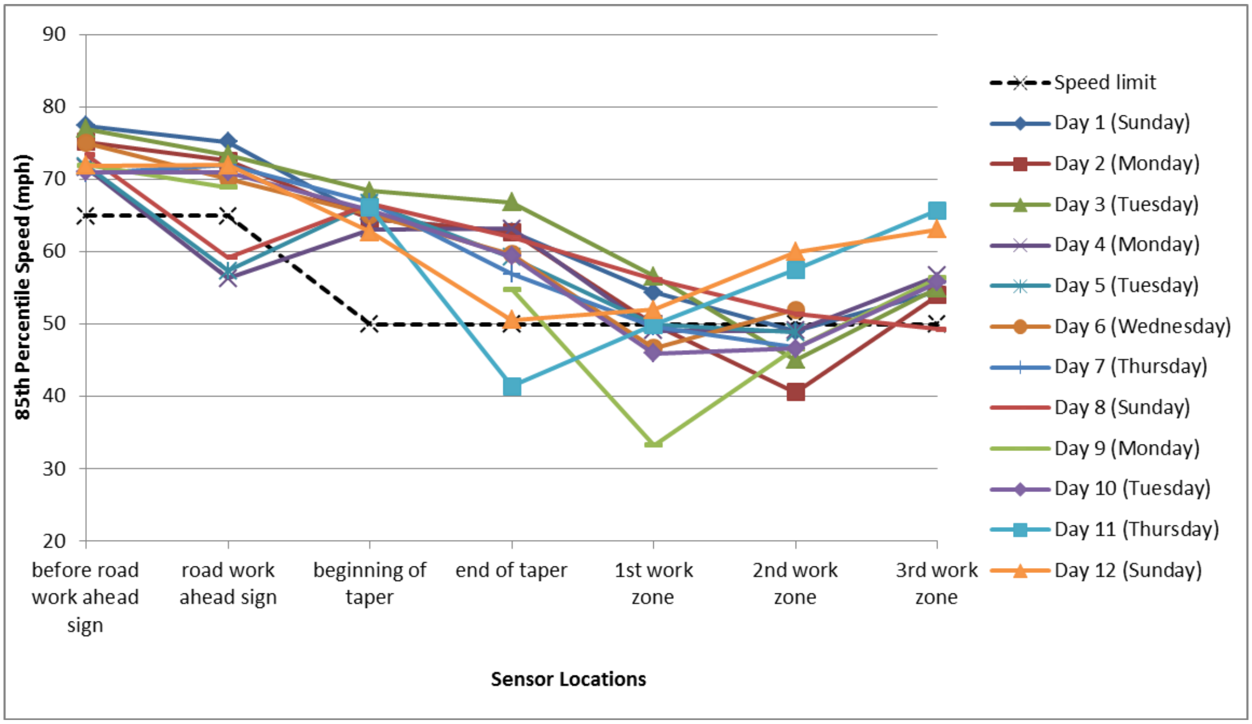


Figure 4.10: Vehicle Speed (85th Percentile) at Different Locations for All Days (Case Study #1)

In this section of I-5, due to the very curvy uphill and downhill sections, heavy-load long haul trucks may create additional hazards for other vehicles and workers. Figure 4.11 shows the number of different types of vehicles, based on vehicle length, for all days. Vehicles with length greater than 25 feet are categorized as trucks; and those less than or equal to 25 feet in length are passenger cars. The figure shows that the majority of vehicles are small passenger cars (0-25 ft in length), and the traffic volume is not very consistent from day to day. The data in the figure comes from the first WZ sensors on each day. Speed data collection typically occurred from 21:00-05:00. The time period in which speed data was collected was different on Days 1 and 5. On Day 1 data collection took place from 22:00-05:00; and on Day 5 from 21:00-02:00.

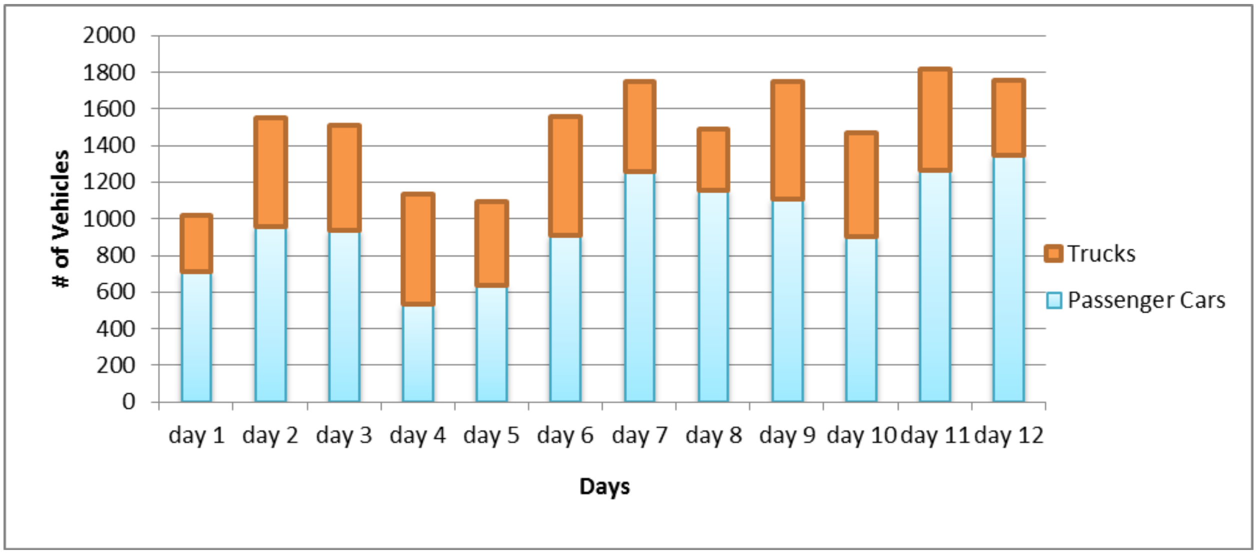


Figure 4.11: Traffic Volume (# of Vehicles) for Different Types of Vehicles for All Days (Case Study #1)

4.3 RESULTS FOR I-5 ROCK POINT – SEVEN OAKS PROJECT (CASE STUDY #2)

The hourly speed data summaries for each day at each sensor location on the I-5 Rock Point – Seven Oaks project are provided in Appendix C. Data was collected from 9:00pm to 5:00am for all days except Day 1 (11:00pm – 5:00am). Figure 4.12 shows a summary of the 85th percentile speed in each hour for all eight days in which speed data was collected. The data shown in the figure is based on the data from the first WZ sensor. During the first hour of work (9:00pm – 10:00pm), the speeds for all days were between 42 mph and 52 mph. After midnight, the speed is shown to increase, likely due to the paver and majority of the work being downstream of the first WZ sensor at that time.

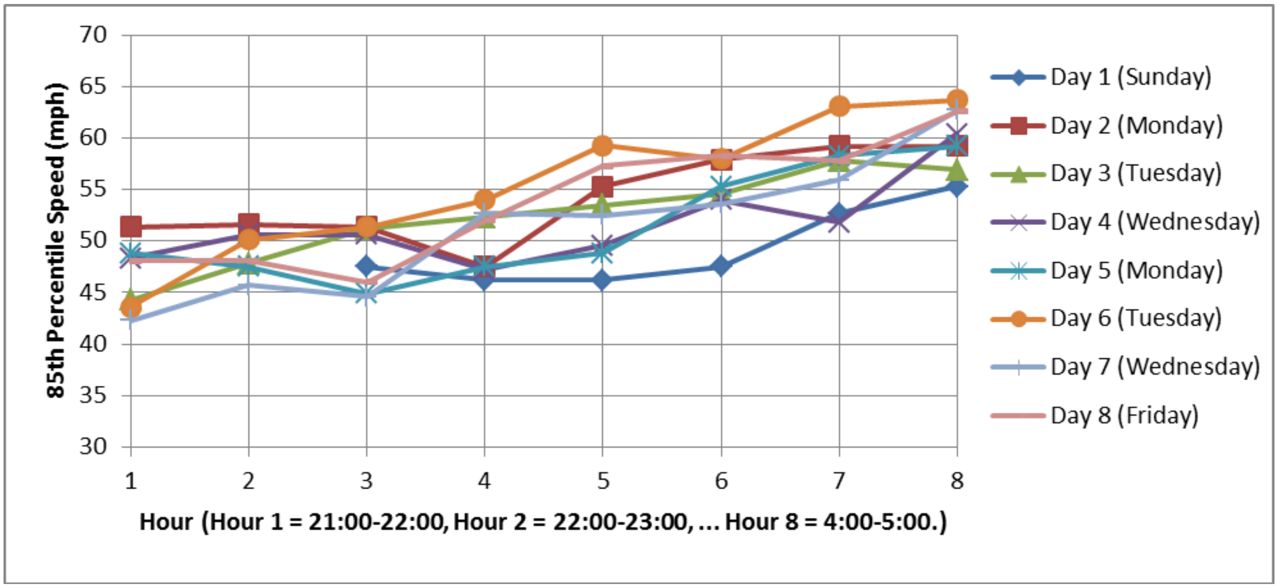


Figure 4.12: Hourly Vehicle Speed (85th Percentile) at First WZ Sensor for All Days (Case Study #2)

Figure 4.13 shows the number of vehicles recorded during each hour of the work shift for all days on this project. Figure 4.14 shows a ratio of the 85th percentile speed to the traffic volume for each hour.

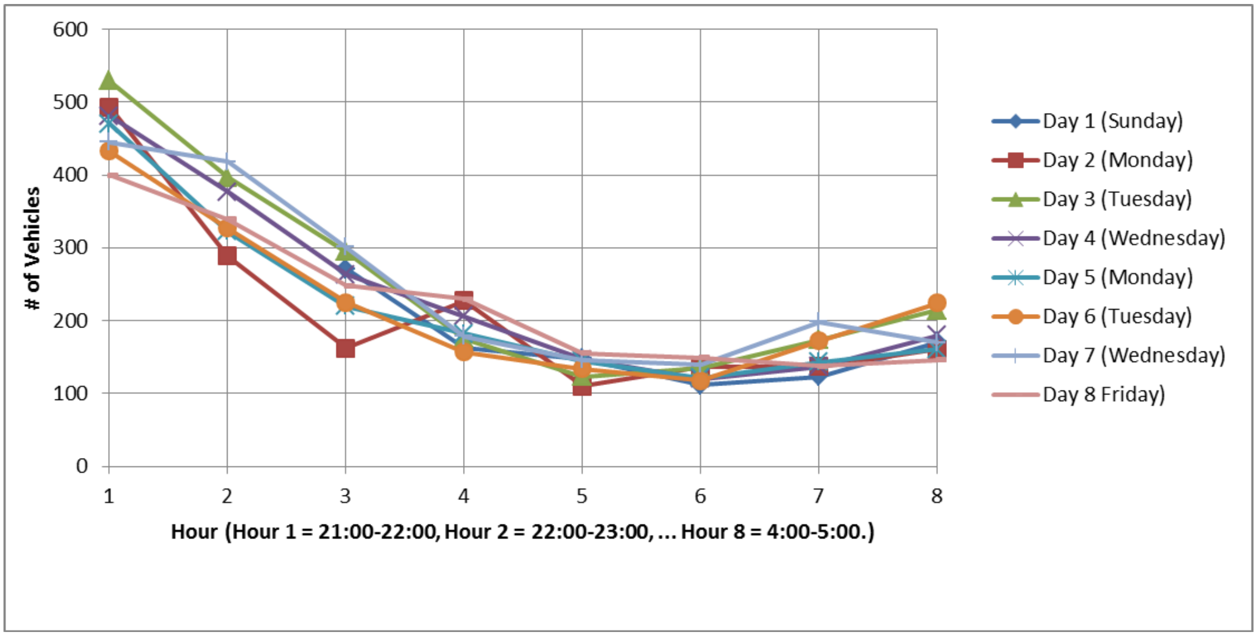


Figure 4.13: Hourly Traffic Volume at First WZ Sensor for All Days (Case Study #2)

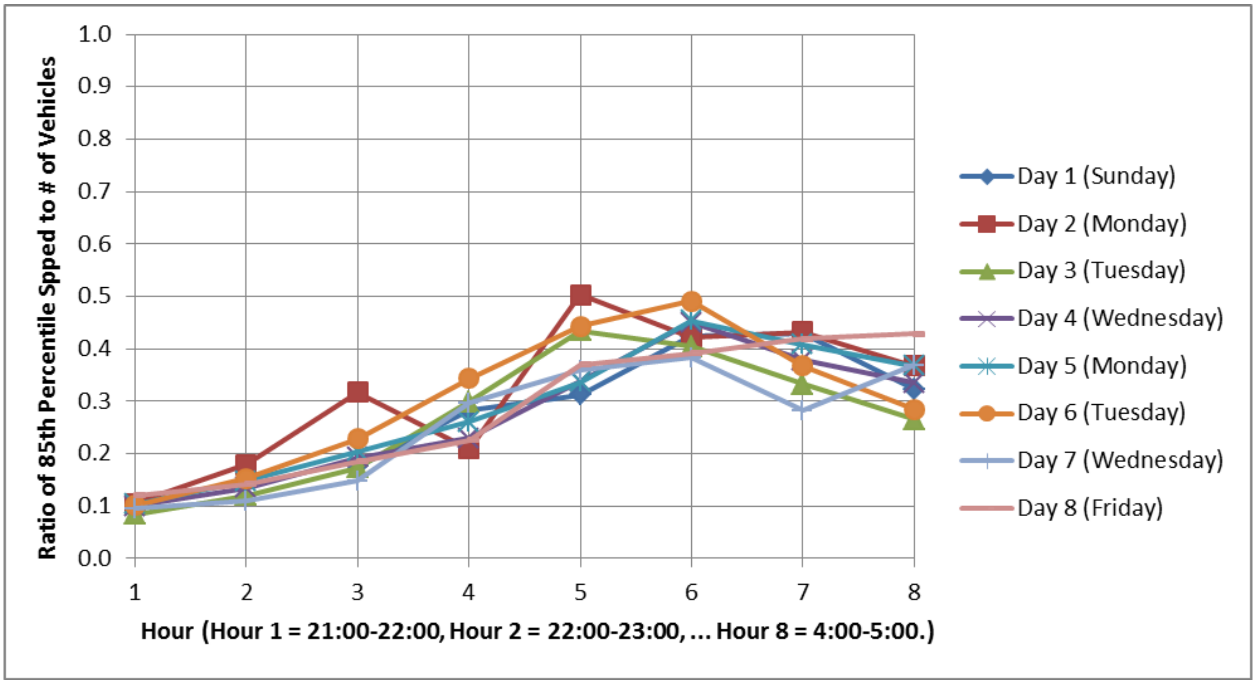


Figure 4.14: Ratio of Hourly Speed (85th Percentile) at First WZ Sensor to Traffic Volume for All Days (Case Study #2)

Figure 4.15 shows the 85th percentile speed for different locations for all days on this project. The speeds for all days are very similar. At the first two locations, the speeds for different days are within a 10 mph range (65-75mph). At the end of taper location, speeds for Day 4 and Day 7 are lower than the other days. This is likely because the treatments for those days are the combination of the 50 mph signs, PCMS on trailers, and radar speed reader. The contractor placed these treatments close to the end of the taper section. Drivers are likely to slow down at this location with the many treatments present. For the first WZ sensors, the speeds are within a 5 mph range (50-55 mph). The second WZ speeds are similar, except higher on Day 2. The third sensor location shows a wide range because for some days this sensor was out of the work zone (the contractor did not pave as far as planned).

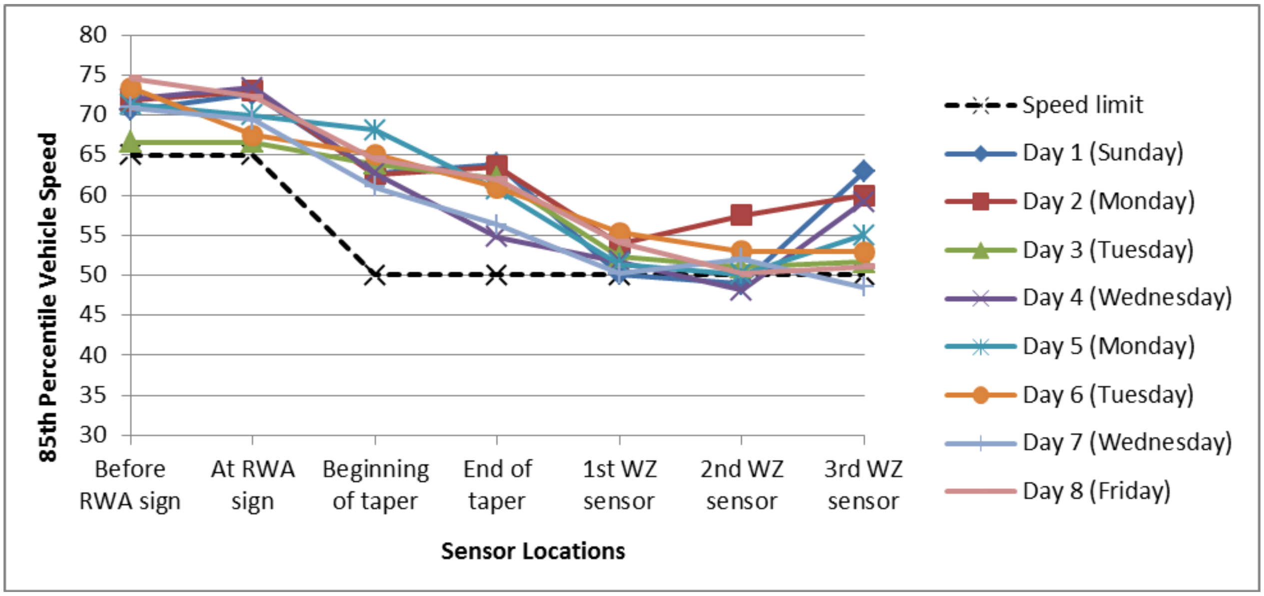


Figure 4.15: Vehicle Speed (85th Percentile) at Different Locations for All Days (Case Study #2)

Figure 4.16 shows the number of different types of vehicles (trucks and passenger cars) during the hours of data collection, based on vehicle length, for all days. Speed data collection on Day 1 took place from 23:00-05:00. On the other days, data collection occurred from 21:00-05:00.

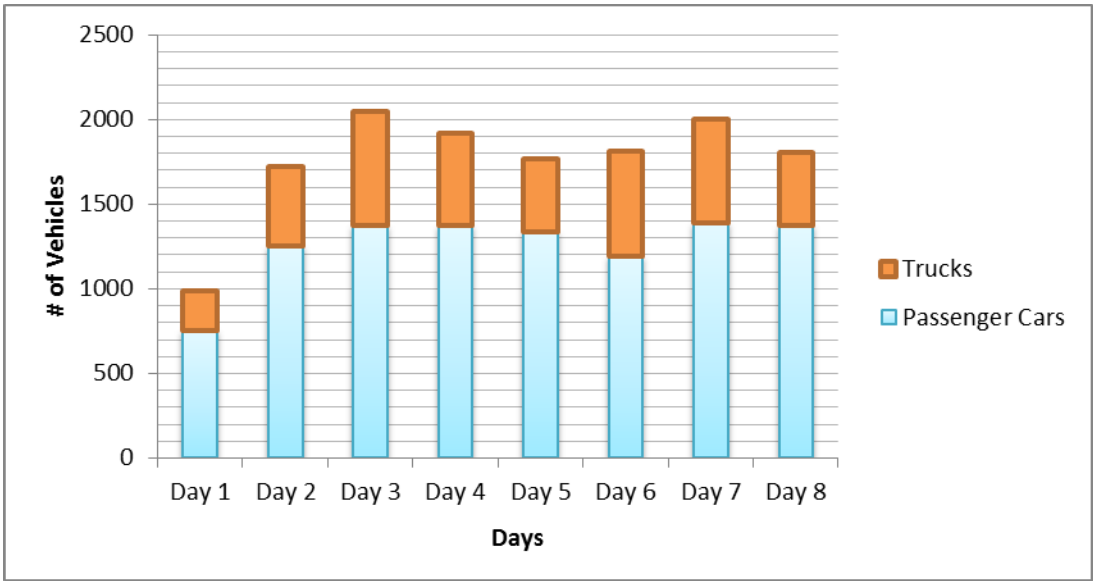


Figure 4.16: Traffic Volume (# of Vehicles) for Different Types of Vehicles for All Days (Case Study #2)

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. Sections 5.2 and 5.3 provide a statistical analysis of the speed data based on the various treatments implemented. Both of these sections provide analyses similar to that conducted for the prior two projects investigated in the first phase of the research study.

The analyses conducted as part of the present and prior studies (SPR-769 and SPR-751) are similar to that commonly conducted as part of transportation and construction research. The research utilizes an experimental approach in which the measured impacts of a treatment are compared to control. Commonly-used statistical tools are also used when comparing sets of data. Similar to common practice, vehicle speed measurements are analyzed and compared using both mean and 85th percentile values. Additional analyses are included in SPR-769 and SPR-751 that are unique. An analysis is conducted in which the speed of passing vehicles is evaluated based on the distance of the vehicle to the paver. This analysis provides an idea of how vehicle speed is impacted by just the presence of the construction equipment. In addition, for SPR-769, an analysis is conducted to determine the impact of the Road Work Ahead signs on vehicle speed, and to determine whether vehicles speed up as they merge in the transition area.

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 (speed sensors) 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 speed sensors recorded vehicle speed, vehicle length, and the time when the vehicle passed the sensor. As part of the construction operations, a construction worker (ticket taker) is assigned to take asphalt volume 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 speed sensor on the roadway is also recorded prior to the start of the paving work. As a result, the distance between the paver and speed sensor can be calculated at any time and for each vehicle that passes over the sensor.

Figure 5.1 provides an illustration of the 85th percentile vehicle speeds according to how far the vehicles were from the paver. The figure (copied from the prior SPR-751 research report) shows the speed data for the first WZ sensor on Day 5 of the I-84 case study project which was studied in the first phase of the research study (SPR-751). Additional speed versus distance to paver graphs are provided in Appendix D and Appendix E.

In the figure below, an OSP officer parked at the end of taper. The first speed sensor in the work zone was at a fixed location also. At the beginning of the paving work, the paver was behind the first WZ sensor (upstream of the sensor). 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 sensor 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 sensor (downstream of the sensor), and the speed recorded is the speed **before** the vehicle passes the paver. For the graphs in the figure below and in Appendix D, a negative distance represents the situation when the vehicle has not yet reached the paver; in other words, the paver has already passed the sensor 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 sensor on the ground.

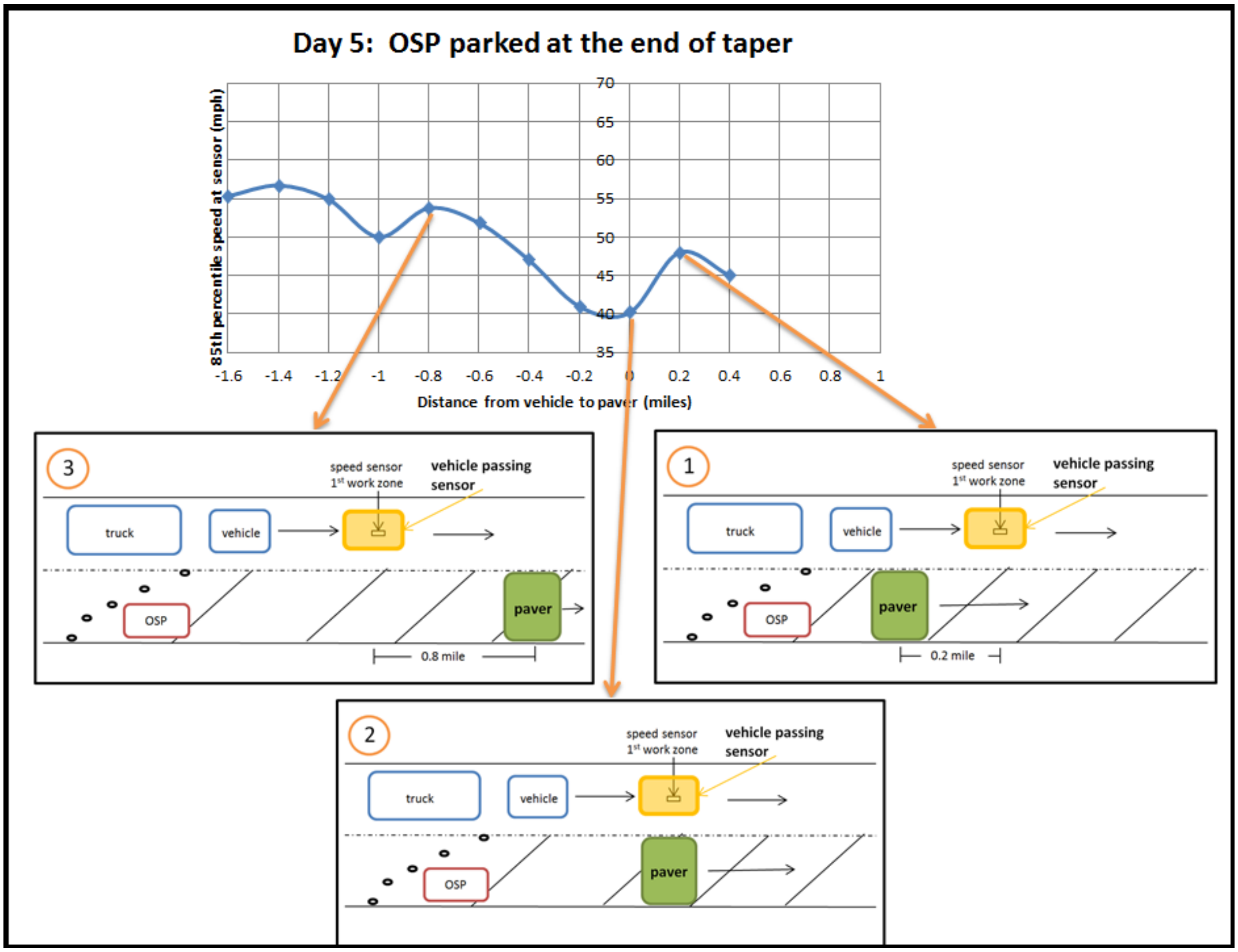


Figure 5.1: Illustration of Distance to Paver Graphs

Given the large volume of traffic recorded as for the study, 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 investigated previously. Table 5.1 shows an example of the data used to draw the distance to paver graphs in Appendix D and Appendix E.

Table 5.1: Data Used for Plotting Illustration of Distance to Paver Graph

First WZ Sensor Location	Paver Location	Time the Paver was at Paver Location	Distance from Sensor to Paver	Time Period	85th Percentile Speed of Vehicles during that Time Period (mph)	Average Speed of Vehicles during that Time Period (mph)
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 sensor, 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 about 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 sensor (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 speed sensor 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 sensor 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.

5.1.2 Speed vs. Distance to Paver Analysis for I-5 Glendale – Hugo Project (Case Study #1)

Figure 5.2, Figure 5.3, and Figure 5.4 show the distance to paver graph for the first day of the I-5 Glendale – Hugo project based on the first WZ sensor, second WZ sensor, and third WZ sensor, respectively. Similar figures for the other days are shown in Appendix D. The contractor started paving work early on some of the days, including Day 1 of this project. As a result, the paver already passed the first WZ sensor when the sensor started to record vehicle speeds. Therefore, the figure for the first WZ sensor (Figure 5.2) shows no data for vehicles downstream of the paver. For the third sensor in the work zone, the sensor is usually close to the end of the work or even beyond the work zone if the work does not progress as far as planned. In some cases, by the time the third WZ sensor stops recording data, the paver has not yet, or just, reached the sensor. Therefore, the figure for the third WZ sensor (Figure 5.4) shows no data for vehicles upstream of the paver.

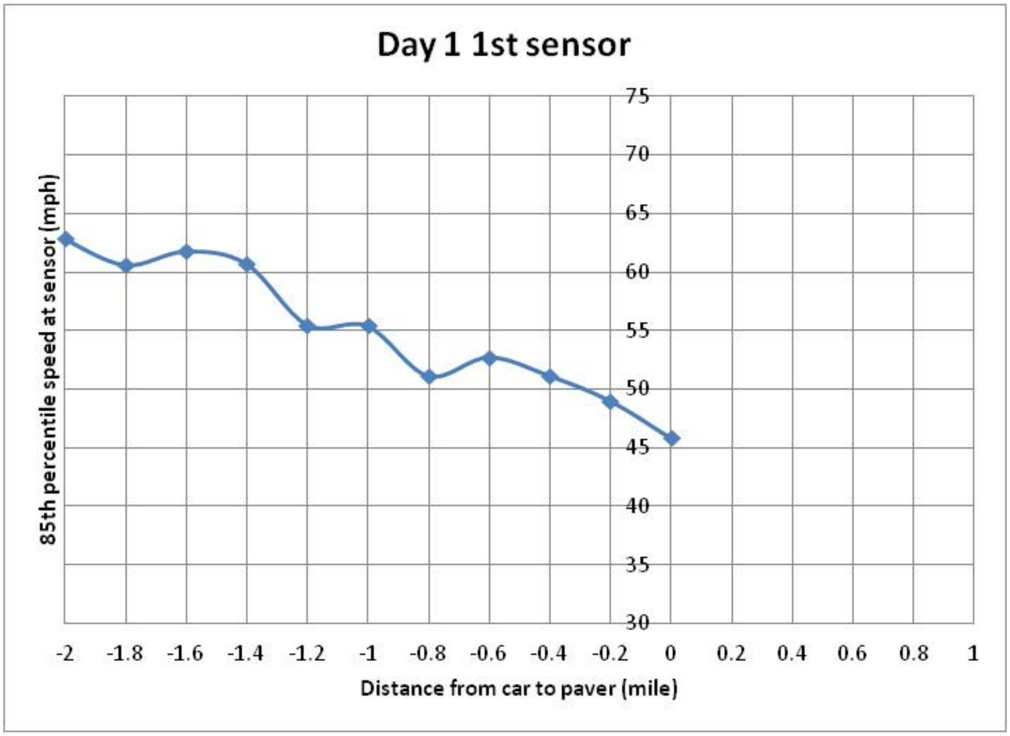


Figure 5.2: Day 1 Distance to Paver Graph Based on 85th Percentile Speed at First WZ Sensor (Case Study #1)

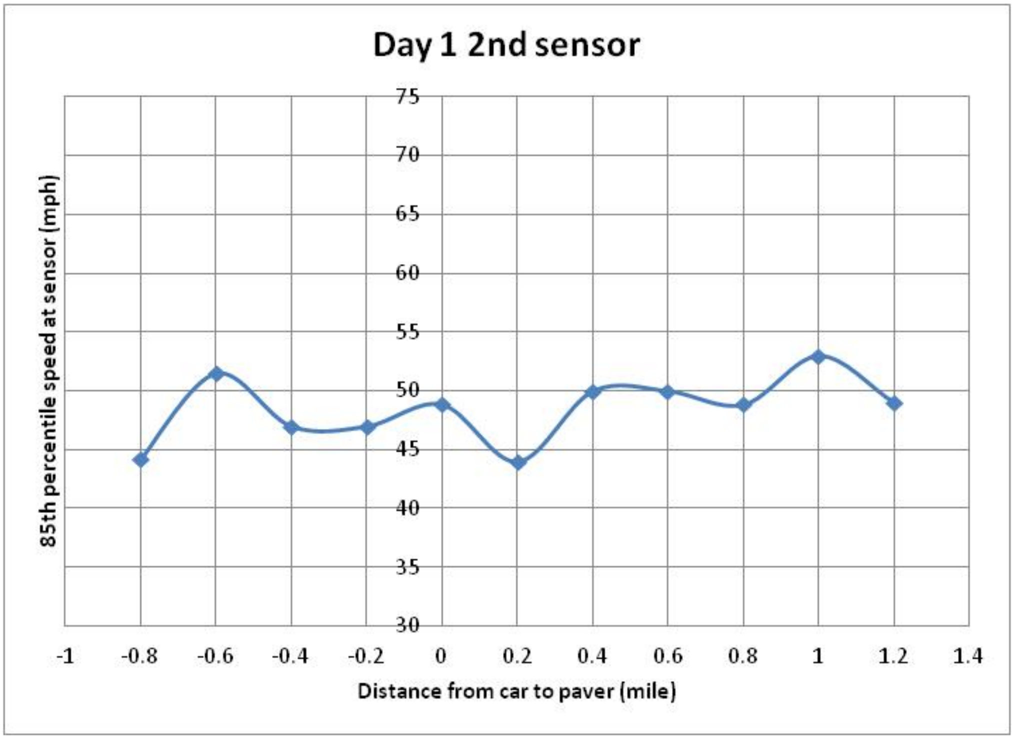


Figure 5.3: Day 1 Distance to Paver Graph Based on 85th Percentile Speed at Second WZ Sensor (Case Study #1)

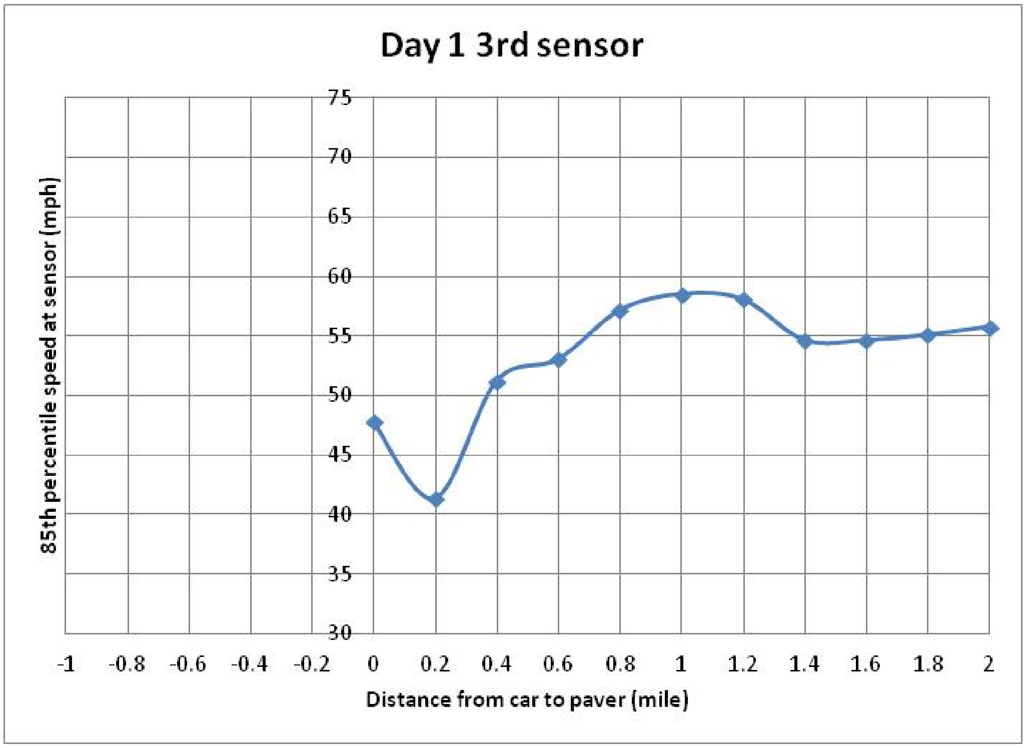


Figure 5.4: Day 1 Distance to Paver Graph Based on 85th Percentile Speed at Third WZ Sensor (Case Study #1)

The distance to paver graphs provide an opportunity to evaluate the speed fluctuations relative to the paver. The figures above, and especially those in Appendix D, typically show that the greatest rate of change in speed (slope of the line) occurs when the vehicle is in the immediate vicinity of the paver. The increases and decreases in speed further away from the paver may be a result of the vehicles traveling near a different piece of equipment (e.g., tack truck, roller, etc.) or a particular traffic control measure (e.g., radar speed reader display). The graphs reveal that, further away from the paver, the vehicles slow down or speed up at a lower rate.

The graphs also show a distance and timeframe in which the vehicles both slow down before the paver and speed up after the paver. When there is a clear slow down adjacent the paver, the vehicles begin to slow down approximately 0.2 to 0.4 miles before researching the paver. The speed increases over a similar distance after the paver. If the vehicles are travelling at approximately 50mph, this equates to a timeframe of approximately 14 to 28 seconds of decrease in speed before the paver and the same amount of time increasing speed after the paver. This result provides an indication of driver behavior and perhaps how far apart traffic control devices, signs, etc. should be spaced to maintain driver attention and consistent driver behavior through the work zone. It may also be used by contractors to plan the optimal spacing of equipment in order to positively affect driver behavior.

Figure 5.5 shows a summary of the distance to paver graphs for all of the days of testing, based on the first WZ sensor. The speeds shown on Day 9 are low, likely as a result of the incident where the asphalt truck dropped its load throughout the roadway and the contractor spent extensive time to clean it up. Days 2 and 11 have lower near-paver speeds than other days; however the rate of speed drop before the paver, and rate of speed increase after the paver, are higher on Days 2 and 11 (sharp changes in speeds). On treatments on day 2 were 50mph speed signs and PCMS on trailers; the treatments on day 11 were 50mph speed signs and radar speed display. The vehicles decelerated and accelerated more gradually on the other days. For this case study, the speeds relative to the paver are also impacted by the roadway grade (i.e., flat, uphill, or downhill grade) and sharp horizontal curves. Given the hilly nature of the project site, it is difficult not only to compare one day to the next, but also the speed at one distance to the paver to the speed at another distance to the paver. For example, the vehicles may be travelling on a downhill section of roadway upstream of the paver but on an uphill section downstream of the paver. Therefore, the distance to paver results from this case study are very inconsistent as seen in the figure. The treatments applied are not the only factors that impact speed.

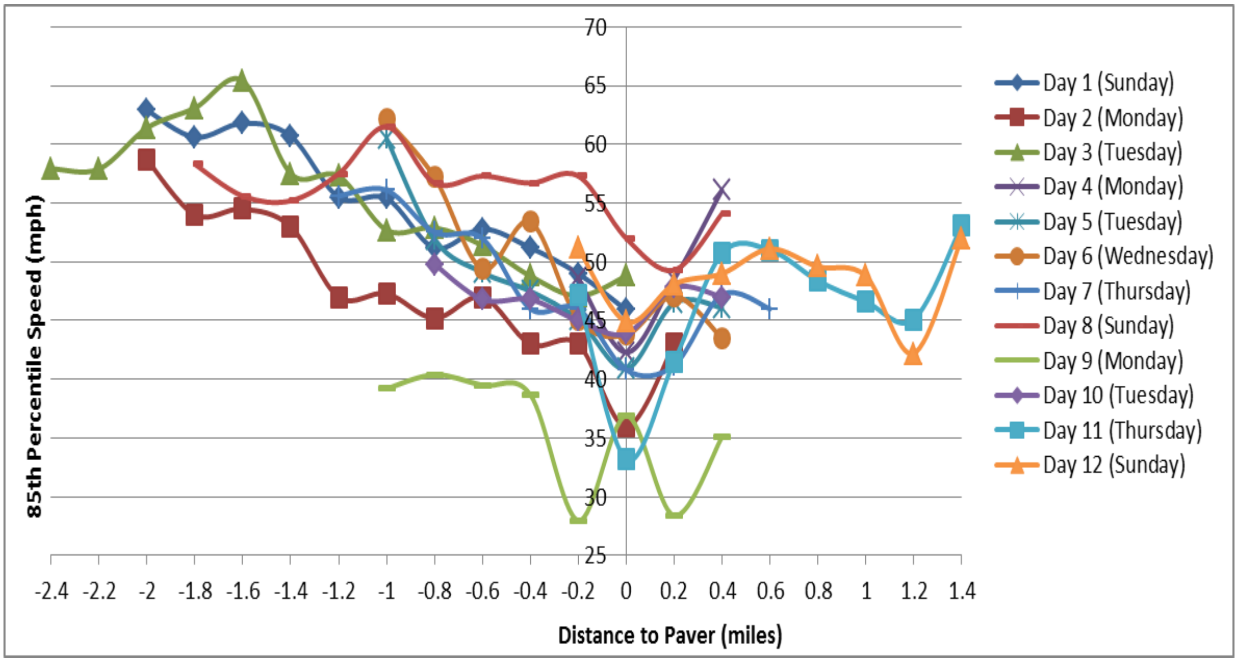


Figure 5.5: Distance to Paver Graph for All Days Based on 85th Percentile Speed at First WZ Sensor (Case Study #1)

5.1.3 Speed vs. Distance to Paver Analysis for I-5 Rock Point – Seven Oaks Project (Case Study #2)

Similar distance to paver graphs for each day for the I-5 Rock Point – Seven Oaks project are provided in Appendix E. A summary graph for the 85th percentile speed on all days is shown in Figure 5.6. Unlike the I-5 Glendale – Hugo project, this project was on a section of roadway that was flat and straight. The majority of days show that the vehicles slow down as they approach the paver location and speed up afterwards. For all days, the speed at the paver ranged from approximately 37 to 52 mph. This is consistent with the findings of the prior study (SPR-751). In addition, on all of the days, except Day 3, the 85th percentile vehicle speed was less than the posted 50 mph speed.

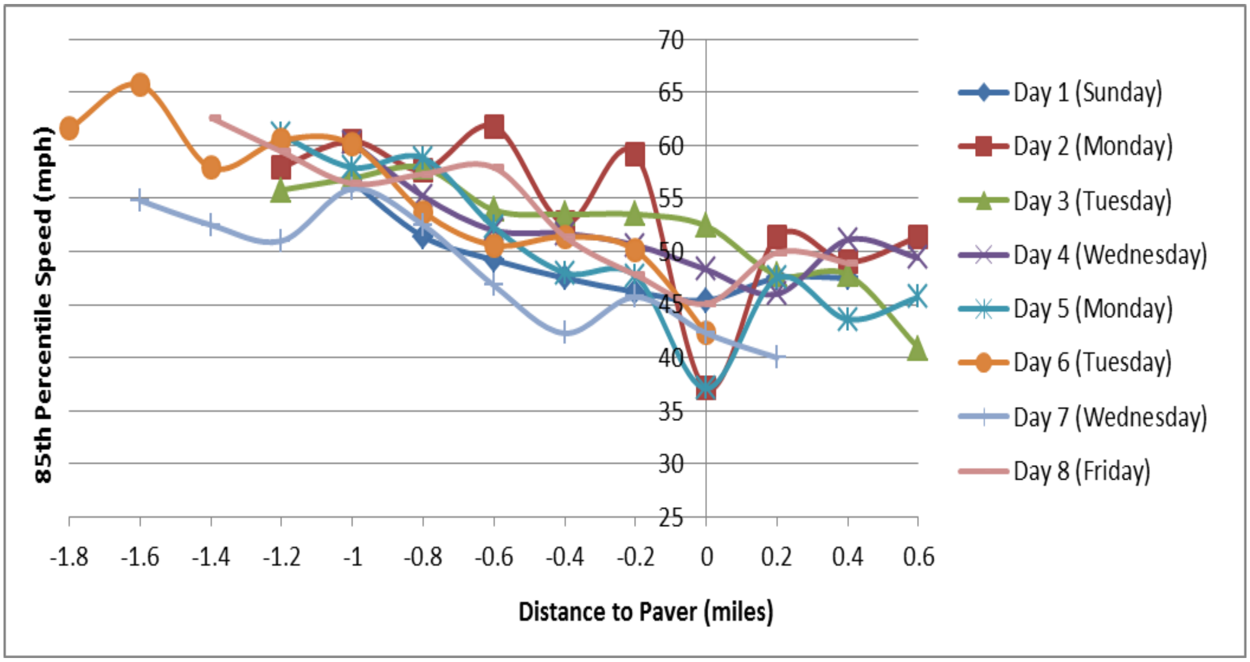


Figure 5.6: Distance to Paver Graph for All Days Based on 85th Percentile Speed at First WZ Sensor (Case Study #2)

5.2 STATISTICAL ANALYSIS FOR I-5 GLENDALE – HUGO PROJECT

On the two case study projects, traffic speed data was collected at seven locations along the roadway each day a total of 20 days. The complicated roadway conditions on the I-5 Glendale – Hugo project (Case Study #1) compared to the I-5 Rock Point – Seven Oaks (Case Study #2), inhibit aggregation of the data from the two projects into one dataset. The I-5 Glendale – Hugo project was located within a section of roadway containing steep grades and sharp curves, while the roadway was predominantly flat and straight on the I-5 Rock Point – Seven Oaks project. Therefore, the data from each case study project was analyzed independently. Additionally, since the third WZ sensor data is not available for each day of the work as described above, the data for that sensor location is excluded from the analyses. Lastly, only normal speed data (outliers omitted), and the vehicle data recorded between 9:00pm and 5:00am, are used.

Figure 3.7 above shows the hilly nature of the I-5 Glendale – Hugo project. As a result of the complex nature of the project conditions, the conditions from one day to the next frequently varied. Therefore, due to the complexity of the roadway conditions on this project, no statistical comparisons were made for all of the days on the project as a whole. However, for some of the days, the speed sensors were put down at the same location as on other days and the vehicle traffic travelled over the same section of roadway. This allowed for conducting pair comparisons for some of the days. These “same-location-days” comparisons are discussed in this section of the report.

The first three days of work on the I-5 Glendale – Hugo project took place between milepoints 78.4 and 81.4. On these days the contractor paved the wearing course of the fast lane, slow lane, and shoulder. The treatment on the first day (Day 1) during fast lane (A-lane) paving day was 50 mph signs only. On the second day (Day 2), the contractor paved the slow lane (B-lane) and implemented 50 mph signs and PCMS signs on trailers. Lastly, on Day 3 the contractor paved the shoulder and used 50 mph signs, PCMS signs on trailers, and the radar speed display. Statistical comparisons were applied to these first three days.

The work on Days 4 and 5 took place between milepoints 77 and 78.4, and included paving the base course of the fast lane and the base course of the slow lane. The treatment for Day 4 was 50 mph signs only, and for Day 5 the treatment was 50 mph signs, PCMS signs on trailers, and PCMS signs on rollers. However, data on Day 5 was only collected from 9:00pm – 2:00am due to the early finish of the work on that day. Therefore, no statistical comparison was conducted between the results of Day 4 and Day 5.

The work on Days 6 and 7 occurred between milepoints 75 and 77. On these days the contractor paved the base course of the fast lane (Day 6) and the slow lane (Day 7). The treatments for Day 6 were 50 mph signs and PCMS signs on rollers. The treatments for Day 7 were 50 mph signs, PCMS signs on rollers, and radar speed display. Pair comparisons were applied to the speed data of these two days.

5.2.1 End of Taper Speed vs Treatments (Case Study #1)

Two sample t-tests were applied to compare the end of taper speeds among Days 1, 2, and 3, and between Day 6 and Day 7. The results are shown in Table 5.2 and Table 5.3. The mean speed at the end of taper location for Day 2 is 1.35 mph lower than the mean speed at the same location for Day 1 (p-value = 3.65e-16). For Day 3, the mean speed is similar to that recorded for Day 1, and the difference was not found to be statistically significant. It should be noted that on Day 3, the contractor paved the roadway shoulder. In this case, the full slow lane (B-lane) was also closed, moving the passing traffic farther away from the actual work taking place. As a result, it is expected that the vehicle speeds would be greater than if the work was directly adjacent the travel lane. That is, when a closed, “buffer” lane is provided, vehicle speeds tend to increase. This may be a reason for the high mean speed for Day 3 compared to both Days 1 and 2. This result is important as it brings up a question of speed and proximity. With the buffer lane present, the vehicles are farther away from the workers, however the traffic travels at a higher rate of speed. Without the buffer lane, the vehicles are closer to the workers, but travel at a slower rate of speed. A more detailed analysis of the associated risk is warranted to determine the preferred method.

Similarly, when comparing Day 6 and Day 7, the mean speeds at the end of taper are close in value and the difference was not found to be statistically significant (see Table 5.3).

Table 5.2: T-test Results for Days 1, 2, and 3 at End of Taper Location Mean Speeds (Case Study #1)

	Mean Speed (mph) for Day	Mean Speed (mph) for Day 1 (50 mph signs)	Difference in Mean Speeds	p-value	95% Confidence Interval
Day 2 (50 mph signs and PCMS on trailers)	47.33	48.68	-1.35	3.65e-16	(-1.67, -1.02)
Day 3 (50 mph signs, PCMS on trailers, and radar speed reader)	48.93	48.68	0.25	0.13	(-0.08, 0.57)

Table 5.3: T-test Results for Days 6 and 7 at End of Taper Location Mean Speeds (Case Study #1)

	Mean Speed (mph) for Day	Mean Speed (mph) for Day 6 (50 mph signs and PCMS on rollers)	Difference in Mean Speeds	p-value	95% Confidence Interval
Day 7 (50 mph signs, PCMS on rollers, and radar speed reader)	47.53	47.84	-0.31	0.06	(-0.63, 0.01)

5.2.2 Work Zone Speed vs. Treatments (Case Study #1)

Two sample t-tests were applied to compare the work zone speed among Day 1, 2, and 3, and between Day 6 and Day 7. The results are shown in Table 5.4 and Table 5.5. For these comparisons, the mean work zone speed was calculated based on the data recorded from both the first and second sensors in the work zone combined. The mean speed in the work zone for Day 2 is 4.93 mph lower than the mean speed at the same location for Day 1, and the difference was found to be statistically significant (p-value < 2.2e-16). The Day 3 mean speed is 1.35 mph lower than Day 1, and this difference was also found to be statistically significant (p-value = 1.44e-05). As mentioned above, due to the shoulder paving on Day 3 and closure of the full slow lane, it is expected that the Day 3 speeds would be higher given the larger separation of the vehicle traffic from the work taking place.

The mean speeds recorded in the work zone on Day 6 and Day 7 are similar, and the difference was not found to be statistically significant (see Table 5.5).

Table 5.4: T-test Results for Days 1, 2, and 3 Work Zone Mean Speeds (Case Study #1)

	Mean Speed (mph) for Day	**Mean Speed (mph) for Day 1 (50 mph signs)**	**Difference in Mean Speeds**	**p-value**	**95% Confidence Interval**
Day 2 (50 mph signs and PCMS on trailers)	36.93	41.86	-4.93	< 2.2e-16	(-5.49, -4.37)
Day 3 (50 mph signs, PCMS on trailers, and radar speed reader)	40.5	41.85	-1.35	1.44e-05	(-1.97, -0.74)

Table 5.5: T-test Results for Days 6 and 7 Work Zone Mean Speeds (Case Study #1)

	Mean Speed (mph) for Day	**Mean Speed (mph) for Day 6 (50 mph signs and PCMS on rollers)**	**Difference in Mean Speeds**	**p-value**	**95% Confidence Interval**
Day 7 (50 mph signs, PCMS on rollers, and radar speed reader)	38.49	38.19	0.3	0.29	(-0.25, 0.83)

5.3 STATISTICAL ANALYSIS FOR I-5 ROCK POINT – SEVEN OAKS PROJECT

For the I-5 Rock Point – Seven Oaks project, a total of 75,388 vehicle data points are included in the statistical analysis. Figure 5.7 shows the distribution of all the speed data. The vehicle speed data is normally distributed around a mean of 51.65 mph, with a standard deviation of 12.86. Figure 5.8 shows the distribution of vehicles based on vehicle length (type). It is clear from the figure that the majority of the vehicles are passenger cars (10-20 ft long). As indicated previously, vehicles from 25-49 feet long are typically long vans, one trailer pick-ups, and small trucks; vehicles from 50-74 feet long are typically mid-size, semi-trucks with trailers; and vehicles 75 or more feet long are long haul trucks with three trailers.

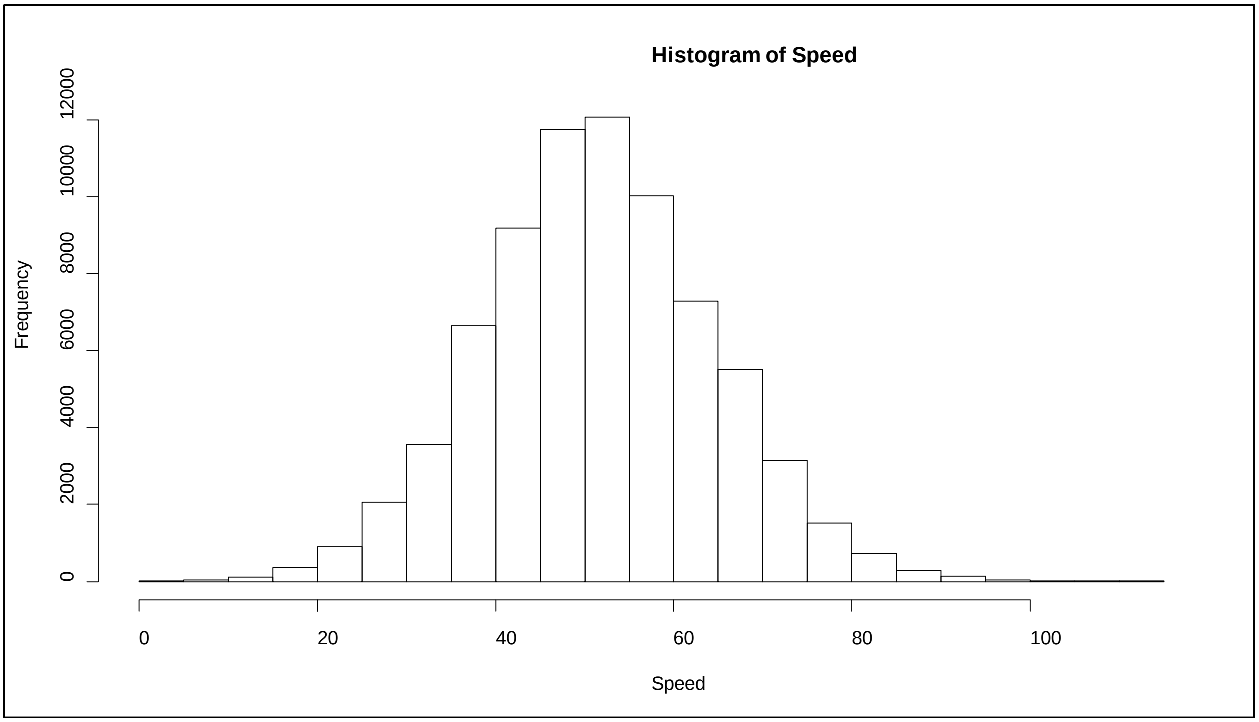


Figure 5.7: Distribution of All Speed Data for I-5 Rock Point – Seven Oaks Project (Case Study #2)

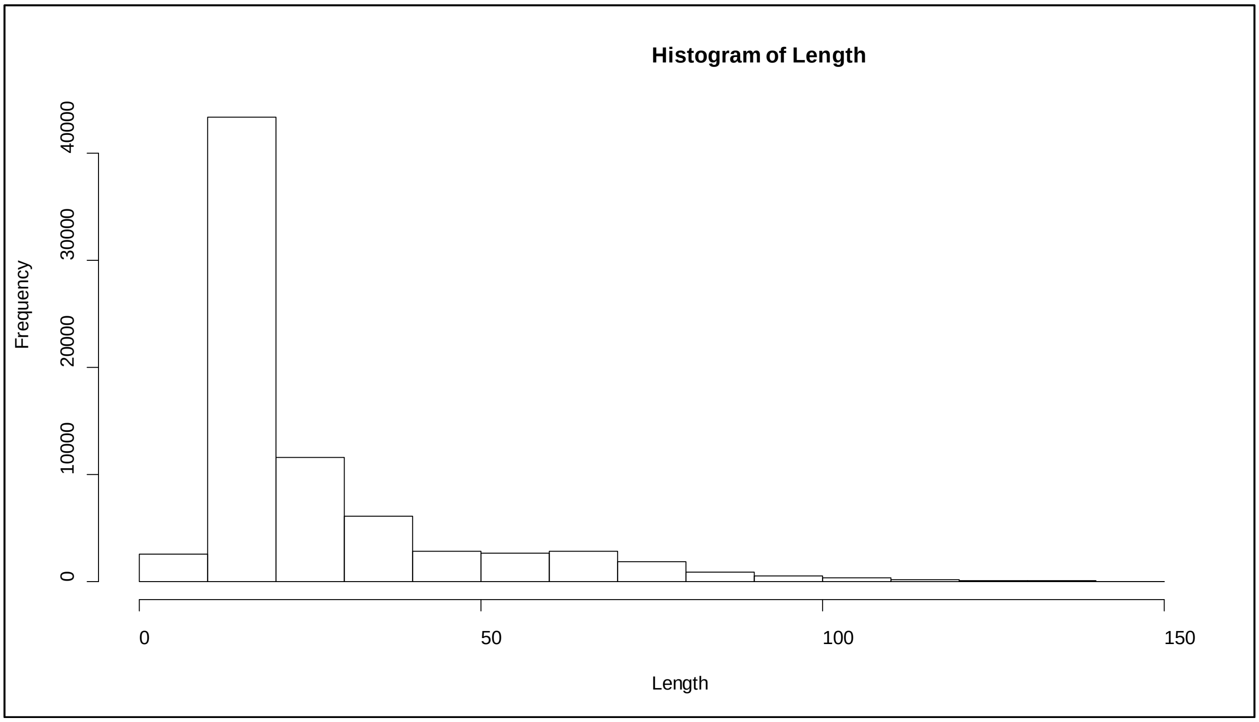


Figure 5.8: Distribution of Vehicle Lengths for I-5 Rock Point – Seven Oaks Project (Case Study #2)

5.3.1 Speed Before RWA Sign Location vs. Speed at RWA Sign Location (Case Study #2)

One of the research objectives was to determine driver behavior when they see the Road Work Ahead (RWA) signs compared to before the RWA signs. As indicated above, two speed sensors (one in each lane) were placed in the roadway approximately 1 mile upstream of the location of the RWA signs. These sensors were placed in order to document vehicle speed before the drivers see that there is a work zone ahead. These additional sensors allowed for comparing the speeds captured before and at the RWA signs.

A two-sample t-test was applied for each day’s data to compare the speeds at the two sensor locations, and a boxplot was drawn to illustrate the difference. Figure 5.9 shows the comparison for Day 1 of I-5 Rock Point – Seven Oaks project at the first two sensor locations.

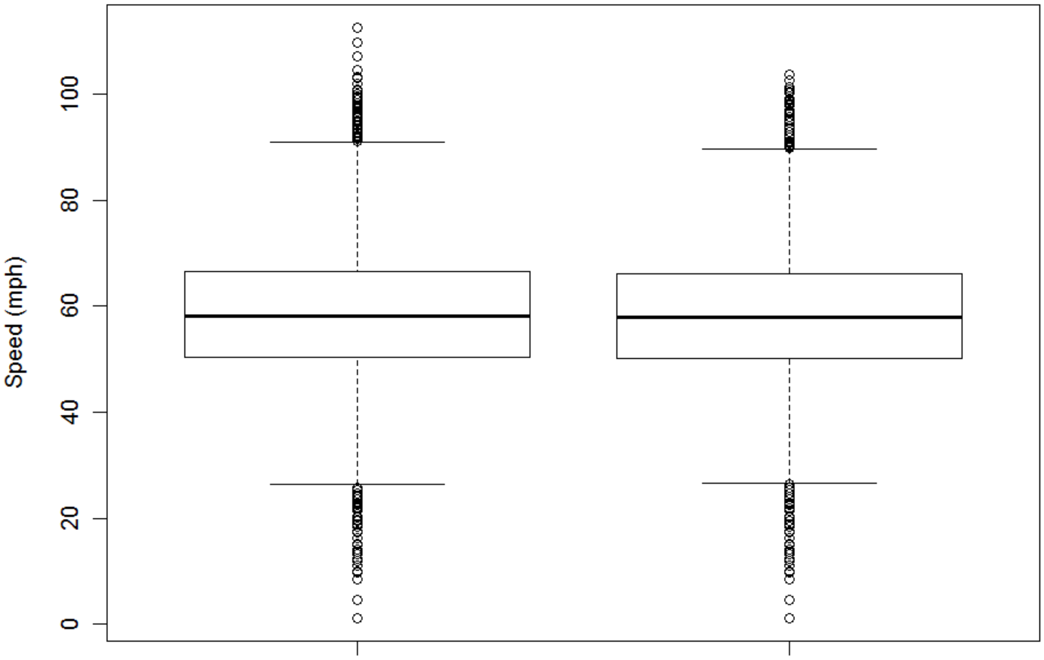


Figure 5.9: Vehicle Speeds before RWA vs Speed at RWA for Day 1 (Case Study #2)

The left boxplot in Figure 5.9 is the data summary at the location before the RWA signs, while the boxplot on the right is the summary of the speed data at the RWA signs location. The boxplots look very similar, however, the t-test reveals that there is a slight difference between the mean vehicle speeds at these two locations. There is convincing evidence (p-value = 0.0061) that the mean speed before the RWA signs is 0.37 mph higher than the mean speed at the RWA signs for Day 1. The result is statistically significant. However, the small difference (0.37 mph) may not have real impact on the roadway. The following table shows the results from the t-tests comparing the mean speed recorded before the RWA signs and the mean speed at the RWA signs for all eight days.

Table 5.6: Comparison between Mean Speed before RWA Signs and at RWA Signs for All Days (Case Study #2)

Day	Mean Speed before RWA Signs (mph)	Mean Speed at RWA Signs (mph)	Difference in Mean Speeds	P-value	95% Confidence Interval
Day 1 (Sun)	58.12	57.74	0.38	0.0061	(0.11, 0.64)
Day 2 (Mon)	57.51	56.93	0.58	2.83e-06	(0.34, 0.83)
Day 3 (Tues)	56.14	55.83	0.31	0.01	(0.072, 0.54)
Day 4 (Wed)	55.99	55.47	0.52	3.774e-05	(0.27, 0.76)
Day 5 (Mon)	56.63	56.33	0.30	0.023	(0.042, 0.57)
Day 6 (Tues)	56.75	56.76	-0.01	0.93	(0.25, 0.23)
Day 7 (Wed)	55.82	55.59	0.23	0.061	(0.01, 0.47)
Day 8 (Fri)	56.46	56.50	-0.04	0.71	(0.28, 0.19)

Table 5.6 shows that for Days 2-5, the mean speeds before the RWA signs are slightly higher than the mean speeds at the RWA signs, and the p-values are less than 0.05. For Days 1 and 7, the p-values are slightly above 0.05, revealing suggestive evidence that the mean speeds are different. For Days 6 and 8, the p-values are high and indicate no different in the mean speeds. The results show no particular pattern related to days of the week.

5.3.2 Speed at Beginning of Taper vs. Speed at End of Taper (Case Study #2)

Similar analyses were conducted comparing the mean speeds at the beginning of the taper and the mean speeds at the end of the taper for each day. The results are shown in Table 5.7.

Table 5.7: Comparison between Beginning of Taper and End of Taper Mean Speeds for All Days (Case Study #2)

Day	Mean Speed at Beginning of Taper (mph)	Mean Speed at End of Taper (mph)	Difference in Mean Speeds	P-value	95% Confidence Interval
Day 1 (Sun)	53.76	51.18	2.58	< 2.2e-16	(2.35, 2.81)
Day 2 (Mon)	54.19	51.80	2.39	< 2.2e-16	(2.17, 2.61)
Day 3 (Tues)	52.59	50.84	1.75	< 2.2e-16	(1.56, 1.95)
Day 4 (Wed)	52.96	51.44	1.52	< 2.2e-16	(1.31, 1.74)
Day 5 (Mon)	52.64	50.97	1.67	< 2.2e-16	(1.45, 1.90)
Day 6 (Tues)	53.44	51.53	1.91	< 2.2e-16	(1.70, 2.13)
Day 7 (Wed)	52.74	51.09	1.65	< 2.2e-16	(1.43, 1.86)
Day 8 (Fri)	53.56	51.66	1.90	< 2.2e-16	(1.69, 2.13)

Table 5.7 shows that the beginning of the taper mean speed is higher than the end of taper mean speed for all days, and the results are statistically significant (p-values less than 0.05). The differences range from 1.52 mph to 2.58 mph. It should be remembered that the data used in the analysis above is taken at the start of the taper and at the end of the taper. The speeds may be higher or lower between these points. Similarly, the difference between the speed at the start of the taper and that prior to the end of the taper may be greater or less than the difference between the start of the taper and the end of the taper. No data was collected mid-way through the taper. Observations of the traffic, however, indicate that, for the given traffic volumes, the reduction in speed through the taper was constant, i.e., no increase or decrease in the rate of change of speed. This result is dependent on the traffic volume.

5.3.3 Speed at Beginning of Taper (Case Study #2)

One of the reasons for having sensors at the beginning of the taper was to determine how many drivers merge into the travel lane at last minute, just prior to the full lane closure. On Days 3, 5, and 6 of the I-5 Rock Point – Seven Oaks project, the beginning of taper sensors were placed right before the first drum in the taper. For this case study project, 68 vehicles were recorded on Day 3 in the fast lane (paving lane) at the beginning of taper location, and 58 of them had normal recorded speeds. The remaining ten vehicles in the fast lane likely hit the sensor or bypassed it.

All of these vehicles were required to merge into the slow lane in order to pass through the work zone. The distribution of vehicle speeds is shown in Figure 5.10. The figure shows a moderate percentage of vehicles travelling at high speeds at the beginning of the taper. This result provides motivation for putting police enforcement in place prior to the work zone in order to help slow the vehicles before they enter the work zone.

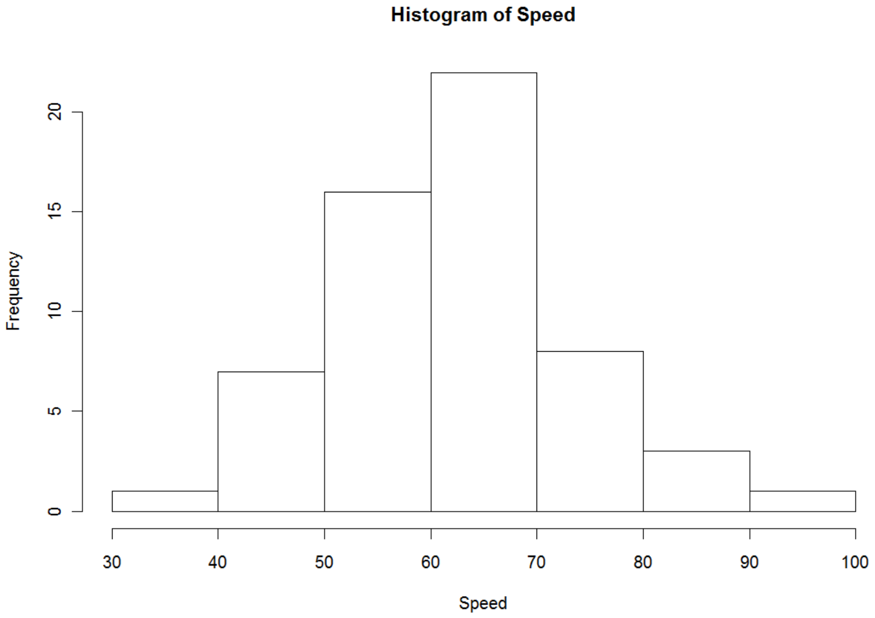


Figure 5.10: Distribution of Vehicle Speeds in Fast Lane (Paving Lane) at Beginning of Taper for Day 3 – Tuesday (Case Study #2)

On Day 5, a total of 55 vehicles were recorded in the fast lane (paving lane) at the beginning of the taper location, and 44 of the vehicles had normal recorded speeds. The distribution of the speeds on Day 5 is shown in Figure 5.11.

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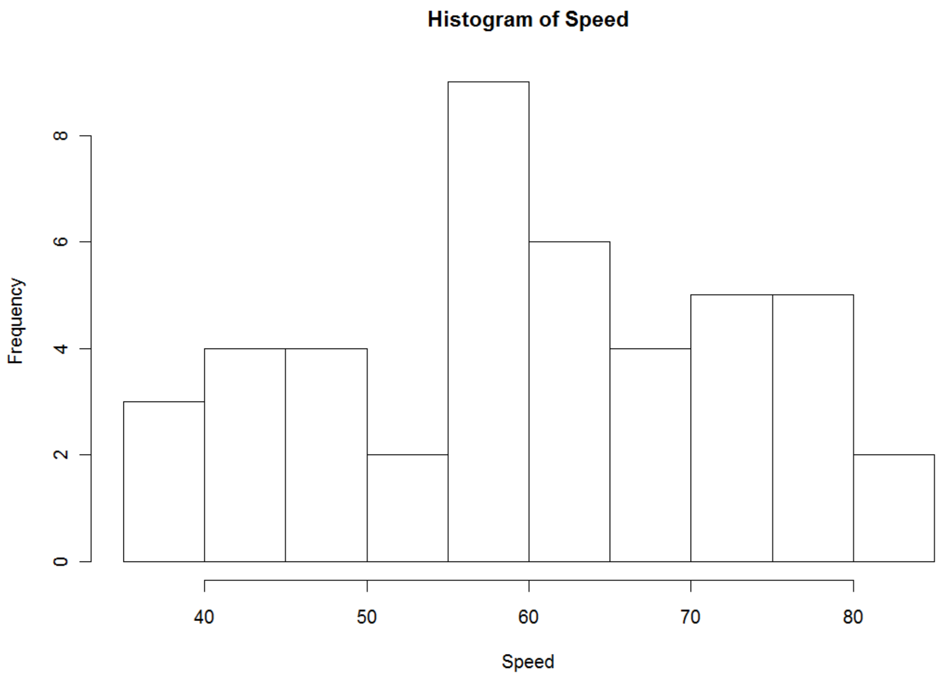

Figure 5.11: Distribution of Vehicle Speeds in Fast Lane (Paving Lane) at Beginning of Taper for Day 5 – Monday (Cast Study #2)

Only 17 vehicles were recorded in the fast lane (paving lane) at the beginning of the taper on Day 6; fourteen of these vehicles had normal recorded speeds. The highest speed was 100.5 mph (after the adjustment), and the lowest speed recorded was 35.2 mph. The distribution of the speeds is shown in Figure 5.12.

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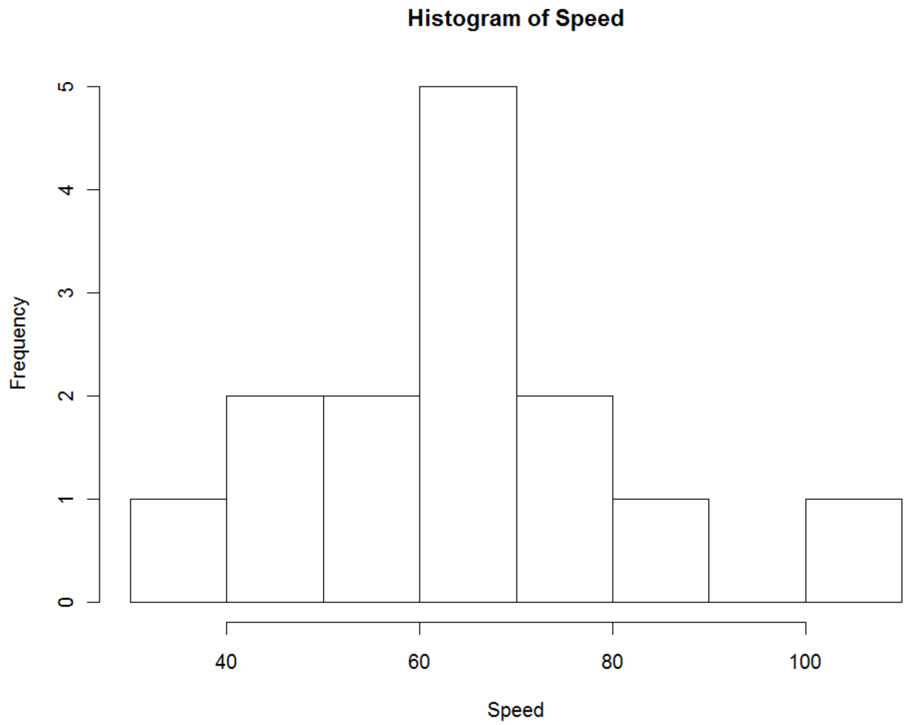

Figure 5.12: Distribution of Vehicle Speeds in Fast Lane (Paving Lane) at Beginning of Taper for Day 6 – Tuesday (Case Study #2)

On Day 8, the contractor paved the slow lane, and the beginning of taper sensors were about 50 feet upstream of the first drum in the taper. On this day, 30 vehicles were recorded on the slow lane (paving lane). Twenty-six of these vehicles had normal recorded speeds. The speed distribution is shown in Figure 5.13.

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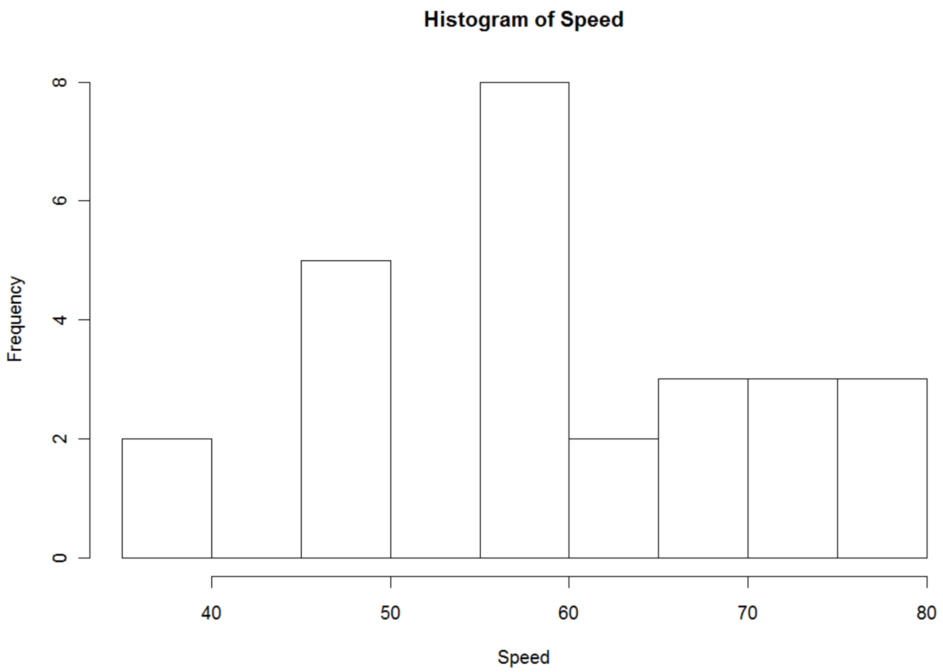

Figure 5.13: Distribution of Vehicle Speeds in Slow Lane (Paving Lane) at Beginning of Taper for Day 8 – Friday (Case Study #2)

5.3.4 End of Taper Speed vs. Treatments (Case Study #2)

Most of the treatments tested were situated around the location of the end of taper. Therefore, statistical analyses were conducted that focused on the end of taper speeds.

5.3.4.1 Mean Speed of End of Taper Location vs. Treatments

The first analysis conducted was to compare the treatment effects on the mean speed at the end of taper for different days. For the I-5 Rock Point – Seven Oaks project, Day 1 and Day 5 had the same treatment of only 50 mph signs (Treatment 1); Days 2 and 8 utilized the 50 mph signs and the PCMS signs on trailers (Treatment 2); Days 3 and 6 employed the 50 mph signs and the radar speed reader/display (Treatment 3); and lastly, on Days 4 and 7 the 50 mph signs, PCMS signs on trailers, and radar speed reader/display (Treatment 4) were used. The overall distribution of the end of taper speeds for all days is shown in Figure 5.14. The mean speed was calculated to be 51.01 mph with a standard deviation of 9.42 mph.

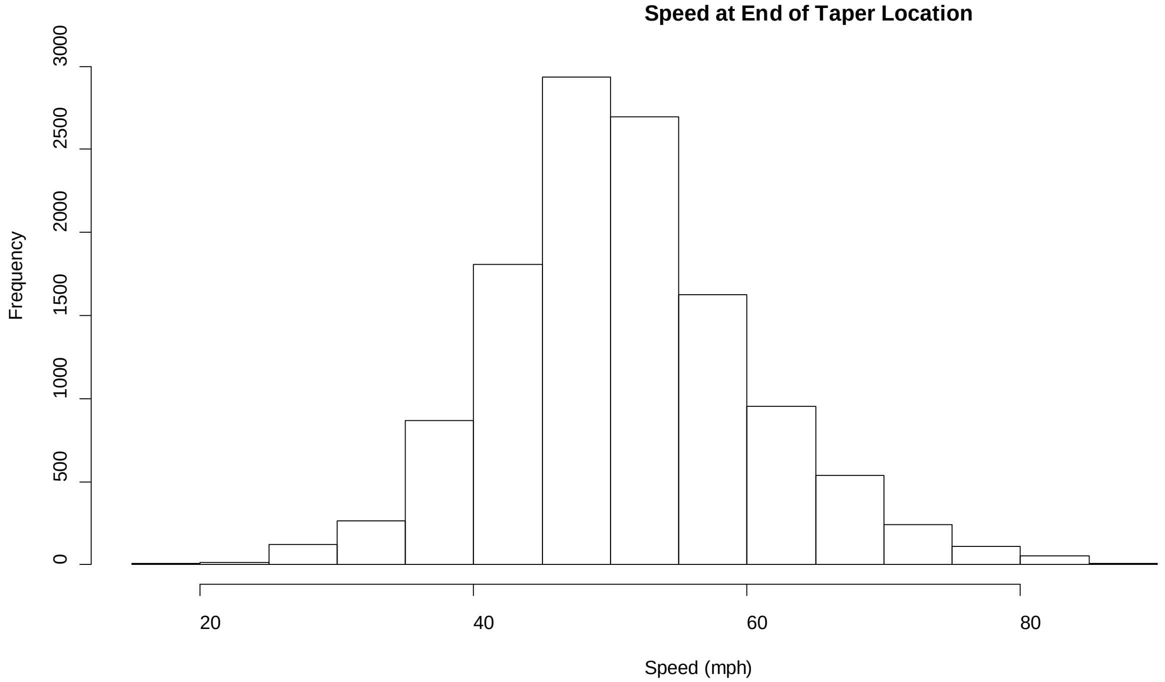

Figure 5.14: Speed Distribution at End of Taper Location for All Days (Case Study #2)

Two sample t-tests were applied to compare Treatments 2, 3, and 4 to Treatment 1. The results are shown in Table 5.8. Treatments 2 and 4 have higher means than Treatment 1. The differences are very small, less than 1.0 mph. Treatment 3 has a mean speed similar to that of Treatment 1. These results indicate that on average, for all types of vehicles, the mean speeds are very similar for all treatments.

Table 5.8: T-test Results for End of Taper Location Mean Speeds (Case Study #2)

	Mean Speed (mph) for Treatment	**Mean Speed (mph) for Treatment 1 (50 mph signs)**	**Difference in Mean Speeds**	**p-value**	**95% Confidence Interval**
Treatment 2 (50 mph signs and PCMS on trailers)	52.03	51.09	0.94	< 2.2e-16	(0.73, 1.15)
Treatment 3 (50 mph signs and radar speed reader)	51.24	51.09	0.15	0.14	(-0.05, 0.35)
Treatment 4 (50 mph signs, PCMS on trailers, and radar speed reader)	51.37	51.09	0.28	0.0078	(0.073, 0.48)

5.3.4.2 Hourly 85th Percentile End of Taper Speed vs. Treatments

In this comparison, the mean 85th percentile vehicle speeds from each hour of each day that were recorded by the end of taper sensors are used as dependent variables. The treatments are the independent variables. Pair comparisons using two-sample t-test were conducted, and the results are shown in Table 5.9. The results show that Treatment 2 and Treatment 3 have mean hourly 85th percentile speeds similar to that of Treatment 1 (p-value > 0.05). However, Treatment 4 has a mean hourly 85th percentile speed that is 5.95 mph lower than that of Treatment 1 at the end of taper location (p-value < 0.01). This result is statistically significant, and illustrates the significant impact of the added traffic control measures at this location.

Table 5.9: T-test Results for Hourly 85th Percentile End of Taper Speeds (Case Study #2)

	Mean of Hourly 85th Percentile Speed (mph) for Treatment	**Mean of Hourly 85th Percentile Speed (mph) for Treatment 1 (50 mph signs)**	**Difference in Mean Speeds**	**p-value**	**95% Confidence Interval**
Treatment 2 (50 mph signs and PCMS on trailers)	62.95	62.25	0.7	0.45	(-1.20, 2.61)
Treatment 3 (50 mph signs and radar speed reader)	61.87	62.25	-0.38	0.73	(-2.57, 1.81)
Treatment 4 (50 mph signs, PCMS on trailers, and radar speed reader)	56.30	62.25	-5.95	4.17e-06	(-7.99, -3.90)

5.3.5 Work Zone Speed vs. Treatments (Case Study #2)

In addition to the speed at the end of the taper, the speed in the work zone was also of interest. The next set of statistical analyses involved the speeds recorded by the 1st, 2nd, and 3rd sensors placed in the work zone.

5.3.5.1 Mean Work Zone Speed vs. Treatments

The first analysis focused on the mean speed. In this case, the mean speed used in the analysis was the mean speed from the first and second WZ sensors combined. The third WZ sensor data was excluded due to its occasional proximity downstream of the end of the paving as described above. The results, shown in Table 5.10, reveal that Treatments 2 and 3 have higher mean speeds than Treatment 1 (2.67 and 2.82 mph higher, respectively). While not as big a difference, Treatment 4 also had a slightly higher mean speed than Treatment 1 (0.58 mph higher). These differences were found to be statistically significant.

These results are surprising, especially after seeing the results of the comparisons at the end of the taper. It was expected that the speeds in the work zone would be less with treatments 2, 3, and 4 applied. The unexpected result may be due to the timing in which the data was collected. Treatment 1 (50mph signs only) was applied on Day 1 (Sunday) and Day 5 (Monday). Day 1 was the first day of mainline paving in the northbound direction. It also started at milepoint 37, which was the start of the work limits for the project (the work extended from milepoint 37 to 43). The local motorists on this day may have driven slower because they were not yet used to the presence of the work zone. They may have had more familiarity with the work zone later in the project, and therefore driven faster. Another reason for the unexpected result could be the day of the week. While Treatment 1 was applied on a Sunday and Monday, the other treatments were applied on either Tuesday, Wednesday, or Friday. Lower speeds may occur earlier in the week.

Table 5.10: T-test Results for Work Zone Mean Speeds (Case Study #2)

	Mean Speed (mph) for Treatment	**Mean Speed (mph) for Treatment 1 (50 mph signs)**	**Difference in Mean Speeds**	**p-value**	**95% Confidence Interval**
Treatment 2 (50 mph signs and PCMS on trailers)	43.03	40.36	2.67	< 2.2e-16	(2.27, 3.06)
Treatment 3 (50 mph signs and radar speed reader)	43.18	40.36	2.82	< 2.2e-16	(2.44, 3.19)
Treatment 4 (50 mph signs, PCMS on trailers, and radar speed reader)	40.94	40.36	0.58	0.0023	(0.21, 0.95)

5.3.5.2 Hourly 85th Percentile Work Zone Speed vs. Treatments

For this analysis, the mean 85th percentile speeds from each hour of each day recorded by the first and second WZ sensors are used as dependent variables. The treatments are the independent variables. Pair comparisons using t-tests were conducted, and the results are shown in Table 5.11. The results show that Treatment 2 and Treatment 3 have larger mean 85th percentile speeds than Treatment 1, and Treatment 4 has a similar mean to Treatment 1. These are unexpected results similar to that found from the analysis of the mean vehicle speeds.

Table 5.11: T-test Results for 85th Percentile Work Zone Speed (Case Study #2)

	Mean of 85th Percentile Speed (mph) for Treatment	Mean of 85th Percentile Speed (mph) for Treatment 1 (50 mph signs)	Difference in Mean Speeds	p-value	95% Confidence Interval
Treatment 2 (50 mph signs and PCMS on trailers)	53.08	49.39	3.69	0.008	(0.99, 6.38)
Treatment 3 (50 mph signs and radar speed reader)	52.68	49.39	3.29	0.012	(0.75, 5.83)
Treatment 4 (50 mph signs, PCMS on trailers, and radar speed reader)	50.23	49.39	0.84	0.52	(-1.78, 3.47)

5.3.5.3 Percentage Reduction in Speed vs. Treatments

The next analysis uses the mean speed of each day at the before the RWA signs location as the reference speed to get the percent reduction in speed in the work zone. It is intended to evaluate the effects of the work zone with the treatments compared to the free-flowing condition prior to when the motorists are notified of the work zone. Similar to above analyses, the work zone speeds from the first and second WZ sensors were used. For the statistical comparison, the percent reduction in speed is then used as the dependent variable and the treatments as the independent variable. This analysis is designed to identify those treatments which slow down the traffic to the greatest extent compared to the speed prior to the vehicles becoming aware of the work zone. The results are shown in Table 5.12.

Table 5.12: T-test Results for Work Zone Mean Speed Percentage Reduction (Case Study #2)

	% Reduction in Mean Speed for Treatment	% Reduction in Mean Speed for Treatment 1 (50 mph signs)	Difference	p-value	Confidence interval
Treatment 2 (50 mph signs and PCMS on trailers)	24%	29%	-5%	< 2.2e-16	(-0.057, -0.043)
Treatment 3 (50 mph signs and radar speed reader)	23%	29%	-6%	< 2.2e-16	(-0.066, -0.052)
Treatment 4 (50 mph signs, PCMS on trailers, and radar speed reader)	27%	29%	-3%	< 2.2e-16	(-0.034, -0.021)

5.3.5.4 Summary of Work Zone Speed Data

Table 5.13 shows a summary of the mean and standard deviation of the work zone speed (first and second WZ sensor data) for the I-5 Rock Points – Seven Oaks project. The table also shows the total traffic volume recorded on the two days in which the treatment was applied. It should be noted again that the time period in which data was collected for the Sunday application of Treatment 1 was limited to a shorter timeframe (23:00-05:00) than on all of the other days of testing. The comparison of mean speeds, and likely reasons for the differences, are described above. Standard deviation is an indication of the variance in vehicle speeds. As shown in the table, the results indicate that Treatment 4 resulted in the lowest variance in vehicle speeds, although the mean speed of Treatment 4 is not the lowest. This difference in variance may explain why the 85th percentile speed for Treatment 4 is much lower than that for Treatment 1, even though Treatment 1 showed the lowest mean speed.

Table 5.13: Mean and Standard Deviation for Work Zone Speed (Case Study #2)

	# of times treatment applied	Total traffic volume during time period analyzed, both days	Mean Speed (mph)	Standard Deviation
Treatment 1 (50 mph signs)	2 (Sun./Mon.)	2,517	40.36	10.45
Treatment 2 (50 mph signs and PCMS on trailers)	2 (Mon./Fri.)	3,333	43.03	11.30
Treatment 3 (50 mph signs and radar speed reader)	2 (Tues./Tues.)	3,642	43.18	10.62
Treatment 4 (50 mph signs, PCMS on trailers, and radar speed reader)	2 (Wed./Wed.)	3,488	40.94	9.99

5.3.5.5 Evaluation of Speed Relative to Work Zone Elements and Paving Locations

As described above, the speed data recorded suggests that the traffic typically slows down as it approaches the significant amount of work activity and lighting surrounding the paver. A similar decrease in speed is assumed adjacent the grinder. In addition, the data suggests that after the vehicles pass the initial PCMS sign and radar speed reader display located at the end of the taper, vehicle speed increases. Analyses of the videotape recordings of the work zones along with the speed data were conducted to further investigate the impacts of the distance to the paving work and end of taper. Table 5.14 shows the work zone elements and paving locations for each day of testing, along with notes/comments related to the vehicle speeds on each day. Analysis of the speed data for each day reveals the following:

- *Day 1 (50 mph signs only)*: The paving work concluded very close to the location of the second WZ sensor. On this day, the lowest speeds recorded by the second WZ sensor were recorded between 4:00am – 5:00am, at approximately the time when the paving work completed and the paver was at the location of the second WZ sensor. This result provides further evidence that vehicle speeds drop as the vehicles approach the paver.

- *Day 2 (50 mph signs and PCMS)*: The first WZ sensor was located a long distance (2.6 miles) downstream of the end of taper where the PCMS sign was placed.

Speeds recorded by the first WZ sensor for the entire night were high. The impact of the PCMS sign on driver speed likely diminishes as the vehicles travel farther downstream. Therefore, the high speeds recorded at the first WZ sensor on this day are expected.

- *Day 4 (50 mph signs, PCMS, and radar speed display)*: Similar to Day 1, the paving work concluded relatively close to the location of the second WZ sensor. The lowest speeds recorded at the second WZ sensor amongst all days were recorded on Day 4.

- *Day 8 (50 mph signs and PCMS)*: The vehicle speeds recorded on this day by the first WZ sensor were relatively high. On this day, the first WZ sensor was located a long distance (1.8 miles) from the end of taper where the PCMS sign was located.

Table 5.14: Work Zone Elements and Paving Locations (Case Study #2)

Testing Day	Work Zone Element Locations (milepoint)						Paving			Notes/Comments
	50 mph ahead signs	50 mph signs	Start of taper	End of taper	1st WZ sensor	2nd WZ sensor	Location (milepoints)	Lane paved	Time	
Northbound Paving										
Day 1 (50 mph signs)	35.5	36.0	36.2	36.4	37.2	38.0	36.6 - 38.2	A (fast lane)	9:40pm – 5:30am	• Data recorded from 11:00pm – 5:00am; on other days from 9:00pm – 5:00am • 2nd WZ sensor very close to end of work; recorded lowest speed from 4:00am – 5:00am
Day 2 (50 mph signs and PCMS)	35.5	36.0	36.2	36.4	39.0	40.0	38.2 - 40.5	A (fast lane)	9:40pm – 6:30am	• Taper location changed during work shift to approximately MP 38. • PCMS on road at approximately 10:00pm • 1st WZ sensor far away from taper; speeds recorded for entire night were high • 2nd WZ sensor recorded highest speed among all days
Day 3 (50 mph signs and radar speed display)	35.5	36.0	40.2	40.3	41.2	42.0	40.5 – 43.0	A (fast lane)	8:25pm – 6:30am	• Radar speed display at end of taper location, and on road before 9:40pm • Radar speed display moved downstream in middle of night

Day 4 (50 mph signs, PCMS, and radar speed display)	35.5	36.0	36.2	36.4	37.2	38.0	36.6 - 38.3	B (slow lane)	10:30pm – 4:30am	• PCMS and radar speed display on road before 9:00pm • Grinder started before 6:30pm, but paver started late • 2nd WZ sensor close to end of paving work • Day 4 has lowest 2nd WZ speed
Day 5 (50 mph signs)	35.5	40.1	40.2	40.4	41.5	42.2	40.5 - 42.7	B (slow lane)	8:10pm – 4:00am	• Did not complete all of northbound lane (400 feet remaining); road closure needed in both directions on next day
Southbound Paving										
Day 6 (50 mph signs and radar speed display)	45.3	43.6 (after taper)	44.0	43.8	43.0	42.4	43.0 – 41.0	A (fast lane)	9:50pm – 5:00am	• SB lane closure started at 8:00pm; paving on SB started at 10:00pm • Radar speed display at end of taper, and on road before 9:30pm • 50 mph signs placed after taper, and before the beginning of the work • Radar speed display moved closer to work at 12:00am
Day 7 (50 mph signs, PCMS, and radar speed display)	45.3	41.6	41.6	41.4	40.4	39.4	41.0 - 38.7	A (fast lane)	7:00pm – 4:30am	• 50 mph signs, PCMS, and radar speed display on road at approximately 10:30pm
Day 8 (50 mph signs and PCMS)	45.3	40.4	40.0	39.8	38.0	37.6	38.7 - 36.6	B (slow lane)	8:00pm – 5:00am	• PCMS on road before 9:00pm • 1st WZ sensor located far from end of taper

6.0 CONCLUSIONS

The research activities conducted in the present study provide additional insight on the impact of selected traffic control measures in high speed work zones. The study was intended to enhance the data previously collected on specific treatments from the SPR-751 study, and provide guidance to ODOT on how to design traffic control plans for work zones. Following the results of SPR-751 study, the present study aimed to:

- More accurately determine the effectiveness of traffic control measures (TCM) and improve confidence in moving forward with recommendations
- Collect additional speed data to better identify the advantages of one TCM over another
- Record speeds further upstream of RWA 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

Conducting such research requires multiple controls to address both internal and external validity, and increase confidence in the study results and recommendations for future practice. As indicated previously, the two case study projects included in this research provided an opportunity to collect field data related to the use of different traffic control measures on vehicle speeds in highway work zones. The case study projects were different in that the I-5 Glendale – Hugo project (Case Study #1) took place in a hilly section of I-5 while the I-5 Rock Point – Seven Oaks project was on a straight, flat section of roadway. The complexity of the roadway sections on the I-5 Glendale – Hugo project prohibited accurate comparison with those on the I-5 Seven Oaks – Rock Point project. Therefore, the data for the projects could not be aggregated for analysis.

In addition, the complexity of the I-5 Glendale – Hugo project limited comparisons of different datasets within the case study project itself. Even though the testing matrix was designed to allow for replication of many of the treatments, a review of the speed data collected along with the roadway conditions precluded comparing some treatments. The differences between the roadway test sections on each day of testing limited confidence in comparisons for some treatments. Comparisons between different treatments could only be made when the treatments were applied on the same sections of roadway. This limitation did not exist on the I-5 Rock Point – Seven Oaks project.

The following conclusions can be made from the graphical and statistical analyses of the data from the two case study projects presented above.

Vehicle type and speed distribution:

Vehicle speeds are normally distributed overall for the two case study projects. The largest percentage of vehicles on the two sections of roadway studied are those which are less than 25 feet in length.

Vehicle speed entering work zone:

Vehicle speeds one mile upstream of the RWA signs are typically similar to those at the location of the RWA signs. For example, for all eight days of the I-5 Rock Point – Seven Oaks project (Case Study #2), the speeds at the two locations are almost the same. Specifically, for the first five days of the case study, the difference in mean speed is statistically significant, yet the maximum difference is only 0.6 mph (lower mean speed at RWA signs). The drivers slowed down prior to the work zone, but the decrease in speed was very minimal on average. For the last three days of the case study, the difference in mean speed is not statistically significant (p-values = 0.93, 0.061, and 0.71).

Vehicle speed relative to construction equipment:

Vehicle speed tends to decrease as the vehicles approach the paver. However, there is no clear evidence that the rate of decrease is impacted by the traffic control measure used. The minimum 85th percentile vehicle speed, which was typically 5 – 10 mph less than the posted 50 mph regulatory speed, usually occurs in the general vicinity of the paver; however there is no clear evidence that the minimum 85th percentile speed at the paver is impacted by the traffic control measure used.

Immediately downstream of the paver, vehicle speeds typically begin to increase. The rate of increase in speed is not consistent with any specific traffic control measure.

Hence, the results of the present study and prior study (SPR-751) reveal that vehicle speed is typically the lowest in the vicinity of the paver. The researchers believe that this decrease in speed is likely due in part to the presence of the paver with its bright lights along with the extensive activity of all of the nearby workers and equipment. Drivers are more cautious and slow down in the presence of extensive equipment, lighting, workers, and activity. A decrease in vehicle speed at the paver occurs regardless of the traffic control measures selected for use. This is an important finding as it suggests that the traffic control treatments implemented may not affect the driving behavior of many drivers in a measurable extent. In addition, it suggests that a large amount of lighting (that does not create glare for the motorists and equipment operators), along with an active work area, are beneficial.

Proximity of travel lane to work area:

When the travel lane is further away from the work taking place, vehicle speed is typically higher. For example, when the contractor paved the roadway shoulder and also closed the slow lane, vehicle speed in the fast lane through the work zone was approximately 3.5 mph higher than when the travel lane was immediately adjacent the paving work. For the same comparison, at the end of the taper, vehicle speed was approximately 1.5 mph higher when the contractor paved the shoulder and closed the slow lane compared to when the travel lane was immediately adjacent the paving work.

The research study did not explore the relationship between the extent of equipment and workers in the work area (i.e., how sparse or crowded the work area is) and the potential severity of impact if an incident occurs. It is expected that severity of impact will vary with both vehicle speed and the presence of equipment in the work area to deflect and/or slow the errant vehicle. Further investigation into this issue is recommended to assess the risk associated with expanding the size of the work zone.

Impact of taper:

End of taper vehicle speeds are typically lower than beginning of taper speeds. For the I-5 Rock Point – Seven Oaks project (Case Study #2), the end of taper speeds ranged from 1.52 to 2.58 mph less than the beginning of taper speeds for all eight days of testing. Vehicle speed did not sharply change from the beginning to the end of the taper. This conclusion will depend on the volume of traffic on the roadway and the location in which drivers typically merge relative to the location of the taper.

Tendency for late merging in taper:

The results indicate that the tendency to speed up and merge at the last second just prior to the end of the taper is not prevalent during these nighttime operations. The vehicles present in the closed lane at the beginning of the taper (at the location of the first drum starting the taper) did not speed up significantly in order to merge into the through lane. In addition, there was no evidence of vehicles slowing down in the taper due to a prevalence of late merging.

Proximity of TCMs to work activity:

At the end of taper location on the I-5 Rock Point – Seven Oaks project (Case Study #2), the lowest 85th percentile vehicle speed occurred with the combination of 50 mph signs, PCMS signs on trailers, and radar speed reader display (Treatment 4). This speed was 5.95 mph lower than the 85th percentile speed at this location when just the 50 mph speed signs were used.

When the PCMS signs on trailers and radar speed display were used, they were typically located after the end of the taper and before the start of the paving area. The drivers could see these TCMs as they approach the end of the taper (beginning of the work area). The presence of these TCMs along with the paver, workers, and other equipment at the beginning of the work shift likely contributed to the reduction in speed at this location. Later in the work shift, as the work progressed downstream of the end of taper, the TCMs were not necessarily located so close to all of the work activity. Keeping these TCMs in close proximity to the work activity is a good practice for reducing speeds immediately prior to and at the location of the work activity. For this study, the TCMs were typically located approximately 1,500 feet before the work area. The optimal distance between the TCMs and work area was not targeted as part of the study, and the data collected does not provide sufficient data to accurately calculate a recommended maximum distance. An important question is at what distance after the TCM does vehicle speed tend to increase when there is a large distance between the TCM and workers. Knowing this distance will provide guidance on optimal spacing and location of TCMs. This information would be of value in the ODOT PCMS handbook. The MUTCD should be consulted to identify a recommended distance, or further research conducted.

Timing of placement of the TCMs:

Within the length of the work zone on the I-5 Rock Point – Seven Oaks project (Case Study #2), the treatment with just the 50 mph signs had the lowest mean speed and the lowest 85th percentile speed compared to the other treatments. This result is not expected. Based on the results of the prior research study (SPR-751), the impact of the additional TCMs at the end of the taper on this case study project, and literature reviewed, it is expected that the additional TCMs would lead to lower speeds within the work zone.

Review of the video taken while driving through the work zones showed that the 50 mph signs were placed at multiple locations along the work zone (approximately every 0.5 – 1 mile). The additional TCMs (PCMS signs on trailers and radar speed reader display) were initially located just downstream of the end of taper, and later moved downstream after the work progressed up the roadway. However, the timing when these TCMs were moved and the new location of the TCMs relative to the paver, were not consistent from one day to the next. On some days when the crews were busy, relocation of the TCMs may have been delayed. This delay is reflected in the vehicle speed data collected and, therefore, the speeds recorded on these days may not reflect the actual capability of the TCMs to impact speed. Without the delay in placement, the vehicle speeds on the days with the additional TCMs present would likely be less than those on the days with just the 50 mph signs. Thus, the research results take into account the variability in the application of the TCMs. That is, the nature of the work is such that the TCMs may not be placed at the same time every day due to construction-related impacts. This confounds the analyses in which one day is compared to another. Therefore, this result indicates the importance of proper planning and execution of the traffic control plan on a daily basis. A well-organized and efficient contractor can help increase the value of the TCMs implemented.

Presence of active work and TCMs:

The impact of the additional TCMs in reducing vehicle speed may diminish as the vehicle travels in the work zone away from the TCMs. Driver attention span will influence the length of time in which the TCM affects driver behavior. No literature on the duration of driver attention span in work zones was found. This may be true especially if there are no or limited workers and equipment visible in the work zone downstream of the TCMs.

This result related to speeds in the work zone, along with the impact of the TCMs at the end of the taper on speeds at the end of the taper as described above, indicates a need to locate the PCMS signs and radar speed reader displays as close to the active work area as possible in order to realize their greatest value. PCMS signs on rollers, rather than on trailers, are especially valuable as they enable keeping the signs close to the active work area. Additionally, greater value would be realized if multiple radar speed reader displays are placed at multiple locations throughout the work zone. If more than one radar speed reader display is not available, special attention should be given to frequently moving the radar speed reader to ensure that it is located a close distance upstream of the active work area as the work progresses up the roadway.

Variance in vehicle speeds:

Within the length of the work zone on the I-5 Rock Point – Seven Oaks project (Case Study #2), the variance in vehicle speed was the lowest for the treatment consisting of the combination of the 50 mph signs, PCMS signs on trailers, and radar speed reader display. As indicated in the analyses above, the variance was calculated by combining all of the speed data from all of the days in which a treatment was applied. In addition, the roadway geometry for this case study was such that no impacts from roadway conditions are expected. The difference in vehicle speeds as the vehicles travel through the work zone is an important indicator of safety in the work zone. A high variance in speed between vehicles can create hazardous conditions, especially in a work zone where there are many driver distractions and only one lane available for traffic flow.

Project complexity and ability to rank TCMs:

Ranking of the treatments in terms of their effectiveness based on the data available and analysis was not performed. The analysis limitations as a result of the complexity of Case Study #1 do not allow for accurately ranking the treatments. In addition, the differences in treatment performance are relatively small.

7.0 RECOMMENDATIONS

The results of the current research study provide an opportunity to more confidently recommend the use of specific traffic control measures on highway paving projects in practice. The results of the present study, especially those from the I-5 Rock Point – Seven Oaks project (Case Study #2), along with the results of the prior study (SPR-751), provide a clearer picture of the impacts of the selected TCMs on vehicle speed and the practicability of implementing the TCMs on highway preservation projects. The recommendations, limitations, and further research described below are based on the results of both studies.

7.1 RECOMMENDED TRAFFIC CONTROL DEVICES

A variety of traffic control measures are available for use in work zones. The research shows that some TCMs work better than others for reducing and maintaining vehicle speeds through the work zone. It is important to remember that, in addition to reducing vehicle speed, other factors related to vehicle speed should be considered when selecting TCMs for use in a work zone, such as speed variability. To get maximum value, the TCMs also need to be located and oriented in a manner that takes into consideration the physical features of the roadway, traffic characteristics, and environmental conditions. Additionally, consideration needs to be given to the ease with which the TCMs can be implemented, the cost and availability of the TCMs, the safety hazards created during their implementation, and the applicability to the project at hand. Multiple criteria need to be considered when selecting TCMs for a project. In practice, ODOT personnel may identify a case where TCMs may be very costly or cumbersome to implement, but may be the best or the only option to reduce speeds and therefore should be selected for use. The recommendations provided below are made primarily with the goal of reducing speed and speed variability in mind. The SPR-751 final report provides additional information related to other selection criteria such as cost, ease of implementation, and availability which also should be considered.

Multiple prior studies, including SPR-751, show that police officer presence is a highly effective means of reducing vehicle speeds. If sufficient resources are available, police presence should be included as part of the traffic control plan. Police presence has been shown to reduce traffic speeds more than other TCMs. For example, one study showed that a parked police vehicle with lights on will cause a reduction in speed of 5 - 7 mph, and when the police officer is patrolling, the reduction will be 2 - 4 mph *(Ullman et al. 2010).*

When utilized, the police officer should park his/her vehicle on the site near the end of the taper with red/blue lights flashing. The vehicle should be situated such that it is clearly visible to oncoming traffic and also stands out from the construction work. The officer should also re-locate downstream periodically as the work progresses down the roadway. Maintaining a close distance just prior to the active work area is important to ensure that, after passing the police vehicle, the drivers do not speed back up in the work area. A second parked vehicle located approximately a half mile downstream of the active equipment will also help decrease the amount of speeding up that occurs after the vehicles slow down while they pass the equipment. One or more additional police officers patrolling the work zone will further control and minimize traffic speeds through the length of the work zone. Inclusion of police officer presence as part of traffic control plans should be considered regardless of the other TCMs included in the traffic control plan.

The research also suggests that, if used, police presence may not necessarily need to be within the work zone. For example, a police vehicle parked prior to the work zone will slow down traffic at the location of the police vehicle and for a distance downstream. The residual effect on the vehicle speeds may carry into and through the work zone. Further research on the impact of police presence upstream of the work zone is needed.

In the present study, when the PCMS sign on trailer and radar speed reader display were used together in combination, the recorded 85th percentile speed at the end of the taper was lower than for other treatments. Their presence near the end of the taper just prior to the work area revealed a decrease in vehicle 85th percentile speed of approximately 6 mph at the end of the taper. No similar significant impact on vehicle speed was found when each of these TCMs was used independently. Use of a PCMS sign on a trailer together with a radar speed reader display near the end of the taper according to the ODOT PCMS Handbook is recommended. The trailer and display should be placed in the buffer area after the end of the taper and immediately prior to the work starting point. Care should be taken such that the equipment is not placed too close together. Sufficient distance (at least 1,000 feet) between the PCMS and radar speed display should be provided so that drivers are able to view and process the information displayed on the equipment. The messages on the PCMS sign should clearly alert the motorists of the worker on the roadway and instruct the drivers to slow down. The following are suggested messages: “Slow for Workers”, “Workers on Roadway”, and “Narrow Lane”.

The research reveals that the impact of the PCMS sign on trailer and radar speed display diminishes as the vehicles progress downstream of these TCMs (i.e., the drivers speed up after traveling a distance down the roadway past the TCMs). To help maintain slower speeds adjacent the active work area, the use of PCMS signs on rollers is recommended. Placement of PCMS signs on the rollers ensures that the signs will maintain a close distance to the active work area. There is little difference in vehicle speed; however the benefit of placing the PCMS signs on the rollers (instead of on stationary trailers) is that, when on rollers, the signs stay up with the paver as the operation moves up the roadway. Similar PCMS signs on other equipment closer to the grinder, such as on the tack truck and sweeper, are recommended as well. Their presence on the other equipment would help reduce the cost of a TCS periodically moving the PCMS signs downstream as the work progresses. Messages similar to that mentioned above are recommended.

If PCMS signs on rollers are not available, and if sufficient space is available in the median or shoulder, placing additional PCMS signs on trailers and radar speed displays at multiple locations within the work zone, such as every 0.5 miles, is recommended. Placing these TCMs at different locations along the work zone may only be feasible if sufficient space is available in the median or shoulder. These TCMs should be in place prior to the time when the work reaches the TCM locations. It is also important to remember to provide enough distance between the PCMS signs, radar speed monitoring displays, and other roadway signs to eliminate driver confusion. Many signs, pieces of equipment, lights and other work zone features in the work zone may be overwhelming for motorists, especially when the drivers are trying to merge lanes or steer clear of construction equipment entering or exiting the work area.

In addition to being located near the paver, grinder, and other equipment, the presence of effective TCMs is also needed for workers who are on the roadway and not near the equipment, such as the inspector taking density measurements or the worker placing “stick-n-stomp” lane markers on the roadway. To help slow down vehicles adjacent these workers and alert drivers of the presence and location of the workers, placing an additional PCMS sign where the workers are present is recommended. One way to do this is to have a PCMS sign on a trailer hooked up to the worker’s vehicle, which is then parked immediately upstream of where the worker is working on the newly paved lane or in the shoulder or median. The vehicle and trailer can then be moved along with the worker as the worker moves down the roadway.

It is important to make the workers present on the roadway visible to the passing motorists. Those workers typically on the roadway and located away from the major equipment are inspectors, traffic control personnel, and other construction crew members placing temporary lane markers and conducting quality control. To make these workers more visible, sufficient lighting is needed and the workers must wear approved reflective clothing. The use of portable lighting wherever workers are present is recommended. The amount of lighting should be enough to effectively illuminate the workers without creating disabling glare for the motorists. The final report from SPR-617 “Optimum Illumination for Nighttime Flagger Operations” provides guidance on the types and amount of lighting for use in mobile operations.

Where the roadway conditions permit, creating additional buffer between the work and travel lane is recommended. Examples of this buffer are when the slow lane is closed to traffic during paving of the shoulder, when the fast lane is closed during paving of the median, and when the fast lane in the opposite travel direction is also closed due to a narrow median. Closing an additional lane pushes the passing traffic away from the workers. This buffer helps to reduce the safety hazards for the construction workers. In addition, as revealed in the I-5 Rock Point – Seven Oaks project, traffic passing through the work zone when a buffer is present, travels at a slightly higher rate of speed. In the I-5 Rock Point – Seven Oaks case study project, this increase in speed was measured to be approximately 1.5 to 3.5 mph.

Lastly, 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 very large amount of data was collected on the case study projects as part of the present research study. Many efforts were made by the researchers to control confounding factors which could limit the ability to generalize the results to other ODOT projects and maintain confidence in the results. As with all research studies, limitations in applying the results exist. The researchers prepared testing plans before the start of each case study project to minimize confounding factors. However, the plans needed to be changed during the course of each case study project to account for the paving progress and other project conditions. Additionally, the implementation of traffic control devices and the placement of traffic analyzers went well on most days, but were impacted by the work on other days. All of these factors can make the data collected from each day unique and difficult to compare to that recorded on other days.

During the course of the study, the weather conditions did not impact the construction work or research activities. Poor weather was not present, and thus did not influence driver behavior. However, good weather may not always be the case in future work. Poor weather conditions will increase the chance of an accident and may impact the performance of some TCMs. Further investigation of the weather impacts on TCMs is needed to determine how to adjust a TCP based on weather conditions.

As described above, some of the speed sensors were found to be inaccurate. The testing and verification of the sensor accuracy that was conducted enabled adjusting the recorded speeds to increase the accuracy of the results. Although adjustments in the recorded speeds were made, and the speed data appears normal after the adjustment, the lack of consistent results may be a result of the inaccuracy of the sensors. As indicated above, the accuracy of speed measurements stated by the sensor manufacturer is +/- 4 mph, 90% of the time.

The roadway conditions on the I-5 Glendale – Hugo case study project limited the ability to gain useful results from this project. The uphill/downhill and curvy sections of the roadway prohibit identifying the impact of solely the TCMs on some days. For example, slow speeds may have been the result of slowly moving trucks on an uphill section of roadway as opposed to the TCMs implemented. Similarly, on downhill sections, the speeds may have been faster than normal due to the downhill grade. The mix of trucks and cars (approximately 35% and 65%, respectively, on all days combined) on the hilly sections may create greater speed variability between the vehicles as well. As a result, comparisons of the speed data within this case study project, and to the data from the I-5 Rock Point – Seven Oaks project, are limited. For future ODOT projects in hilly/curvy areas, it is recommended that TCP designers and contractors pay special attention to uphill and downhill grades, especially with regard to visibility as vehicles approach and travel through the hills/curves. Additional traffic control devices should be added at locations where visibility is minimized, where very slow vehicles may be present on uphill grades, and at the top of and throughout downhill grades. Temporary speed bumps may effectively provide the needed warning at such locations and should be further investigated.

Other recommendations related to research methods based on the researchers' experience on both the present and prior studies 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. Additional research efforts and/or testing equipment would likely be needed in order to collect the appropriate data to make these measurements.

- 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. Utilizing the driving simulator may be beneficial for single projects as well. For example, the scope and budget of a very large, complex, and long-term project may allow for testing specific TCPs using the driving simulator prior to the start of construction in order to optimize the TCP design.

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

7.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The present research study concludes the second phase of research on how to reduce vehicle speeds on high speed preservation projects. Multiple traffic control measures were tested and evaluated, with replication of each TCM on different case study projects. Further research on each of the TCMs evaluated in the present study is not recommended at this time. Other TCMs are available for use which were not evaluated as part of the present or prior research study. Examples of other TCMs that are available for use are: temporary rumble strips, speed photo enforcement, work zone intrusion alarms, and drone radar systems. Advanced worker personal protective equipment, such as hats and vests with LED lights attached, are also available and recommended for further study. An additional treatment that has been suggested is the placement of advisory speed signs recommending speeds less than 50 mph (such as 35 mph) at multiple locations within the work zone in addition to the regulatory signs reducing the speed to 50 mph. The advisory signs would further help to reduce vehicle speed without the need for additional reductions in the regulatory speed. Lastly, for large projects, and where the roadway profile consists of many hills and curves, additional media announcements and OSP involvement during high traffic weekends should be considered. Further research on these and other types of TCMs available would be valuable.

The research results revealed that the presence of large equipment on the roadway with multiple workers nearby like the paver has an impact on vehicle speed. Further research on this result could reveal some valuable information. Of interest as well are the distance before the equipment in which the vehicles start slowing down, and the distance away from the paver in which they are back up to their previous speed. These distances, along with the recorded speeds, will indicate the rate of speed change. Knowing such distances allow traffic control designers the opportunity to plan where to place traffic control devices for optimal impact. Additionally, such information may allow contractors to plan the spacing of large pieces of equipment to prevent significant and periodic decreases and increases in speed through the work zone.

The presence of a buffer lane when paving the shoulder is another area of recommended research. When a buffer lane is provided, there is greater distance between the workers and passing traffic, yet this study reveals that the vehicle speed is greater. On the other hand, the speeds are slower yet the vehicles closer to the workers without the buffer lane. The results of this study are not sufficient to provide a clear recommendation for practice. A more detailed study of the risk associated with the buffer lane present compared to not having the buffer lane would be of interest.

A survey of state agencies regarding their work zone designs and the extent to which they use different types of traffic control devices in their work zones would also be of value. The survey would give ODOT new ideas for improving its work zones and also confidence that it is on the right track.

One of the critical issues that has been addressed in this and previous studies is the differential in vehicle speeds (speed variability). The amount of vehicle deceleration that occurs as a result of speed variability is particularly important. High levels of deceleration are likely indicators of hazardous work zones. In the present study, speed variability was analyzed by comparing speeds across the work zone. However, an assessment of speed variability amongst a group (“clump”) of vehicles traveling at the same time through the work zone at different points in the work zone is also needed. This research would focus on speed relative to the “nearest neighbor(s)”, i.e., speed variability of one vehicle compared to that of another nearby vehicle or vehicles. The results of the study would more accurately reflect the safety impacts of the actual speed variability on the roadway.

Further research is also recommended that focuses on selection of traffic control devices based on vehicle composition on the roadway. Previous research shows that, for example, trucks behave differently than passenger vehicles in terms of driver behavior. An additional study on how to tailor the traffic control measures to the expected vehicle composition on the roadway would be of value to further optimize the traffic control plan. For example, if the percentage of trucks on a specified day is known, perhaps different or additional traffic control measures can be planned and implemented on that day.

This study and SPR-751 target preservation projects. Pavement overlays are not the only type of preservation projects. Chip seals and guardrail repair/replacement are examples among others. Do the results of the current study apply to the other types of preservation projects also? It is expected that the results and recommended practices would be similar if the projects incorporate multiple, large pieces of equipment spread throughout the work zone and are mobile operations. Those projects that are more stationary in nature and which do not have a similar concentration of equipment may see different results. Therefore, further research is recommended to verify that the results apply to other types of projects as well.

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APPENDIX A

The appendices to the report are provided in a separate file titled “High Speed Reduction Report—Appendices.docs”.