AN ABSTRACT OF THE THESIS OF

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Title: Investigation of Effectiveness of Radar Speed Signs and Additional Lighting for Speed Control in Highway Construction and Maintenance Work Zones

Abstract approved:

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Salvador Hernandez John A. Gambatese

Every year thousands of people are killed or injured in work zone crashes in the US due to excessive speed, distraction, inattentiveness, low visibility, and other factors. Roadway construction and maintenance operations often occur at night when the traffic volume is low, creating less congestion and delay to the traffic. The operations commonly require 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. Nighttime brings a reduction in visibility for both workers and drivers. High speed roadways with low visibility and limited protection make an unsafe and dangerous situation for both motorists and workers.

Safely controlling and reducing vehicle speeds through work zones decreases the safety risk associated with highway construction and maintenance work. Work zone speed control has been the subject of several research efforts in the past. As such, various techniques and procedures have been tested and evaluated. These include, but are not limited to, variation of traditional fixed signage, changeable message displays, radar units with speed sign messages, and a range of electronic devices to sense and display information related to speed. The present research has been conducted to evaluate the effectiveness of a truck-mounted radar speed sign and additional lighting on speed control during construction and maintenance work.

The first phase of the research included evaluating radar speed signs (RSSs) as a speed reduction measure through work zones. RSSs have been known as a way to slow down the traffic flow speed. In this study, the influence of truck-mounted RSSs on vehicle speed for mobile maintenance operation has been tested. In this regard, truck mounted RSSs were employed in two, multi-lane maintenance work zones in the state of Oregon in the US. In each case study, the authors conducted two periods of testing: one with the RSS display turned on (treatment) and one without the RSS display turned on (control), and recorded vehicle speeds.

The second phase of the research involved investigating the impact of additional temporary lighting on vehicle speed in highway work zones. In addition, the impact of wearing personal lighting equipment was also examined during paving operations. Two common types of lighting equipment, a light tower and a balloon light, were set up in work zones and a personal, wearable light was used during two paving projects on

Oregon highways. Traffic speed and other vehicle and lighting data were collected on different nights when the lighting equipment was turned on and also when it was turned off.

Descriptive statistics were used in both studies to summarize collected data and to compare the speed difference between control and treatment cases. The research findings indicate that vehicle speeds are typically lower, and there is less variation in speeds between adjacent vehicles, with the RSS turned on. The results show that the RSS proves to be a promising device for controlling vehicle speed and making the work zones safer for both motorists and workers. Field observations confirmed that both additional temporary roadway lighting and personal lighting help to make workers more visible to motorists and equipment operators. Although a temporary light leads to slightly higher vehicle speeds, it makes the work zone and workers more visible for motorists and equipment operators. Statistical analysis revealed that there is no difference between mean vehicle speed with and without personal lights turned on. Personal, wearable lights are highly recommended for workers who are located away from large equipment and other light sources.

The results of this research can be used by DOT Construction and Maintenance Offices for planning construction and maintenance work. The research output can also be used by the Transportation Safety Divisions and Transportation Safety Coordinators within DOTs as a resource for effectively designing work zones and planning construction and maintenance operations.

Investigation of Effectiveness of Radar Speed Signs and Additional Lighting for Speed Control in Highway Construction and Maintenance Work Zones

by
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APPROVED:

Co-major Professor, representing Civil Engineering

Co-major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

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Ali Jafarnejad, Author

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1 INTRODUCTION

Every year thousands of people are killed or injured in work zone crashes in the US due to excessive speed, distraction, inattentiveness, low visibility, and other factors. In 2014, one out of every 100 roadway fatalities that occurred in Oregon happened in a work zone. From 2000 to 2014, there was an average of 473 work zone-related crashes each year in Oregon. Approximately 70% of work zone crashes occurred on interstate and state highways where vehicles travel at high rates of speed. Both roadway workers and motorists are exposed to the danger of being involved in an accident in a work zone (*1*). The Oregon Department of Transportation reports that, compared to other occupations, the risk of death is seven times higher for roadway workers than for the average worker in all work industries combined (*2*). Workers conducting mobile highway construction and maintenance operations experience a hazard that is absent on many other types of construction sites: high speed traffic travelling within a very short distance from the construction area, and often low visibility of workers.

Roadway work zone activities expose workers to the possibility of being in close proximity to vehicles travelling at high speeds. Highway construction and maintenance projects typically require workers to reduce traffic flow to a single lane while work is undertaken in an adjacent lane. In some cases, workers only have a line of cones and a few feet separating them from passing traffic. Areas of limited protection create considerable safety risk for both the workers and passing motorists.

Much of the construction and maintenance work that occurs on high-speed roadways takes place at night in order to minimize impacts to drivers. Research studies have pointed to a wide range of benefits associated with conducting construction work at night including reduced congestion and delay, decreased project duration, decreased material delivery time, and reduced economic impact of construction operations on the surrounding businesses (3-7). Despite these advantages, performing work at night also exposes workers to hazards that are not present or not as great during the daytime, such as the presence of impaired drivers, higher traffic speed, and lack of sufficient visibility for both workers and motorists (*3-7*). The loss of visibility for workers results in the need for supplemental lighting that satisfies the visibility requirements of workers. These requirements are determined by the work task and available contrast. The loss of visibility for drivers results not only from the absence of daylight and the inefficiency of headlighting, but also from the negative effects of glare produced by other vehicles, illuminated signs and other visual clutter, and possibly the illumination of the work zone itself (*8*). As a result, special measures are taken during nighttime work to protect workers and motorists in work zones. Examples of these additional safety controls are: workers wearing reflective clothing, flaggers using lighted STOP/SLOW paddles, use of illuminated signs for traffic control, and any traffic control devices to reduce vehicle speed.

The severity of crashes has been shown to increase as the speed of passing traffic increases (*9*). Accordingly, construction and maintenance projects on high-speed roadways present an increased risk of serious and/or fatal injuries to workers, motorists, and their passengers. Safely controlling and reducing vehicle speeds through work zones decreases the safety risk associated with construction and maintenance work. Studies show that there is little change in speed with only standard regulatory or advisory signs used to regulate speed in the work zones. Therefore, application of new techniques and strategies is essential to slow down traffic in the work zone and improve safety of all road users. These techniques and strategies include, but are not limited to, changeable message displays, radar units with speed sign messages, speed cameras, and a range of electronic devices to sense and display information related to speed. The most effective speed reduction will probably involve some combination of speed reduction and control techniques instead of using just one type of control measures. Research has been conducted to identify best practices and means for traffic control and speed reduction during construction and maintenance nighttime work.

One means of affecting driver behavior and reducing speeds that has shown promise is the use of radar speed displays. These units use radar technology to measure the speed of oncoming vehicles and display the vehicle speed to the drivers. The vehicle speed is usually displayed along with the regulatory or advisory speed and/or a message alerting the drivers to use caution.

In addition, the potentially positive impact that work area lighting can have on visibility could be promising for speed control and safety in a work zone. Adding lighting to areas where the construction or maintenance equipment, and typical work area lighting, are currently not present may be a low cost means of making motorists more aware of workers on the roadway, reducing vehicle speeds throughout the work zone, and further protecting workers on the roadway.

Although radar speed signs and work zone illumination guidelines and lighting specifications do exist, the impact of these devices on passing vehicle speeds during mobile operations has not been investigated. This thesis contains two standalone papers that focus on speed control in highway work zones: the effectiveness of radar speed sign in mobile maintenance operations, and the impact of temporary portable work zone lighting on vehicle speeds in highway construction projects.

1.1 Organization of Thesis

This thesis is divided into four parts. Following this introductory section are two documents that address speed control measures in high speed roadway work zones. The first document (chapter two) contains a paper presenting research involving an investigation of highway maintenance project speed control by implementation of truck-mounted radar speed signs. Maintenance projects are short-term projects that involve sweeping, drainage cleaning operations, guardrail repair/replacement, and similar operations. The study was designed to quantify the impact of the displays on vehicle speeds in maintenance work zones and identify best practices for their use as part of maintenance work operations.

The second document (chapter three) includes a paper which details the evaluation of the impact of additional temporary work zone lighting on vehicle speeds. Implementation of additional lighting is expected to reduce the risk exposure of workers and motorists, lead to fewer worker injuries and fatalities in work zones, and improve mobility through work zones. The study includes case studies on multi-lane preservation projects in Oregon in which different types of lighting systems were implemented: a light tower, balloon light, and a personal, wearable light.

The final chapter summarizes the major findings and contributions of the work with respect to vehicle speed reduction and control in work zones. Practical applications of the results and implications for future research are also discussed.

This thesis is based on two research projects funded by Oregon Department of Transportation (ODOT). Further details of each project can be found in the full research reports published by ODOT whose addresses are provided in the Appendix.

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2 INFLUENCE OF TRUCK-MOUNTED RADAR SPEED SIGNS IN CONTROLLING VEHICLE SPEED FOR MOBILE MAINTENANCE OPERATIONS: Oregon Case Study

Ali Jafarnejad, John Gambatese, and Salvador Hernandez

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2.1 Abstract

Radar speed signs (RSSs) as a speed reduction measures through the work zones have been known as a way to slow down the traffic flow speed. In this study, the influence of truck-mounted RSS on vehicle speed for mobile maintenance operation has been evaluated. In this regard, truck mounted RSSs are employed in two multi-lane maintenance work zones in the state of Oregon in the US. In each case study, the authors conducted two periods of testing: one with the RSS display turned on (treatment) and one without the RSS display turned on (control), and recorded vehicle speeds. Descriptive statistics was used to summarize collected data, and a two-sample t-test was applied to each case study to compare the speed difference between control and treatment cases. The research findings indicated that vehicle speeds are typically lower, and there is less variation in speeds between adjacent vehicles with the RSS turned on. The results have shown that the RSS proves to be a promising device for controlling vehicle speed and making the work zones safer for both motorists and workers.

2.2 Introduction

In the wake of an already aging road infrastructure and increasing traffic volumes, existing roadway networks in the US have experienced rapid deterioration. As a result, there is an ever increasing need for safe and timely maintenance and rehabilitation operations on these roadway networks (e.g., Interstate, state routes, etc.). That said, maintenance and rehabilitation operations typically consist of mobile operations over a short duration of time (up to one work shift) and are defined as any activity associated with short-duration work such as roadway sweeping, surface patching, line painting, and other mobile operations that move continuously or intermittently along a road segment. The work might be done directly from the moving vehicle or equipment, or it may involve workers on foot *(1)*.

Roadway work zone activities often expose workers to the possibility of being in close proximity to vehicles traveling at high speeds. Highway maintenance and rehabilitation projects typically require workers to reduce traffic flow to a single lane while work is undertaken in an adjacent lane. During lane closures, maintenance operations can place workers on the roadway within a marked work zone. Areas of limited protection create a 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.

Furthermore, work zone workers conducting mobile highway maintenance and rehabilitation operations experience a hazard that is absent in many other types of construction sites; like high speed traffic traveling within a very short distance from the construction area. Federal Occupational Safety and Health Administration (OSHA) Fatality Investigation reported highway construction among one of the three industries with the highest number of fatalities *(2)*. Compared to other occupations, the risk of death is seven times higher for roadway workers than for the average worker in all work industries combined *(3)*.

Work zone injuries and fatalities can be prevented in many ways. Providing sufficient warning of the work zone to the motorists and providing proper safety training to workers are examples of measures taken to prevent injuries and fatalities. To have successful mobile operations, the advance warning area must move with the work area or be repositioned periodically to provide adequate warning for the motorists *(4)*. It is generally perceived that slowing traffic in a work zone improves the overall safety of the work zone *(5–7)*. By decreasing the vehicle speed, motorists have more time to react and reduce their stopping distance and prevent additional maneuvers to control the vehicle. It also increases the time for workers to move out the way of the vehicle and reduces the likelihood of serious and/or fatal injuries to workers, motorists and their passengers *(5)*.

In response to these concerns, the Oregon Department of Transportation (ODOT) Research Division elected to investigate highway maintenance project safety enhancements. Types of maintenance work where ODOT anticipates using traffic control equipped with a mobile radar speed sign (RSS) primarily includes sweeping and drainage cleaning operations. Sweeping operations are typically continuously moving, and advance along at about 3-5 mph. Drainage cleaning operations are usually not continuously moving, but rather stop-and-go with the work vehicle stopping in front of a drainage inlet for several minutes before proceeding to the next inlet up the highway. Considering this, the present study aims to quantify the impact of a truck-mounted RSS on vehicle speeds in maintenance work zones and to identify best practices for their use as part of mobile maintenance work operations. These signs are attached to the back of maintenance trucks and deployed as part of the traffic control measures during maintenance work. The research includes observations of the traffic when the truck is moving as part of the maintenance operations.

2.3 Literature Review

Work zone speed control has been the subject of several research efforts in the past. As such, various techniques and procedures have been tested and evaluated. These include, but are not limited to, variation of traditional fixed signing, changeable message displays, radar units with speed sign messages, and a range of electronic devices to sense and display information related to speed. Based on this previous research, informational measures (e.g., static signage, variable message signage) have been shown to lead to small-to-moderate effects on speed reduction *(8, 9)* and physical measures, such as rumble strips and optical speed bars, were found to be ineffective for transient and moving work zones *(9)*. While, enforcement measures (speed camera, police presence) have the greatest effects in reducing work zone speeds *(9–13)*, educational measures also have significant potential to improve public awareness of road worker safety and to encourage slower speeds in work zones *(9)*.

Correspondingly, past studies have shown that speed monitoring displays with radar have a statistically significant effect in reducing mean speeds and the percentage of drivers exceeding the posted speed limit. McCoy et al. *(14)* examined the effectiveness of speed displays at a rural interstate work zone in South Dakota. They used a stationary trailer with speed monitoring display placed at the beginning of the taper. The study revealed that the speed monitoring display reduced mean vehicle speeds by 4 mph.

Furthermore, Garber and Fontaine *(15)* used changeable message signs (CMS) with a radar unit at rural interstate work zones in Virginia. Based on the 85th percentile speed reduction of about 8 mph, the researchers concluded that the CMS system, coupled with a radar unit, has an impact on reducing speeds of the fastest segment of the driving population. The effectiveness of this technology which was approved in another study, resulted in a decrease in the mean speed of up to 2 mph, and a 1 to 4 mph reduction in the 85th percentile speed *(16)*.

After police patrol presence, radar speed display has also been shown to influence speeds effectively through work zones *(13, 17)*. For instance, a study by Caltrans in 2013, revealed that lane closure, the use of a radar speed sign and police enforcement together resulted in a reduction of speed by 10.5 to 14 mph. In the absence of police enforcement, the radar sign trailer improved the safety regarding reduced speeds by 8 to 12.5 mph, at least for short duration work zones *(18)*.

In addition to these studies, there have been research efforts that have included radar speed signs in mobile operations. These studies evaluated the effectiveness of radar speed signs through the use of focus group surveys to gain insights and to develop guidance for radar speed sign usage in mobile maintenance operations *(19, 20)*.

Based on previous literature, radar speed signs often achieved their objective of a reduction in speeds. Depending on the application and problem being addressed, changes in speeds can range from small to significantly large. It appears that in no case did the deployment of radar speed sign worsen the existing operational conditions, and that drivers have shown positive driving behavior toward the speed monitoring display. Some studies have suggested future research on truck-mounted speed display signs to reduce work zone speeds and possibly minimize the severity of crashes *(11, 20)*. The review of the literature revealed that the effectiveness of the mobile radar speed sign on speed reduction during maintenance and mobile operations were not evaluated before.

2.4 Research Methodology and Data Collection

For the purpose of this research, a radar speed sign is installed on an ODOT Maintenance truck in each case study. The truck moves with a low speed (usually 5-10 mph) behind the maintenance equipment used to display vehicle speed or provide a warning to approaching vehicles about the work zone.

Four case studies were selected for data collection, however, in this paper, the results of only two case studies, which are very similar to other case studies, are presented. Vehicle length, speed and time of day were collected by NC-200 portable traffic analyzers (sensors). The sensor utilizes vehicle magnetic imaging technology to count the number of passing vehicles and detect vehicle speed and length *(21)*. The analyzers were secured to the pavement using adhesive tape to cover the analyzer and its protective cover.

In each case study to fully understand motorist behavior and vehicle speed through a long mobile operation work zone, 14 portable traffic analyzers were placed directly in the traffic lanes. The first analyzers were placed near the “Road Work Ahead” (RWA) sign to capture vehicle speeds before the vehicles enter the work zone. Two analyzers were placed at the beginning of the taper. Other analyzers were placed in the travel lane(s) at different points in the working area. The actual location and spacing of the analyzers in the work zone were dependent on the number of travel lanes, amount and location of work being performed on the given day or night. Prior to the testing, the analyzers were calibrated to determine their accuracy and adjust collected data before any statistical analysis.

2.4.1 Case Study #1: I-84 Vactoring (Drain Cleaning)

The first case study was performed in the westbound (WB) direction of Interstate 84, between I-5 and I-205. At this location, the highway has three travel lanes in each direction. The posted regulatory speed on this section of roadway is 55 mph. The maintenance operation involved vactoring (drain cleaning) the drains along the right shoulder of the roadway. There was no lane closure during the operation. A truck with an arrow board directed the traffic to the left-hand lanes near the operation. It was an intermittent mobile operation involving frequent short stops near each drain, and a worker exited his/her vehicle to perform the vactoring operation while standing on the roadway.

Two consecutive nights of maintenance operations were conducted: one without the RSS displaying the vehicle speeds (Day 1), and one with the RSS displaying the vehicle speeds (Day 2). Only every other drain was cleaned each night. For the first night, only odd-numbered drains were selected to be cleaned, and on the second night, the even-numbered drains were selected. For this case study, in addition to the RSS sign, an advisory speed sign was also mounted on the back of the RSS truck or arrow truck. The maintenance operation was conducted around one hour on each night. The difference between the hourly traffic volumes between two nights in the corresponding locations is 12 percent (1170 in Day 1 and 1316 in Day 2). In addition, the percentage of trucks (vehicles > 25 feet in length) were approximately the same in both days (between 5 to 10 percent in the different duration of time).

2.4.2 Case Study #2: I-205 Sweeping

The I-205 sweeping case study was located in the southbound (SB) direction of I-205, west of Oregon City between the Sunset Ave. overpass and 10th Street. The operation consisted of sweeping the left (median) shoulder of the highway with a sweeper. The highway has two travel lanes in each direction. This operation differed from the vactoring operation in Case Study #1, in the number of traffic lanes and type of mobile operation (intermittent mobile operation in case study #1 and continuously moving mobile operation in case study #2).

At this location on the roadway, there are 20 light poles in the median of the highway. Traffic sensors placed a consistent distance apart at the location of every fifth light pole. The sweeping was a very quick operation, so both control and treatment tests were performed on one night. The maintenance work was performed twice over the same section of roadway without the RSS displaying the vehicle speeds. Then the work was performed two times over the same section of roadway with the RSS displaying vehicle speeds. The first pass of the sweeper through the work zone took approximately 22 minutes to clean the shoulder of any dust and debris, but the other three passes of the sweeper took approximately 12 minutes since the road was clean and it could travel faster without any stops. There were 10-20 minutes of gap between each sweeper pass for preparation and travel time to return to the starting point of the work zone. During the absence of the sweeper as it was returning to the starting point, there was no presence of maintenance equipment in the work zone and therefore free flow traffic through the work zone.

2.5 Results and Data Analysis

Following data collection on each case study project, the researchers downloaded the vehicle data from the traffic analyzers for analysis. Then descriptive statistics were used to summarize collected data, and a two-sample t-test was conducted on each case study to compare the speed difference when the RSS was turned on and when it was not turned on. Additionally, analyses were only conducted within each case study; analytical comparisons between different case studies were not made. The differences in site conditions, vehicle distribution, test layout, and maintenance work operations between each case study limit confidence in the comparisons due to the confounding factors.

2.5.1 Case Study #1: I-84 Vactoring

Figure 2.1 illustrates how the 85th percentile speed changed from the RWA signs to the end of the work zone at Drain #8 for both cases (with and without RSS turned on). The 85th percentile speeds on both nights were above the 55 mph regulatory speed limit on this section of roadway. As seen in figure 2.1, the speeds with the RSS turned on were lower than without the RSS turned on. It should be taken into consideration that the free flow speed (speed at RWA sign) in Day 2 with RSS was consistently higher than on Day 1 without the RSS turned on over the course of the testing time period.

A comparison of 85th percentile speeds at Drain #3 (without RSS turned on) to that at Drain #4 (with RSS turned on) is shown in figure 2.2. Drains #3 and #4 were selected for illustration purposes only; similar charts showing comparisons between adjacent drains are provided in the full report *(22)*. It can be seen that the vehicle speeds are lower when adjacent

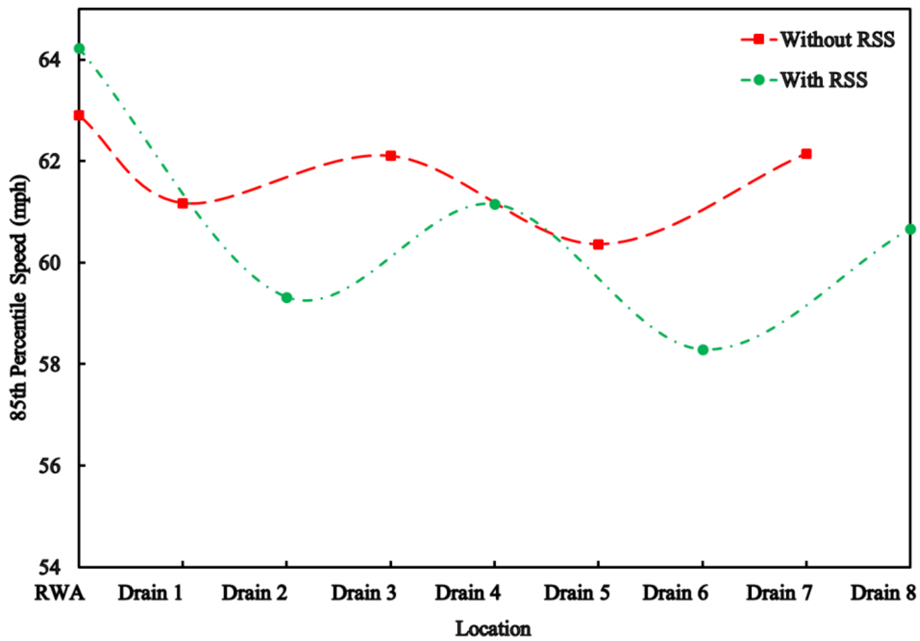

Figure 2.1 Vehicle speed (85th percentile) at different locations during operation time, I-84, Vactoring.

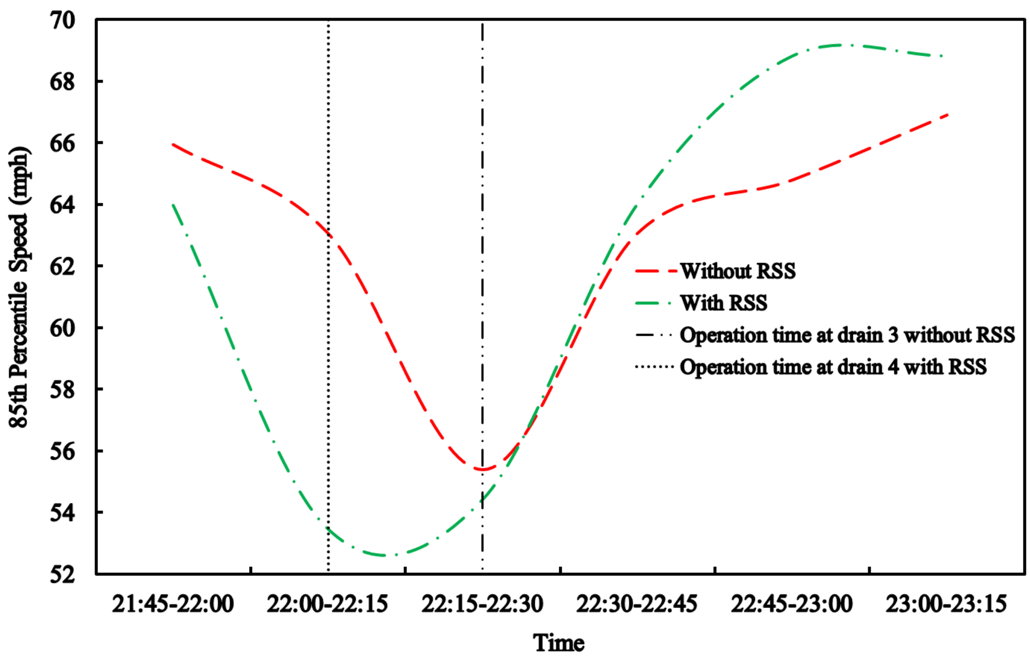

Figure 2.2 Vehicle speed (85th percentile) at drain 3 (without RSS) and drain 4 (with RSS) during operation time, I-84, Vactoring.

to work equipment. For example, between 22:15 and 22:30 on Day 1 without the RSS turned on, the work took place at Drain #3. At this time, the 85th percentile speed was approximately 55.4 mph. On the second day of testing (with the RSS turned on), the work on Drain #4 took place earlier in the evening. From 22:15-22:30 on Day 2 there was no work going at Drain #4 and the 85th percentile speed was approximately 54.4 mph, slightly lower than the prior day at the adjacent Drain #3. On Day 2 with the RSS turned on, the 85th percentile speed at the location of the work equipment was less at 53.5 mph. During the whole period of operation, regardless whether the RSS display was turned on, the vehicles slow down as they approach the equipment and then speed up downstream of the work equipment. However, comparison of the figures shows that the 85th percentile speed was lower by approximately 7-8 mph with the RSS turned on as the vehicles approached the work equipment.

Table 2.1 is the comparison of the amount of decrease in speed from the RWA signs to the work zone for both days of testing. The speeds in the work zone (WZ) were those recorded by all of the traffic sensors adjacent to all of the drains. For all vehicles (passenger cars and trucks), mean speed decreased from 56.6 mph at the RWA signs to 53.0 mph in the work zone, a 6% decrease, on Day 1 without the RSS turned on. On Day 2 with the RSS turned on, the amount of decrease for all vehicles was greater at 12% (57.2 mph to 50.5 mph). When analyzing cars and truck separately, similar results were found: the percentage decrease in mean speed was greater with the RSS turned on. For all cases, the mean speed in the WS with the RSS turned on was less than without the RSS turned on.

Table 2.1 Percentage of Vehicle Speed Decrease in the Work Zone Area, I-84, Vactoring

Type of vehicle	**Mean Speed (mph) without RSS (Day1) at RWA**	**Mean Speed (mph) without RSS (Day1) at WZ**	**Decrease in mean speed (%) without RSS (Day1)**	**Mean Speed (mph) with RSS (Day2) at RWA**	**Mean Speed (mph) with RSS (Day2) at WZ**	**Decrease in mean speed (%) with RSS (Day2)**
All Vehicles	56.6	53.0	6%	57.2	50.5	12%
Passenger Cars	56.7	53.0	7%	57.2	50.6	12%
Trucks	54.5	52.8	3%	56.0	50.2	10%

An additional comparison of mean speeds within the work zone is shown in table 2.2. For all vehicles, the mean speed in the WZ on Day 1 without the RSS turned on was 45.5 mph and the mean speed in the WZ on Day 2 with the RSS turned on was 39.9 mph, a difference of 5.6 mph. This difference was found to be statistically significant ($p < 0.0001$). A similar statistically significant result was found for cars: mean speeds throughout the work zone were less with the RSS turned on. For trucks, while the difference in mean speed was greatest, the difference was not found to be statistically significant ($p = 0.269$), likely due in part to the low volume of trucks recorded.

Analyses were also conducted that focused on the difference in speed between adjacent vehicles as they passed through the work zone. The speed difference between adjacent vehicles is a concern if the difference is large. A faster vehicle approaching a slower vehicle may increase the risk of rear-end crashes. Speed difference is calculated as the difference in speed between a vehicle and the vehicle in front of it. A positive value for speed difference indicates that the vehicle is traveling at a faster rate of speed than the vehicle in front of it. A negative value for speed difference shows that the vehicle is traveling slower than the vehicle in front of it.

Table 2.2 Effect of Radar Speed Sign on Vehicle Speed, I-84, Vactoring

Type of vehicle	Mean Speed (mph) without RSS (Day1)	Mean Speed (mph) with RSS (Day2)	Difference in mean speed (mph)	p-value
All Vehicles	45.5	39.9	5.6	< 0.0001
Passenger Cars	45.3	39.70	5.6	< 0.0001
Trucks	48.6	42.60	6.0	0.2692

Statistical tools were used to analyze the treatment effect of implementing the RSS display. A two-sample t-test was conducted to see whether turning on the RSS display has an effect on the speed difference. In the analysis, positive value of speed difference is used as the dependent variable. This situation is possibly hazardous as it can lead to rear-end crashes. The statistical test was conducted for all vehicles combined, for only passenger cars, and for only trucks.

Table 2.3 summarizes the results of this analysis. The data used to create the table consisted of all of the data recorded at Drains #3 (without RSS turned on) and #4 (with RSS turned on) as an example. There is no statistical evidence that the RSS display has an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it for all vehicles combined ($p = 0.0994$) and for just trucks ($p = 0.292$). However, for passenger cars (vehicles < 25 feet), the difference of 0.85 mph is statistically significant ($p = 0.048$). The result of this table in this case study shows that the speed difference between adjacent vehicles is a little larger when the RSS is turned on. The difference is significant only for passenger cars, but not for trucks. However, in other case studies, the difference in speed between adjacent vehicles is less when the RSS was turned on. For the vactoring case study the speed difference between adjacent vehicles in the RWA sign, which was not under the effect of RSS, shows similar results between Day 1 and Day 2. Therefore, the larger mean of speed difference when the RSS was turned on may not be affected by RSS. This could be because of other factors such as the difference in volumes between Day 1 and Day 2 of testing. In the vactoring case study, there is also three travel lanes instead of two travel lanes in other case studies which could be another variable that causes a little larger speed difference between with and without RSS turned on.

Table 2.3 Effect of Radar Speed Sign on Vehicles with Positive Speed Differences between Adjacent Vehicles, I-84, Vactoring, Drain 3 and Drain 4

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

2.5.2 Case Study #2: I-205 Sweeping

Similar to Case Study #1, the traffic analyzers also provided the opportunity to view the vehicle speeds at various locations through the work zone. Figure 2.3 illustrates how the 85th percentile speed changed from the RWA signs to the end of the work zone at Pole #20 for all cases (with and without RSS turned on, and free flow). As seen in the figure, for much of the work zone, the speeds with the RSS turned on were lower than without the RSS turned on. This difference ranged from approximately 1 to 3 mph.

An 85th percentile speed over the testing period is illustrated in figure 2.4. The 85th percentile speed was consistently lower (by about 2 – 2.5 mph) than without the RSS turned on over the course of the testing time period. Free flow speeds while the sweeping equipment was

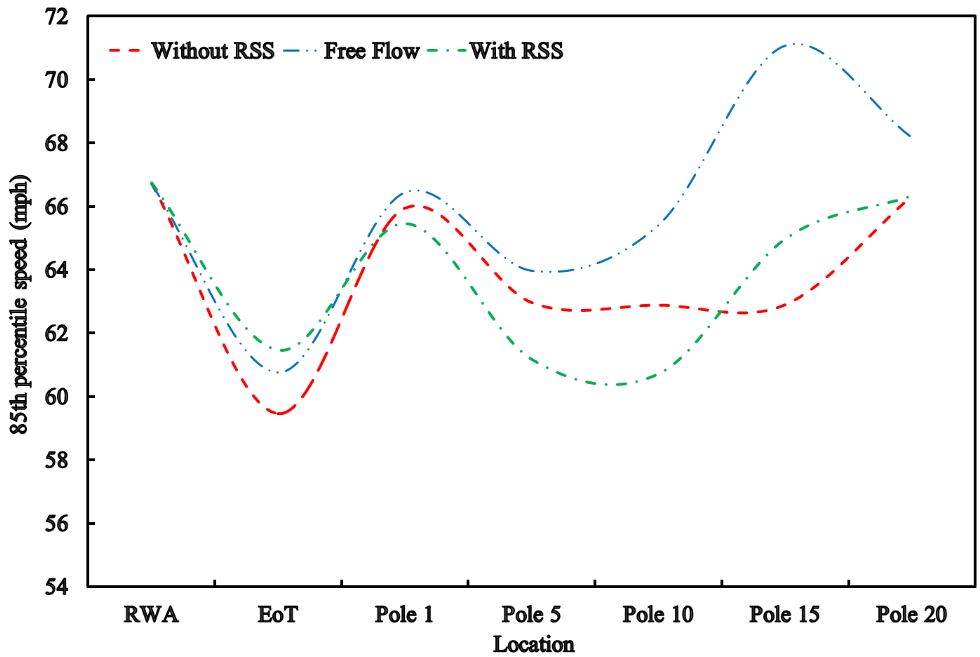

Figure 2.3 Vehicle speed (85th percentile) at different locations during operation time, I-205, Sweeping.

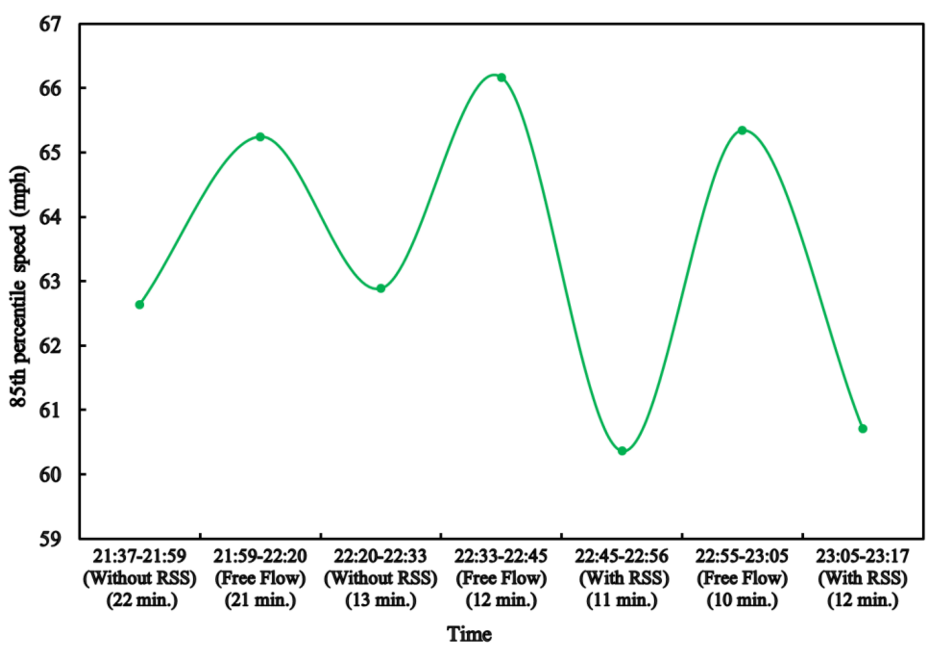

Figure 2.4 Vehicle speed (85th percentile) at pole 10 during operation time, I-205, Sweeping.

returning to the start of the work area to make another pass were always higher than the periods when the sweeping operation was taking place.

A comparison of 85th percentile speeds at Pole #10 with and without the RSS turned on is shown in figure 2.5. Pole #10 was selected for illustration purposes only. The figure illustrates the effect of the presence of the work equipment at Pole #10. The vehicles slow down as they approach the work operation and then speed up afterwards. Over the same distance, the amount of decrease was greater with the RSS display turned on. For example, from Pole #1 to Pole #10, the speeds decreased from approximately 67 to 55 mph (12 mph decrease) with the RSS turned on, and from approximately 64 to 55 mph (9 mph decrease) without the RSS turned on.

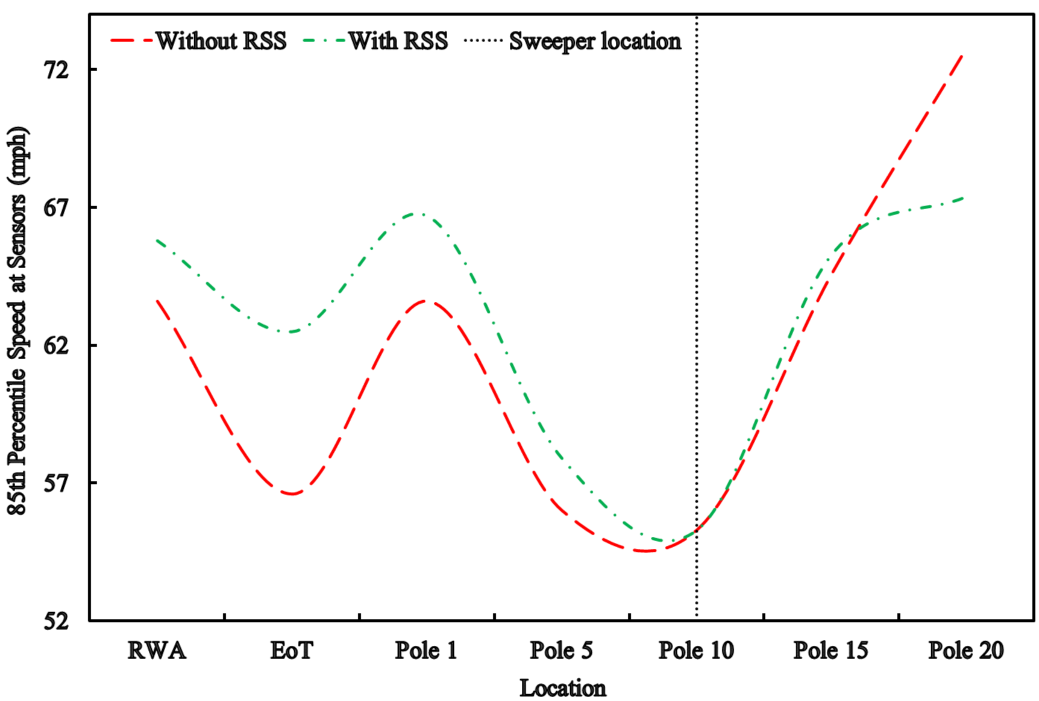

Figure 2.5 85th percentile speed at different distances from the operation, I-205, Sweeping, pole 10.

The data in table 2.4 indicates that for all vehicles, mean speed decreased from 60.3 mph at the RWA signs to 55.7 mph in the work zone, a 7.6% decrease, without the RSS turned on. During the work periods with the RSS turned on, the amount of decrease for all vehicles was greater at 12%. In addition, the magnitude of the mean speed in the work zone was less. When analyzing cars and truck separately, similar results were found: the percentage decrease in mean speed was greater with the RSS turned on.

Table 2.5 shows an additional comparison of mean speeds, this time just comparing the speeds within the work zone adjacent the poles. For all vehicles, the mean speed in the WZ during the periods without the RSS turned on was 55.6 mph and the mean speed in the WZ with the RSS turned on was 54.8 mph, a difference of 0.79 mph. This difference was found to be statistically significant (p = 0.029). Suggestive evidence of a difference in mean speeds was found for cars (p = 0.058), while no difference was found for trucks (p = 0.360). For this case study, the amount of difference in the mean speeds was less for cars (0.7 mph) than for trucks (1.2 mph).

Table 2.4 Percentage of Vehicle Speed Decrease in the Work Zone Area, I-205, Sweeping

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

Similar to case study #1, a two-sample t-test was conducted to see whether turning on the RSS display has an effect on the speed difference between adjacent vehicles. The results of the analysis for positive values of speed difference, shown in Table 2.6. There is no statistical evidence that the RSS display has an impact on speed difference between adjacent vehicles where the speed of the trailing vehicle is greater than the vehicle in front of it.

Table 2.5 Effect of Radar Speed Sign on Vehicle Speed, I-205, Sweeping

Type of vehicle	Mean Speed (mph) without RSS	Mean Speed (mph) with RSS	Difference in mean speed (mph)	p-value
All Vehicles	55.6	54.8	0.8	0.0290
Passenger Cars	55.8	55.1	0.7	0.0579
Trucks	53.6	52.4	1.2	0.3604

Table 2.6 Effect of Radar Speed Sign on Vehicles with Positive Speed Differences between Adjacent Vehicles, I-205, Sweeping, Pole 10

Type of vehicle	Mean of positive value of Speed difference (mph) without RSS (Day1)	Mean of positive value of Speed difference (mph) with RSS (Day2)	Difference in mean values (mph)	p-value
All Vehicles	6.4	6.0	0.4	0.6049
Passenger Cars	6.3	6.1	0.2	0.7384
Trucks	7.5	5.7	1.8	0.5306

2.6 Conclusions

The results of this study provide insights into the impacts of a truck-mounted radar speed sign on vehicle speeds during mobile maintenance operations on high-speed roadways. Overall, the RSS display proved to be effective in reducing vehicle speeds in the work zone when it displayed the vehicles’ speeds, compared to when the speeds were not displayed. This impact occurs for both continuously mobile operations (e.g., sweeping) and intermittent operations (e.g., vactoring).

At the RWA sign location, vehicles travel at normal highway speeds. Passenger cars tend to travel faster than trucks. However, all vehicles begin to slow down as they enter the active work area. There is a gradual decrease in speed to the end of the taper. In the work zone, vehicles typically travel at a lower speed when they pass by the work equipment as described above. After passing the equipment, the vehicles typically increase their speed. These results are similar to that observed in previous ODOT studies *(13, 23)*.

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

2.7 Acknowledgements

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3 IMPACT OF TEMPORARY PORTABLE WORK ZONE AND PERSONAL LIGHTING ON VEHICLE SPEEDS IN NIGHTTIME HIGHWAY PRESERVATION PROJECTS

Ali Jafarnejad, John Gambatese, and Salvador Hernandez

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3.1 Abstract

Every year thousands of people are killed or injured in work zone crashes in the US due to excessive speed, distraction, inattentiveness, or low visibility. Many highway construction, maintenance, and pavement projects occur at night when the traffic volume is low, creating less congestion and delay to the traffic. During nighttime operations, however, ability of drivers to see workers is diminished. High speed roadways with low visibility make an unsafe and dangerous situation for both motorists and workers. In this paper the impact of additional temporary lighting on vehicle speed in highway work zones was investigated. In addition, the impact of wearing personal lighting equipment was also examined during paving operations. Two common types of lighting equipment, a light tower and a balloon light, were set up in work zones and a personal, wearable light was used during two paving projects on Oregon highways. Traffic speed and other vehicle and lighting data were collected on different nights when the lighting equipment was turned on and also when it was turned off. The research findings indicate that both additional temporary roadway lighting and personal lighting help to make workers more visible to motorists and equipment operators. Although a temporary light leads to slightly higher vehicle speeds, it makes the work zone and workers more visible for motorists and equipment operators. Statistical analysis revealed that there is no difference between mean vehicle speed with and without personal lights turned on. Personal, wearable lights are highly recommended for workers who are located away from large equipment and other light sources.

3.2 Introduction

Construction on high-speed roadways often takes place at night in order to minimize impacts to motorists. Conducting construction work at night is associated with a wide range of benefits including reduced congestion and delay, decreased project duration, decreased material delivery time, and reduced economic impact of construction operations on the surrounding businesses. Although working at night may help to reduce construction durations, worker visibility and the ability of drivers to see the roadway conditions can decrease. Nighttime work operations expose workers to hazards that are not present or not as great during the daytime, such as the presence of impaired drivers, higher traffic speed, and lack of sufficient visibility for both workers and motorists (*1*–*6*). These factors can decrease work quality and worker safety, and increase the chance of accidents (*7*). As a result, special measures such as reflective clothing, flashing STOP/SLOW paddles for flaggers, and other illuminated traffic control signs are often implemented during nighttime work to protect workers and motorists in work zones.

Proper and adequate work zone lighting, along with proper reflective personal protective equipment (PPE), can help workers see better and be seen by drivers and equipment operators. Decreased visibility in the work zone is one of the main concerns of nighttime construction which can negatively impact both workers and drivers. The loss of visibility for workers results in the need for supplemental lighting that satisfies the visibility requirements of workers. The potentially positive impact that work area lighting can have on visibility is promising for safety in a work zone. Adding lighting in the vicinity of the construction or maintenance equipment, and where typical work area lighting is not present, may be a low cost means of making motorists more aware of workers on the roadway, reducing vehicle speeds, and further protecting workers on the roadway from jobsite hazards. With the increasing need to construct during the nighttime in order to avoid disruption of traffic flow, state transportation agencies are experimenting with different types of lighting systems, such as balloon lights and wearable lights. The present study evaluated the impact of temporary work zone lighting on vehicle speeds. The study includes two case studies on multi-lane preservation projects in Oregon in which different types of lighting systems were implemented: a light tower, balloon light and a personal wearable light.

3.3 Background

Ellis et al. (*8*) developed preliminary illumination guidelines for nighttime highway work and suggested different illumination levels based on highway construction activities. Researchers have subsequently promoted a decision support systems to design the lighting plan based on maximizing the illuminance and uniformity ratio and minimizing glare and costs (*6*) . The output of the model was a set of solutions that satisfy the design objectives stated by the designer.

Light towers, balloon lights, or other types of commercially available lighting systems are some examples of typical lighting equipment employed to provide the necessary lighting during construction. To select the types of lighting that are best suited for a work zone, factors such as efficiency, ability to satisfy minimum requirements while controlling glare, availability of power, light trespass, and cost should be considered. These factors have been incorporated into a lighting design model based on a number of pieces of lighting equipment, equipment positioning, mounting height, aiming angle, and rotation angle (*9*). Performance of various lighting arrangements were evaluated through field experiments in nighttime highway construction zones (*10*). The researchers tested lighting performance in the work zone activity, transition, and termination areas. The experimental results showed different solutions for each activity location; for example light towers can be used effectively to satisfy lighting requirements for nighttime operations in the activity area. Each lighting arrangement provides a varying degree of satisfaction of each criterion. Another example is the selection of the lighting arrangement for flagger stations. Although the research revealed that a light tower performed the best in terms of illumination, uniformity, and mobility, using a tripod balloon light is also recommended when considering glare and cost (*11*).

Previous studies have primarily focused on light arrangement specifications such as height, power, and glare. However, the effect of lighting in work zones on vehicle speed has not been investigated yet. During construction, existing roadway lighting or lighting attached to the construction equipment may not be sufficient to eliminate the need for additional lighting of the work zone. Implementation of additional lighting is expected to reduce the risk exposure of workers and motorists, lead to fewer worker injuries and fatalities in work zones, and improve mobility through work zones. Work zone lighting conditions have been identified as one of the risk factors in highway work zones (*12*, *13*). The researchers found that the lighting condition is a significant factor in crash severity. Poor light conditions (i.e., dark without streetlights) contributed to a much larger percentage of fatal crashes (*13*, *14*). However, there are some studies which found that the lighting condition could have an opposing effect and, in some cases, can increase the probability of a crash (*15, 16*).

Different lighting arrangements in nighttime highway construction will greatly increase awareness of surroundings and create an easier work environment in which to maneuver. Another reason for illuminating the work zone is to alert drivers of the presence of workers. Wearing reflective clothing in combination with the lighting makes the workers visible to other workers, equipment operators, and passing motorists. Researchers at the Texas A&M Transportation Institute (TTI) conducted a study to evaluate the impact of work zone lighting on the ability of drivers to detect low-contrast objects and workers wearing high-visibility vests (*17*). The results for the illuminated roadway section showed that properly installed temporary work zone lighting could increase the distance at which workers and low-contrast objects could be detected. Overall, all of the temporary work zone lighting conditions (even those with glare) resulted in worker detection distances that were greater than the stopping sight distance for the conditions studied (*17*).

The goal of the present study is to improve highway work zone safety by providing additional lighting. Although work zone illumination guidelines and lighting specifications do exist, the impact of additional lighting on passing vehicle speeds has not been investigated. Controlling and reducing speed in the work zone can reduce the injury severity of crashes. The study also integrates assessment of lighting worn by workers (wearable lighting) to assess whether these safety features contribute to the ability of the lighting systems to illuminate the workers and affect vehicle speeds.

3.4 Data Collection

The objective of the research was to determine whether additional lighting added at strategic locations can reduce passing vehicle speed throughout the work zone. This objective was accomplished by conducting field experiments on two case study projects. In both case studies, the temporary lighting equipment was placed on different nights during the work operations and at specific locations in the work zones. For comparison, some nights were conducted without the light systems turned on to use as a baseline case. Portable traffic analyzers (speed sensors) were located at multiple locations prior to and within the work zones to measure the impact of the lighting equipment on vehicle speeds at different locations and with respect to specific pieces of construction equipment during each work shift. In addition, at various times during the work period, the researchers had one or more workers use a wearable light located on their hardhat.

Temporary lighting equipment used in case studies included a standard light tower (light plant) and a balloon light (Figure 3.1). The light tower includes four light fixtures containing 1,000-watt lamps mounted to a mast arm capable of holding the luminaires at various mounting heights and angles. The actual light towers available for use during each case study were provided by the contractor. For each case study, a balloon light was also implemented. The balloon light consisted of a large balloon-type luminaire atop a portable tripod mast and powered by a portable generator. It was an Airstar balloon light, Sirocco 2000, mounted on a tripod with two 1,000-watt halogen lamps surrounded by an envelope (balloon) that is 3 feet in diameter and 2 feet tall.

Figure 3.1 Lighting equipment tested: balloon light (left) and light tower (right).

The wearable light used by workers was a Halo Light by Illumagear attached to their hardhats. It produces a ring of light around the wearer, enabling him/her to see the surroundings and be seen in all directions. Providing up to 276 lumens of power in 360°, the light illuminates the wearer's task area and makes them more visible (Figure 3.2). Two workers, the density technician and dump person, who are on foot and typically located in more hazardous locations, were asked to wear a Halo Light. The workers were asked to turn on and off the light every two hours during each working shift. For example, from 0:00-02:00 the light was turned on and from 02:00-4:00 it was turned off.

Figure 3.2 Personal wearable light (Halo Light by Illumagear) attached to hardhat.

A total of 17 portable traffic analyzers (NC-200 and NC-350) were used to collect vehicle data on the roadways. The data collected includes the passing vehicle speed, length, and time of passing. Prior to the start of work during each night of data collection, all of the traffic analyzers were programmed to start recording data at a designated time. The sensors were secured to the pavement using adhesive tape which completely covered each analyzer and its protective cover. The first two analyzers were placed near the “Road Work Ahead” (RWA) sign to capture vehicle speeds before the vehicles entered the work zone. One analyzer was placed at the end of the taper. Additional analyzers were placed in the travel lane at increments of approximately every quarter mile in the working area. Figure 3.3 shows an example of a plan view of the portable traffic analyzer placement for a typical night of testing. The locations of the portable traffic analyzers are indicated with rectangles in the figure. The sensors remained in place during the entire duration of the work on each work night. At the

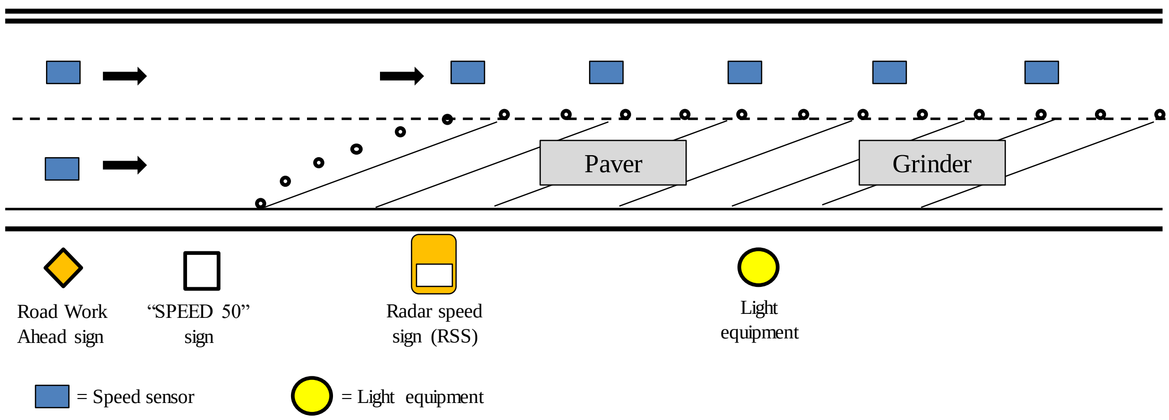

Figure 3.3 Example of traffic control devices, analyzers, and light equipment placement in the work zone.

end of each work night, the sensors were removed and the speed data downloaded for analysis. The sensors were then relocated at the same or different locations for the next work night.

The data collected from the case study projects was analyzed to determine the effectiveness of the lighting strategies tested. Each lighting system was implemented and compared independently. The researchers compared the vehicle speeds, speed variability, and visibility of the workers associated with the baseline case (without the lighting system) to that when the light system is implemented and turned on.

3.5 Case Study Projects

The first case study project (case study #1) consisted of a 14-mile asphalt concrete paving project on Interstate 84 from Jordan Road to Multnomah Falls in northern Oregon. Data was collected while the contractor paved the eastbound slow lane (B lane) of I-84 on five consecutive nights from Monday to Friday. The highway in this location has two lanes in each direction with a posted regulatory speed limit of 60 mph for cars and 55 mph for trucks.

During the paving operation, the regulatory speed limit was reduced to 50 mph in the work zone for all vehicles. There was one open lane for passing traffic, separated by cones from the activity area during the paving operation. The operation typically started with traffic control placement at 19:00 each day and ended at 07:00 the following day. Considering placing the sensors after dark and the time required to pick them up before traffic became too heavy the following morning, vehicle specifications were recorded by sensors from 23:00 to 5:00 each work day.

On the first night of testing on the first case study project, the balloon light and light tower were placed near the end of the taper where there was a wide shoulder and safe place to locate them in advance of the activity area. The lights were switched on and off alternately every hour starting at 23:00 with the balloon light. Days 2 and 5 were control nights during which no additional portable light equipment was placed in the work zone. On the third day of testing, the light tower was placed in the middle of the work zone on the right shoulder next to the working lane. On the fourth night of testing, the balloon light was placed in the middle of work zone. The light tower and balloon light were not moved during each night and stayed turned on the whole night (Days 3 and 4).

The second case study project (case study #2) was a paving project on Interstate 5 between Ashland and Medford in southern Oregon. The project included grinding two inches of open graded mix and replacing it with two inches of dense grade mix. The data was collected over five days of paving two lanes (one in the northbound and the other in the southbound direction) from 21:00 to 05:00. One passing lane remained open each night, separated from the activity area by a line of cones during the paving operation. The posted regulatory speed limit is 65 mph for cars and 55 mph for trucks. During the paving operation, the regulatory speed limit was reduced to 50 mph in the work zone for all vehicles. Because of a limited number of days which the paving work was going to take place, the researchers conducted two nights of testing in the northbound direction and three nights of testing in the southbound direction. Details of the testing plan are provided in Table 3.1.

Table 3.1 Case Study Testing Plans

Case Study #	Day	Paving Lane	Direction	Light Equipment	Light Location
1	1	Slow lane	EB	Balloon light and light tower	End of Taper
1	2	Slow lane	EB	None (control night)	Not applicable
1	3	Slow lane	EB	Light tower	Middle of the work zone
1	4	Slow lane	EB	Balloon light	Middle of the work zone
1	5	Slow lane	EB	None (control night)	Not applicable
2	1	Slow lane	NB	Light tower	Middle of the work zone
2	2	Slow lane	NB	None (control night)	Not applicable
2	3	Slow lane	SB	Balloon light	Middle of the work zone
2	4	Slow lane	SB	Light tower	Middle of the work zone
2	5	Slow lane	SB	None (control night)	Not applicable

3.6 Speed Change Distribution

In case study #1, traffic volume and truck percentage were very similar on different days. The total number of vehicles ranged from approximately 200 to 250 vehicles at the start of data collection on each day from 23:00 to 24:00. Later in the work shift, the total number of vehicles decreased to approximately 120, and then at 03:00 the number started to increase. From 04:00-05:00, the total number of vehicles was typically approximately the same as the total number of vehicles from 23:00-24:00 at the start of testing. In this case study, there was a large percentage of trucks (vehicles > 25 feet in length) during the test period. The truck percentage varied from 30% to 60% on most days. Between 23:00 and 24:00 the truck percentage was at its lowest, and from 02:00 to 03:00 or 03:00-04:00 it was at its highest. It should be noted that in both case studies, the traffic volumes and speeds recorded included asphalt trucks and other construction equipment used for the construction operation.

Traffic sensors provided an opportunity to analyze vehicle speeds through various locations in the work zones. Figure 3.4 shows how the 85th percentile vehicle speed changed from the RWA sign to the end of the work zone on a sample day (Day 3) of testing. Throughout the work zone, there were traffic control signs, a portable light, and construction equipment that may have influenced the speed of a vehicle. During each testing period, the locations of the grinder, paver, and density technician were tracked with a GPS unit attached to each of them to allow for correlating their location with the vehicle speeds. In Figure 3.4 and 3.5, the paver, grinder, density technician, radar speed sign (RSS), and light equipment are displayed by different letters and lines. The paver location is identified by a line with the letter “P” on each end. When there are two similar lines (i.e., for the paver location), the first line represents the location at the start of that time duration, and the second line shows its location at the end of that time duration. Similarly, the density technician is presented by a line with the letter “D” at each end. The location of the RSS is shown by a line with the letter “R” at each end. Also, the location of the light is shown by a line with the letter “L” at each end. The grinder progressed passed the last sensor before 23:00 on Day 3 and therefore its location is not shown in the figure.

Figure 3.4 reveals that the 85th percentile speed of passenger cars (vehicles < 25 feet in length) was typically 5 to 10 mph higher than the 85th percentile speed of trucks. The 85th percentile speed of all vehicles was commonly approximately 70-75 mph at the RWA sign. Entering the work zone, the vehicle speed decreased gradually until the RSS location. After the vehicles passed the RSS, if there was no construction equipment present, the vehicle speed increased. The lowest 85th percentile speed, ranging from 40-42 mph, typically occurred adjacent the paver. There is no noticeable change in 85th percentile speed around the light when it was in the middle of the paving train.

There was a difference in the number of passing vehicles on different days in case study #2, specifically in the northbound direction. However, the changing trend in hourly traffic volume is very similar in different nights. Like case study #1, the traffic volume at the start of recording from 21:00-22:00 was at its highest, later decreased until 03:00, and then started to

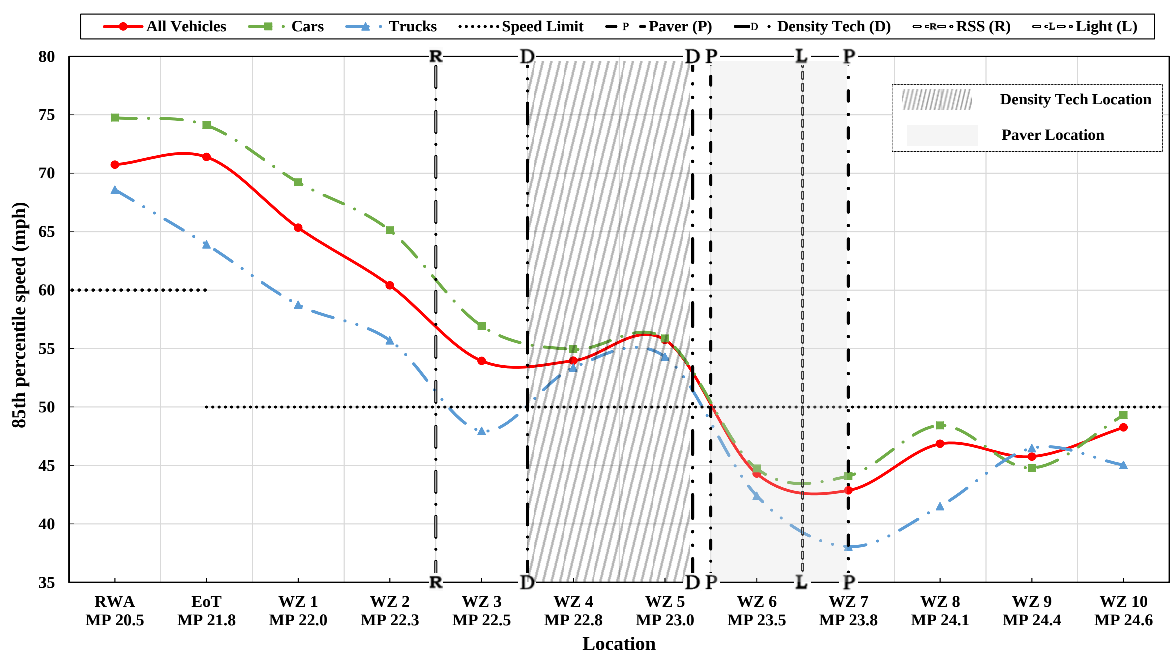

Figure 3.4 Vehicle speed (85th percentile) at different locations, 0:00-1:00, Day 3, Case study #1.

increase. In general, the percentage of cars and trucks varied from one day to the next. Days 1 and 2 (both northbound paving) are similar to each other in the percentage of trucks in most hours of recorded data. Days 3 and 4 (both southbound paving) are also approximately the same as each other in terms of the percentage of trucks during different hours of testing. Truck percentage ranged from 10% to 54% with the minimum percentage recorded between 21:00 and 22:00 on most days. The maximum truck percentage time is different on each day, and was recorded between 01:00 and 04:00.

Figure 3.5 show how the 85th percentile speed changed from the RWA sign location to the end of the work zone on Day 3 for case study #2. Similar to case study #1, the locations of the grinder, paver, and density technician were tracked with a GPS unit to understand their impact on vehicle speed. The figures show that the 85th percentile speed of passing vehicles decreased from 65-70 mph at the RWA sign to a lower speed at the end of the taper (EoT) at milepoint (MP) 27.8. Speed continued decreasing until the location of the RSS. Then, if paving equipment was near the RSS, the decreasing trend would continue and after passing the paver the speed started to increase. Otherwise, after the RSS (without paving equipment present) the speed increased and then decreased again downstream near the paver. The sensor near the light (on this day, the balloon light) shows a subtle drop in 85th percentile vehicle speed.

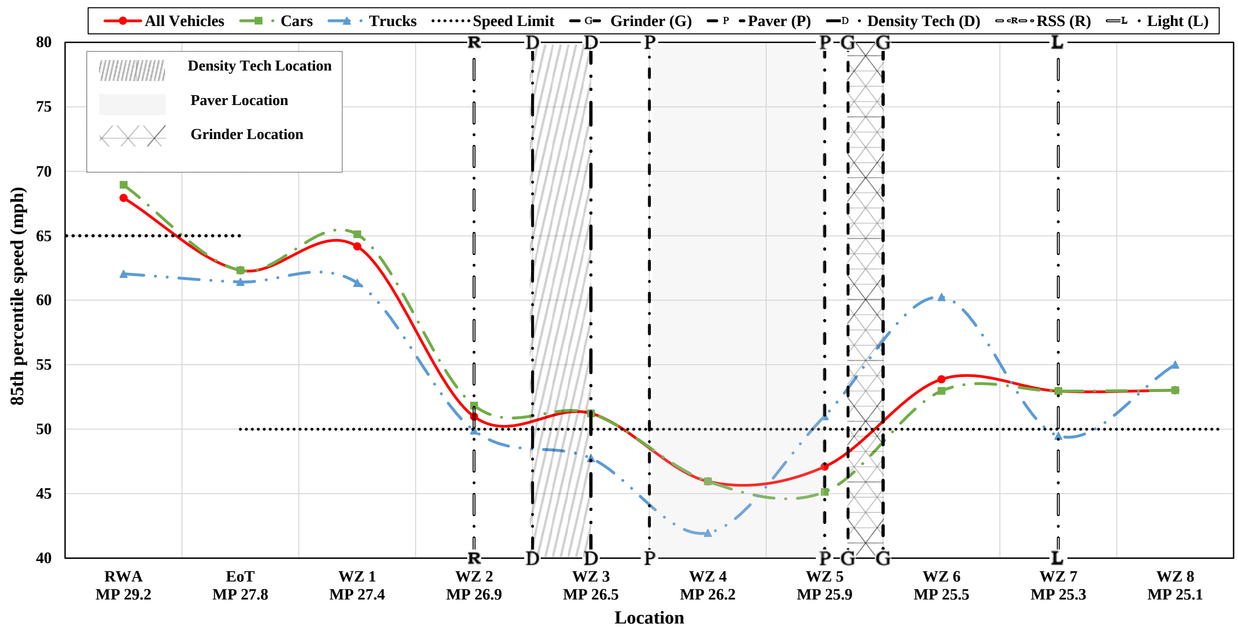

Figure 3.5 Vehicle speed (85th percentile) at different locations, 0:00-1:00, Day 3, Case study #2.

3.7 Impact of Portable Work Zone Lighting

To determine the impact of the lights, speed data from the sensors upstream, next to, and downstream of the portable light equipment was considered for comparison. For the nights of testing without additional lighting equipment, speed data was considered from the sensors which were placed at similar locations in the paving operation during nights with the additional lights present.

Descriptive statistics of the speed data to test the impact of the light in case study#1 are presented in Table 3.2. In order to compare several means simultaneously, a one-way analysis of variance (ANOVA) test was utilized to determine if the speed means were similar on different nights (Table 3.3). The analysis indicated significant difference in the mean speed among different nights. However, the magnitude of the effect size (20,611.846 / 1,504,383.386 = 0.14) indicates a small effect. The results indicate that although there is a difference in mean speed on different nights, it is not practically significant. That is, when a difference is found to be statistically significant, the result does not necessarily indicate that the difference is large, important, or helpful. The result simply provides confidence that there is a difference.

A more in-depth analysis was performed to investigate the specific differences between different nights of testing. For this analysis, the Games-Howell multiple comparison test for each of the five nights were performed, with the results shown in the Table 3.4. The Games-Howell test is used when there are different sample sizes and variance. The table shows that there is no significant difference in the mean speed between control night 1 (Day 2) and control

Table 3.2 Descriptive Statistics of Recorded Speeds, Case Study #1

Day	**No. of Data Points**	**Mean Speed (mph)**	**Std. Deviation**	**Std. Error**	**95% Confidence Interval for Mean**		**Minimum Speed (mph)**	**Maximum Speed (mph)**
					Lower Bound	Upper Bound		
Day 1 (LT/BL at RWA)	1992	39.6	10.37	0.23	39.12	40.03	19.7	97.1
Day 2 (Control Night 1)	2579	41.4	13.14	0.26	40.85	41.86	19.3	100.5
Day 3 (Light Tower)	3015	42.8	10.33	0.19	42.38	43.12	19.3	92.7
Day 4 (Balloon Light)	2988	43.2	9.99	0.18	42.81	43.52	19.3	99.5
Day 5 (Control Night 2)	2114	40.8	9.83	0.21	40.41	41.25	19.3	93.0

Table 3.3 Speed Data ANOVA Test Results, Case Study #1

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F**	**Sig.**
Between Groups	20,612	4	5,152.962	44.047	0.000
Within Groups	1,483,772	12,683	116.989		
Total	1,504,383	12,687			

night 2 (Day 5). Also, there is no significant difference in the mean speed between the light tower (Day 3) and balloon light (Day 4).

The mean speed when there was a light present (Days 3 and 4) is approximately 2 mph more than when there was no additional light in the work zone (Days 2 and 5). The difference is statistically significant but not practically significant. Drivers having better visibility of the work zone could be a reason for higher speed when there is a light present. In case study #1, on Day 1, there was an RSS located near the portable light tower and balloon light. To see the

Table 3.4 Multiple Comparisons Games-Howell Post-Hoc Test, Case Study #1

Day (I) Treatment	**Day (J) Treatment**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
LT/BL @ RWA	Control Night 1	-1.8*	0.35	0.000	-2.73	-0.83
	Light Tower	-3.2*	0.30	0.000	-3.99	-2.36
	Balloon Light	-3.6*	0.30	0.000	-4.40	-2.79
	Control Night 2	-1.3*	0.32	0.001	-2.12	-0.40
Control Night 1	LT/BL@RWA	1.8*	0.35	0.000	0.83	2.73
	Light Tower	-1.4*	0.32	0.000	-2.27	-0.52
	Balloon Light	-1.8*	0.32	0.000	-2.67	-0.95
	Control Night 2	0.5	0.34	0.521	-0.39	1.44
Light Tower (LT)	LT/BL@RWA	3.2*	0.30	0.000	2.36	3.99
	Control Night 1	1.4*	0.32	0.000	0.52	2.27
	Balloon Light	-0.4	0.26	0.505	-1.13	0.30
	Control Night 2	1.9*	0.29	0.000	1.14	2.70
Balloon Light (BL)	LT/BL@RWA	3.6*	0.30	0.000	2.79	4.40
	Control Night 1	1.8*	0.32	0.000	0.95	2.67
	Light Tower	0.4	0.27	0.505	-0.30	1.13
	Control Night 2	2.3*	0.28	0.000	1.57	3.10
Control Night 2	LT/BL@RWA	1.7*	0.32	0.001	0.40	2.12
	Control Night 1	-0.5	0.34	0.521	-1.44	0.39
	Light Tower	-1.9*	0.29	0.000	-2.70	-1.14
	Balloon Light	-2.3*	0.28	0.000	-3.10	-1.57

*: *The mean difference is significant at the 0.05 level.*

impact of the light on Day 1, the impact of the RSS on this night of testing should be investigated and accounted for.

On case study #2, sensors were placed earlier in the day than for case study #1, which provided an opportunity to collect data related to the light equipment before the grinder reached the light or after the paver passed the light. Therefore, the impact of the light can be investigated without any confounding impact of the paving equipment. Similar to case study #1, speed data from sensors upstream, next to, and downstream of the portable light equipment is considered for comparisons.

The mean speed when there was a light tower in the work zone was 50.20 mph in the northbound direction, while the mean speed when there was no additional lights at a similar sensor location in the work zone was 48.16 mph. The results of a two-sample t-test confirm that the difference in mean speeds is statistically significant (Table 3.5). For the southbound direction, data was collected on three nights of testing. The mean speeds with the presence of the light tower, the balloon light, and without the presence of additional portable light were 45.8, 49.0 and 43.9 mph, respectively. The results of the two-sample t-test comparing between the light tower and no light, and also the balloon light and no light, reveal similar findings to the analysis for the northbound direction: the mean speed when there was a light in the work zone was higher than without any light in the work zone and the difference in speed is statistically significant.

Table 3.5 Two Sample T-test for Comparison With and Without Lighting Equipment, Case Study #2

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Equal variances assumed	2.918	0.088	-3.796	1079	0.000	-2.0	0.54	-3.10	-0.99
Equal variances not assumed			-3.931	816.97	0.000	-2.0	0.52	-3.06	-1.02

3.8 Impact of Personal Light

For all nights of testing on both case studies, the density technician and dump person wore a personal light (Halo Light) while conducting their work. The personal light was turned on between midnight and 02:00, and also from 02:00-04:00; during the other times in the work shift the light was turned off.

The speed data from the sensors in the vicinity of the density technician when the light was turned on are compared to the speed data when it was turned off. The GPS tracker unit carried by the density technicians recorded their location relative to the sensors. The researchers found that density technicians stay mostly upstream of the paver, although sometimes they moved to a location slightly downstream of the paver. Based on the observations and GPS unit data which indicated the technicians were located upstream of the paver most of the time, for simplicity the speed data recorded by the sensors more than 0.0 to 0.4 miles behind the paver was considered as the vehicle speeds corresponding to the location of the density technicians. A two-sample t-test statistical analysis was performed to determine the impact of the light worn by the technicians. Table 3.6 shows the descriptive statistics of vehicle speeds around the density technicians when the light was turned on and turned off. The results of the two-sample t-tests for the cases with and without the personal light turned on, shown in Table 3.7, indicate that there is no significant difference in the passing vehicle mean speed when the light is turned on compared to without the light.

3.9 Conclusions

In this study the impacts of additional temporary roadway lighting and a personal light worn by a worker on the speed of passing vehicles in construction work zones were investigated. The initial statistical analysis showed that mean vehicle speed adjacent to the density technician wearing a personal light turned on, does not have a significant difference than the mean speed of the passing vehicles when the light is turned off. On-site observations, however, suggest that a personal (wearable) light increases worker recognition and visibility of the worker when there is no other additional light in the vicinity. In many cases the density technician, "stick-and-stomp" workers, and traffic control crew members are located in areas where there is no

Table 3.6 Descriptive Statistics of Recorded Speed near Density Technician, Case Studies #1 and #2

Case Study	Personal Light Status	N	Mean Speed (mph)	Std. Deviation	Std. Error Mean
#1	OFF (without personal light)	2874	40.3	10.93	0.20
	ON (with personal light)	2461	40.7	11.66	0.24
#2	OFF (without personal Light)	2230	43.1	8.75	0.19
	ON (with personal Light)	1802	43.0	10.44	0.25

Table 3.7 Two-sample T-test for Comparison With and Without Personal Light, Case Studies #1 and #2

	Levene's Test for Equality of Variances		T-test for Equality of Means						
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Equal variances assumed (Case Study #1)	5.777	0.016	-1.448	5333	0.148	-0.5	0.31	-1.06	0.15
Equal variances not assumed (Case Study #1)			-1.441	5089.52	0.150	-0.5	0.31	-1.06	0.16
Equal variances assumed (Case Study #2)	28.90	0.000	0.289	4030	0.773	0.1	0.30	-0.51	0.68
Equal variances not assumed (Case Study #2)			0.284	3512.81	0.777	0.1	0.31	-0.52	0.69

additional light provided by the construction equipment and could benefit from wearing a personal light.

Overall, the addition of portable lighting equipment resulted in worker detection distances that were greater with the lights turned on than without the lights on. This result is consistent with results of previous lighting studies (17) that showed that properly installed temporary work zone lighting helps to increase the distance at which workers and low-contrast objects can be detected. Future research is needed to determine whether the improvement in visibility by providing additional light in the work zone has a greater positive impact on work zone safety than the negative impact resulting from increased speed due to providing additional light.

3.10 Acknowledgments

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4 CONCLUSIONS AND RECOMMENDATIONS

This chapter provides conclusions from the research performed to investigate the effectiveness of radar speed signs and additional portable lightings for speed control in highway construction and maintenance work zones. In addition, recommendations for future research and implementation in practice are provided.

4.1 Speed Control in Work Zones

Nighttime roadway work zone activities often expose workers to the possibility of being in close proximity to vehicles traveling at high speeds with low visibility. High speed roadways with low visibility and limited protection make an unsafe and dangerous situation for both motorists and workers. Safely controlling and reducing vehicle speeds through work zones decreases the safety risk associated with highway construction and maintenance work. A variety of traffic control measures are available for speed control in work zones. The traffic control measures can lead to small-to-moderate effects on speed reduction. The most effective speed reduction will probably involve some combination of traffic control measures instead of using just one type of control measure.

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

While the present research reveals that adding temporary roadway lighting does not necessarily lead to reductions in vehicle speed, the additional lighting can improve visibility of the workers and awareness of the work operations. Similarly, wearing personal lights and highly reflective apparel and equipment helps to increase visibility of the construction activity area and the workers in the work zone. The additional lighting, whether on the roadway or on the worker, helps to increase driver recognition that a worker is present. Both of these conditions – higher visibility and greater driver awareness – help to improve safety performance in highway work zones.

The results of this research can be used by DOT Construction and Maintenance Offices for planning construction and maintenance work. The research output can also be used by the Transportation Safety Divisions and Transportation Safety Coordinators within DOTs as a resource for effectively designing work zones and planning construction and maintenance operations.

4.1.1 Radar Speed Signs

The quantitative analyses of the speed data from the four case study projects (two case study projects were presented in this document) included in this research study reveal the following:

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

- Vehicle speed is lower as the vehicles approach and pass by the work equipment with the RSS display turned on than without the RSS display turned on. 85th percentile speeds for the case study projects were approximately 2.0 mph less with the RSS display turned on compared to without the RSS display turned on.
- When comparing the percentage of vehicles travelling above the posted regulatory speed limit ("speeders") at the RWA signs to the percentage of speeders in the work zone during the entire test period, there is typically a decrease in the percentage of speeders between the two locations (i.e., fewer speeders in the work zone). The amount of decrease in the percentage of speeders is greater with the RSS turned on than without the RSS turned on. The percentage decrease ranged from 27% to 48% in the case studies when the RSS was turned on, and ranged from 15% to 36% without the RSS turned on. In addition, the decrease in the percentage of speeders is greater in the vicinity of the maintenance equipment than in the other areas of the work zone.
- The mean speed of the speeders in the work zone during the entire test period with the RSS turned on ranged from 59.9 to 61.6 mph, and without the RSS turned on ranged from 59.5 to 62.8 mph. However, the decrease in mean speed from the RWA sign to the work zone is greater with the RSS turn on than without the RSS turned on.
- The difference in speed between adjacent vehicles as the vehicles pass through the

work zone is typically less with the RSS display turned on than without the RSS display turned on. For all vehicles, the maximum mean speed difference was approximately 2.0 mph less with the RSS display turned on than without the RSS turned on.

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

Overall, the amount of decrease in vehicle speed between the RWA signs and the active work area, and the amount of decrease in the percentage of speeders, are greater with the RSS display turned on than without the RSS display turned on. The Vehicle speeds are typically lower, and there is less variation in speeds between adjacent vehicles with the RSS turned on. Decreasing the vehicle speed and variation, can reduce the likelihood of serious and/or fatal injuries to workers, motorists and their passengers and increase safety in work zone safety.

4.1.2 Temporary Portable Lighting

The quantitative analyses of the collected speed data from the two case study projects provided evidence of the impact of additional lights on vehicle speed. The following is a summary of the conclusions that can be drawn from the case study analyses:

- There is a statistically significant difference in mean speed when an additional temporary light (light tower or balloon light) is present on the roadway in the work zone compared to when a light is not present. The mean vehicle speed when there is a light tower or balloon light in the middle of the work zone is 1.8 to 5 mph greater than when there is no additional temporary light present in the work zone. Increasing the amount of lighting in, and therefore visibility of, the work zone, may cause drivers to feel more safe, have greater confidence in their assessment of the work zone, bring greater attention to the work zone, or result in other similar impacts to driver risk assessment and driving behavior, all of which could cause the drivers to increase their speed. Further research is needed to determine why speed differs with the additional temporary light present.

- There is no significant difference in mean vehicle speed when comparing the presence of the light tower to the presence of the balloon light in the work zone.
- When comparing vehicle speed adjacent to the density technician who is wearing a personal light, there is no statistically significant difference in mean speed of the passing vehicles when the personal light is turned on compared to when the light is turned off. The results of the pilot testing, however, suggest that a personal (wearable) light such as a Halo light increases worker recognition and visibility of the worker when there is no other additional light in the vicinity.
- Mean vehicle speed at the RSS is between 5.8 and 11.2 mph less than the mean speed at approximately a quarter mile before the RSS. The variance in vehicle speed is also typically lower at the RSS. Lower variance represents less difference in the speed of the passing vehicles and therefore less chance of a crash due to speed differential.

- A vehicle's speed varies as it travels through the work zone. At the RWA sign, the speed of the passing vehicle can be considered as the "normal" speed. As the vehicles approach the work area, the vehicles initially slow down at the taper and then reduce their speed gradually in the beginning of the work zone. Generally, vehicles travel at a lower speed when approaching and passing the paving equipment such as the paver, sweeper, tack truck, and grinder. Greater reduction in speed occurs near the larger pieces of equipment that have mobile lighting attached to the equipment and extensive worker activity in the immediate vicinity. After the vehicles pass by the equipment, their speed typically increases. If another piece of equipment is encountered, the vehicles slow down again. The changes in speed at and between the equipment typically repeat until all of the equipment is passed. If no other equipment is encountered, vehicle speed remains high and constant through to the end of the work zone.

The density technician, dump person, spotters, "stick-and-stomp" workers, and traffic control crew members are examples of personnel who are regularly on foot on the roadway throughout the work shift, placing them in locations of high exposure to oncoming traffic. Worker position with respect to the light has a significant impact on all of these workers being visible to oncoming motorists and equipment operators. Sometimes a difference of just a few feet can make a big difference in their visibility.

Visibility of workers to equipment operators is also a significant concern. Additional lighting, whether a light tower or balloon light located on the roadway, a mobile light attached to the equipment, or a personal light worn by the workers, also help to make the workers visible to the equipment operators.

A significant consideration of any paving project is mobility of equipment and workers. Equipment that is not mobile severely limits the feasibility of using the equipment. Lighting systems that are attached to the equipment will be more applicable and acceptable than those that are stationary.

4.2 Limitations of The Study

A limited number of case study projects were conducted in this study. Initially, more data collection was planned to measure the effectiveness of radar speed signs and additional lighting systems, but a limited number of projects were available. Further research on more case study projects in different roads and highway conditions would be beneficial to improving and confirming the results of current study.

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

The applicability of the research to all preservation projects is dependent on the number and types of tests performed. The number of workers on the case studies who wore the personal light, for example, was limited due to the number of available personal lights and the available workers to wear the lights. Further research that includes additional workers wearing personal lights will increase confidence in the research results and provide more detailed guidance on their use.

4.3 Recommendations and Future Research

Truck-mounted RSS displays are applicable to and useful for both continuously moving (e.g., spraying and sweeping) and intermittent mobile (e.g., relamping and vactoring) work operations. Use of truck-mounted RSS signs are recommended for all such operations, and especially those which do not include a lane closure or in which additional support equipment is lacking or minimal. Exposed equipment and workers during operations that do not include a lane closure or have additional support vehicles for protection can especially benefit from the reduced speeds and increase in driver attention created by the RSS display. DOTs and contractors should consider expanding availability and use of a truck-mounted RSS unit throughout all their projects. The present study also exposed the possibility for additional research to fully understand the impacts of RSS displays and optimize their use. Further research to investigate and evaluate motorist reactions based on different sign settings and different messages is warranted. Standardized messages and RSS speed settings should be developed and used in order to make maintenance work zones appear as consistent as possible throughout a state.

The addition of both the balloon light and light tower resulted in worker detection distances that were greater with the lights turned on than without the lights on. Properly installed temporary work zone lighting helps to increase the distance at which workers and low-contrast objects can be detected. Future research is needed to determine whether the improvement in visibility by providing additional light in the work zone has a greater positive impact on work zone safety than the negative impact resulting from increased speed due to providing additional light.

Additional lighting on the front and rear of each piece of equipment can further illuminate workers on foot that are located between each piece of equipment. The benefits of such lighting and impacts on worker safety, and potential negative impacts on glare for motorists and equipment operators, is another recommended area of future research.

Lastly, the present research focused on mobile paving projects. The research should be expanded to other types of projects as well. Additional investigation into the impacts of radar speed signs and lighting systems on vehicle speed is needed for stationary projects on high-speed roadways.

5 APPENDIX

I. Gambatese, J. A., and A. Jafarnejad. *Evaluation of Radar Speed Display for Mobile Maintenance Operations*. Report OR-RD-16-09. Oregon State University, Corvallis, Oregon Department of Transportation Research Section, Salem, and FHWA, U.S. Department of Transportation, 2015.
http://www.oregon.gov/ODOT/Programs/ResearchDocuments/RSS_Final_Report_OR_RD_16_09.pdf

II. Gambatese, J. A., and A. Jafarnejad. *Use of Additional Lighting for Traffic Control and Speed Reduction in Work Zones*. SPR791. Oregon State University, Corvallis, Oregon Department of Transportation Research Section, Salem, and FHWA, U.S. Department of Transportation, 2017.
http://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR791WP.pdf
(Final research report forthcoming)