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# Examination of the Current Practice of Lighting in Virginia: Nighttime Work Zones and Improving Safety Through the Development of Nighttime Lighting Specifications: Summary Report

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16. Abstract:

This project evaluated current nighttime work zone lighting practices for limited-access highways and primary routes in Virginia through (1) an on-site evaluation of lighting levels in work zones; (2) an illuminance characterization of various commercially available light towers; and (3) a human factors evaluation of those light towers and developed effective nighttime work zone lighting requirements for Virginia.

The majority of the static nighttime work zones used metal halide portable light towers. Mobile operations such as milling and paving used equipment-mounted balloon lights and LEDs. Horizontal illuminance levels in the work zones were affected by the number of light towers, locations of the light towers, and number of traffic lanes in the work zone. The measured horizontal illuminance levels in the work zones were much higher than recommended levels. Milling and paving operations that used equipment-mounted lights had lower illuminance levels than operations that used portable light towers. Vertical illuminance levels in the traffic lane were significantly affected by the aiming of the luminaires on the portable light towers. Luminaires aimed into the traffic travel lane produced higher vertical illuminance levels, which can result in disability and discomfort glare and consequently reduce visibility.

The visual performance of drivers in a work zone can be influenced by the type and orientation of the light tower. An orientation aimed toward the driver resulted in lowering drivers' visual performance, both objectively and subjectively. This decrease in visual performance could be attributed to higher vertical illuminance. To increase the drivers' visual performance and reduce glare in the work zone, efforts should be taken to aim the light towers in an active nighttime work zone away from the direction of traffic or perpendicular to it. In these orientations, all the three light towers tested had similar visual performance measures. The increase in the mean vertical illuminance level in the critical range is associated with higher perceived ratings of glare.

Results showed that the mean vertical illuminance in the distance range of 260 to 65 ft to the light tower could be used as an objective measure of glare. A mean vertical illuminance of less than 17 lux resulted in lower perceived glare ratings. Results also indicated that light towers should be oriented so that the angle between the beam axis and driver line-of-sight axis is always greater than or equal to 90 degrees. Finally, a draft specification outline including a plan for on-site lighting evaluation of a work zone is presented.


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**FINAL REPORT**

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## ABSTRACT

This project evaluated current nighttime work zone lighting practices for limited-access highways and primary routes in Virginia through (1) an on-site evaluation of lighting levels in work zones; (2) an illuminance characterization of various commercially available light towers; and (3) a human factors evaluation of those light towers and developed effective nighttime work zone lighting requirements for Virginia.

The majority of the static nighttime work zones used metal halide portable light towers. Mobile operations such as milling and paving used equipment-mounted balloon lights and LEDs. Horizontal illuminance levels in the work zones were affected by the number of light towers, locations of the light towers, and number of traffic lanes in the work zone. The measured horizontal illuminance levels in the work zones were much higher than recommended levels. Milling and paving operations that used equipment-mounted lights had lower illuminance levels than operations that used portable light towers. Vertical illuminance levels in the traffic lane were significantly affected by the aiming of the luminaires on the portable light towers. Luminaires aimed into the traffic travel lane produced higher vertical illuminance levels, which can result in disability and discomfort glare and consequently reduce visibility.

The visual performance of drivers in a work zone can be influenced by the type and orientation of the light tower. An orientation aimed toward the driver resulted in lowering drivers' visual performance, both objectively and subjectively. This decrease in visual performance could be attributed to higher vertical illuminance. To increase the drivers' visual performance and reduce glare in the work zone, efforts should be taken to aim the light towers in an active nighttime work zone away from the direction of traffic or perpendicular to it. In these orientations, all the three light towers tested had similar visual performance measures. The increase in the mean vertical illuminance level in the critical range is associated with higher perceived ratings of glare.

Results showed that the mean vertical illuminance in the distance range of 260 to 65 ft to the light tower could be used as an objective measure of glare. A mean vertical illuminance of less than 17 lux resulted in lower perceived glare ratings. Results also indicated that light towers should be oriented so that the angle between the beam axis and driver line-of-sight axis is always greater than or equal to 90 degrees. Finally, a draft specification outline including a plan for on-site lighting evaluation of a work zone is presented.

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## INTRODUCTION

Work zone safety is an important consideration for construction and maintenance activities on our nation's roadways. A preliminary analysis of 2012 Virginia data shows that 3,065 crashes, 1,582 injuries, and 13 deaths occurred in work zones (Virginia Department of Transportation, 2013). As traffic volumes increase and more construction activities occur at night, the safety issues grow more complex. Although traffic volumes are lower at night, travel speeds are generally higher and visibility is lower, leading to potentially higher risks for motorists and workers. During 2011, for example, approximately 40% of all work zone crashes occurred at night (Virginia Department of Transportation, 2013).

One of the key safety issues concerning nighttime work zones is lighting. A 2012 study of 208 nighttime work zones in Virginia found that the lighting of the work area by the contractor, as well as lighting on Virginia State Police vehicles, appeared to be excessive and caused brief periods of glare to workers and travelers. Currently, the *Virginia Work Area Protection Manual* (VDOT, 2011) only requires the lighting of flagger stations and the wearing of American National Standards Institute (ANSI) Class 3 high-visibility safety apparel. Unlike some other states (e.g., North Carolina, Florida, Georgia, and New Jersey), the Virginia Department of Transportation (VDOT) does not currently have any additional nighttime lighting requirements for work zone areas or equipment.

## State-of-Practice Survey in Virginia

To fulfill the goal of the project to make night work zones safe places for both workers and motorists without creating unnecessary expense or annoyance, a survey was designed to collect information regarding current lighting practices employed by contractors and their workers. This section summarizes the results of the Work Zone Lighting Survey. Overall, 18 responses were received. The main results from the state-of-practice survey are summarized as follows:

- A significant majority (74%) of the responses were provided by private companies contracting with VDOT. A majority (52%) of the respondents indicated that nighttime operations involved milling and resurfacing, or pavement markings.

- Seventy percent of the respondents are in charge of providing the necessary lighting to conduct nighttime activities. Sixty-seven percent of the respondents indicated that lighting is taken into consideration as soon as they know the work will include nighttime operation. A strong majority (88%) of the respondents indicated that their own company is responsible for developing lighting plans. Lighting plans for the work zones used *Manual on Uniform Traffic Control Devices* (MUTCD) guidelines (FHWA, 2009), state specifications, Occupational Safety and Health Administration (OSHA) requirements, and organizations' own specifications. The reference standards used for each type of operation (stationary and mobile) are shown in Figure 1.

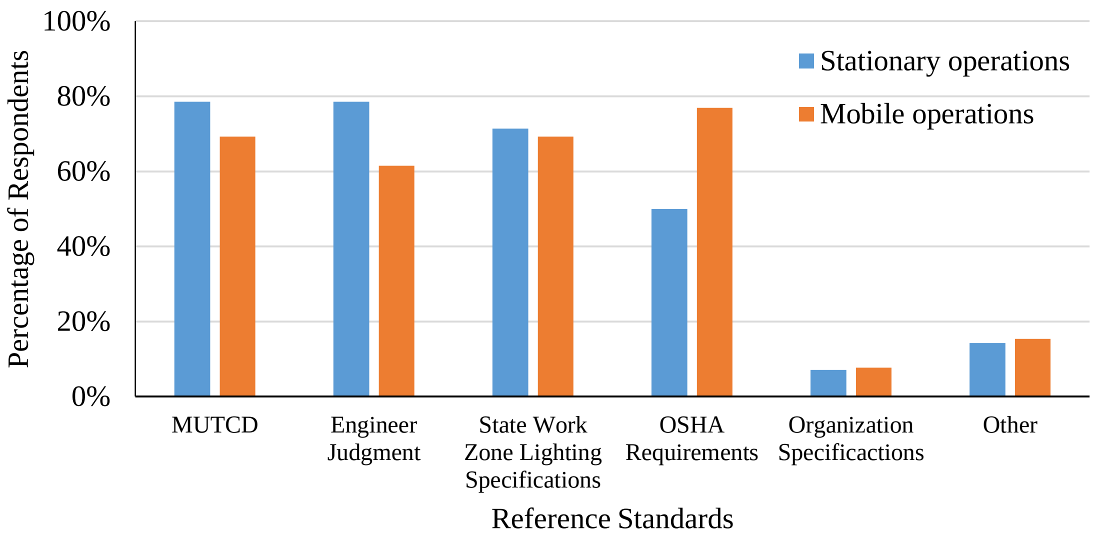


**Figure 1. Reference standards used to select lighting specifications.**

- Seventy-one percent of the respondents indicated that they need not submit a work zone lighting plan. Respondents that submit a work zone lighting plan indicated that the plan often includes number and type of lighting equipment (86%), measures to reduce glare, and the method for evaluating that glare to drivers (71%). Placement of lighting equipment and illuminance level were included on the lighting plan by 57% of these respondents. Less frequently included in the lighting plan were methods to evaluate if the lighting was too bright and methods for evaluating glare for workers (43% and 29%, respectively). Fifty-seven percent of the respondents evaluate the presence of street lighting but do not measure it.

- Seventy-one percent of the respondents indicated that glare is evaluated subjectively by performing a drive through. Twenty-one percent responded that they do not evaluate glare at all. The majority of the respondents indicated that lighting (83%) and glare (73%) are evaluated only during setup.

- Portable light towers are the most common types of lighting equipment used (89%). The majority of the respondents indicated that portable light towers produce the right amount of light. Repositioning the equipment was the countermeasure most selected for the different types of equipment for reducing glare, with response percentages ranging from 77% for portable light towers to 40% for semi-permanent high-mast lighting. The exception was balloon lights (6% of responses). Aiming the luminaires was selected as a successful countermeasure to prevent glare for portable light towers (55%), equipment lighting (50%), and equipment/work-vehicle headlamps (35%). Dimming was not ranked high for any of the lighting equipment.

Finally, it should be noted that that because the survey responses were self-reported, there could be some bias associated with the responses.

## Research Gaps and Needs

Based on the literature review and the state-of-practice survey, the following research gaps have been identified:

1. Glare is evaluated subjectively and only at setup. This is a major problem because subjective evaluation has the inherent bias of the engineer or the inspector performing the evaluation. If that person has a higher tolerance to glare, then the result could be higher glare for drivers entering the work zone. Furthermore, when portable light towers are used, often the aiming and the orientation of the light tower are changed depending on the task. If the evaluation is conducted only at setup, then there is a risk that a new orientation of the light tower could result in higher glare.

2. Glare specification is limited to minimizing glare for the traveling public. There are no lighting level specifications, recommended light positions, or orientations to guide the contractors to reduce or control glare.

3. No on-site evaluation of lighting in the work zone is performed. This is separate from the glare evaluation mentioned earlier. Without an on-site evaluation, it is extremely difficult to check whether the minimum required lighting levels for the work area are being met.

This research effort has three overarching goals, and achieving these goals is intended to address the existing research gaps in work zone lighting in Virginia. The three goals are as follows:

1. To identify an objective measure of glare and recommend acceptable levels of glare based on this measure. This goal will also help in developing a measurement procedure for the objective measure of glare.

2. To recommend light tower positions and orientations that will result in lower glare for motorists entering the work zone.

3. To develop a work plan for an on-site evaluation of the lighting in the work zone.

To achieve these goals, first, an on-site evaluation of lighting levels in work zones in Virginia was conducted to understand and document existing procedures. Second, an illuminance characterization of various commercially available light towers was conducted to understand the effect of light tower orientation on distribution of light in the work zone. Finally, a human factors evaluation of these light towers was conducted to understand the effect of different light tower types and orientations on visibility, glare, and driver behavior. This human factors evaluation also help identify an objective measure of glare, recommend illuminance levels, and orientations that reduce glare.

## PURPOSE AND SCOPE

The purpose of this study was to evaluate the current lighting practices used in nighttime work zones on limited-access highways and primary routes and to develop effective nighttime work zone lighting requirements for Virginia.

## METHODS

Evaluation of existing lighting practices in nighttime work zones and development of lighting requirements for Virginia was conducted in three phases. In the first phase an onsite evaluation of lighting levels in active nighttime work zones was conducted. In the second phase, luminaires commonly used in the active nighttime work zones along with the newer technologies were characterized for horizontal and vertical illuminance levels in a simulated work zone. In the third phase, the commonly used and newer work zone light sources were evaluated in terms of visibility and glare from the drivers' point of view.

## Phase 1 – On-Site Evaluation of Lighting Levels Used in Active Nighttime Work Zones in Virginia

On-site evaluation of lighting levels in active work zones in Virginia served two objectives:

1. To document the most common configuration of lighting used in Virginia work zones.

2. To conduct a field measurement of the lighting performance parameters and compare them to the recommended levels.

## Phase 2 – Characterization of Lighting Performance of Common Luminaires and New Lighting Sources

In this task, three light tower types were characterized on the Virginia Smart Road (hereinafter Smart Road) in terms of both vertical and horizontal illuminance. Since the aiming of the light tower plays a crucial role in the levels of vertical illuminance levels experienced by the driver, it is important to understand the impact of various orientations on vertical illuminance levels. The goal of this task was to understand the changes in the distribution patterns of the illuminance levels when the orientation of the tower was changed. This characterization also informed the research team about the critical distances where vertical illuminance levels increase rapidly.

### Types of Portable Light Tower

Three types of portable light tower were used (Figure 2). The first was a metal halide portable light tower (manufacturer: Grandwatt Electric Corp, model 4TN4000D-1700) with four 1,000-W metal halide luminaires. These light towers are commonly used in active nighttime work zones in Virginia. The second was a balloon light tower (Manufacturer: 812 Illumination, model 4000W HID) with four 1,000-W metal halide luminaires enclosed within a balloon, which diffuses the light. Balloon light towers are being used in mobile milling and paving operations and are usually mounted on vehicles. The third light was a newer LED light tower (Manufacturer: Grandwatt Electric Corp, model Pitmaster LED 6HTM1500). LED portable light towers were not encountered in on-site lighting evaluations conducted in the earlier task. A mounting height of 20 ft was used.


**Figure 2. Portable light towers used in Virginia Smart Road characterization.**

## Light Tower Orientation

The on-site evaluation of vertical illuminance levels showed that the light tower orientation has a significant impact on the vertical illuminance levels experienced by a driver approaching a work zone. Therefore, three different orientations were selected for evaluation. In the first orientation (the "Towards" orientation), the light tower and the luminaires were oriented toward the traffic in such a way that the angle between the driver sight axis and the luminaire beam axis was 45 degrees (Figure 3a). This is the maximum angle recommended by NCHRP 498. In the second orientation (the "Away" orientation), the light tower and luminaires were orientated away from the traffic in such a way that the angle between the driver sight axis and luminaire beam axis was 135 degrees (Figure 3b). In the final orientation (the "Perpendicular" orientation), the light tower and luminaires were oriented perpendicular to the direction of traffic in such way that the angle between the driver sight axis and luminaire beam axis was 90 degrees (Figure 3c). For the metal halide and the LED light towers the angle between the vertical and center of the beam axis was 60 degrees.

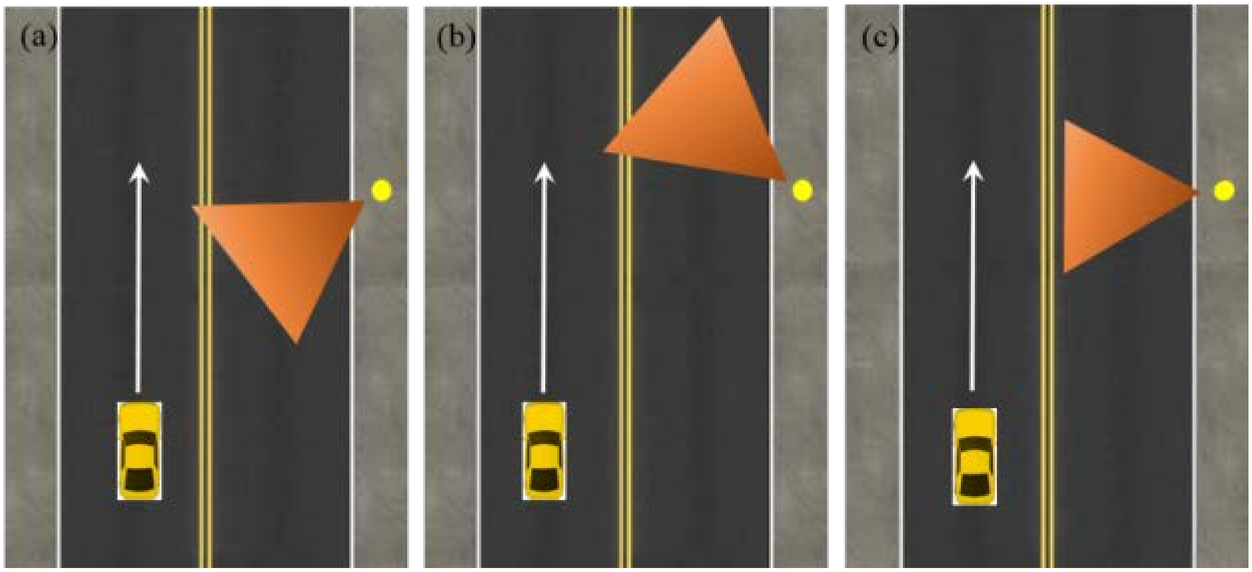

**Figure 3. Light tower orientations used for illuminance characterization. (a) Towards oncoming traffic. (b) Away from oncoming traffic. (c) Perpendicular to traffic.**

### Characterization Method

The characterization was performed on the Smart Road at VTTI. The TRLMMS was used to measure the illuminance levels for the three light towers, each in three orientations.

## Phase 3 – Smart Road Field Testing

The objective of this task was to evaluate a subset of the lighting configurations found in active nighttime work zones in Virginia, both objectively and subjectively, in a simulated work zone in the safety of a closed test course. The closed test course would give the research team the ability to manipulate different factors of interest.

This task had two goals. The first was to evaluate objectively the effect of the three types of portable light towers and their orientations on driver visual performance. The second was to understand the perceptions of drivers for the three types of light towers and their orientations in terms of visibility and glare. Results from this task helped to develop specifications for lighting work zones in Virginia to reduce glare from drivers and increase the visibility of workers.

The independent variables used in the study and their categorical values are summarized in Table 1, with additional details below.

**Table 1. List of independent variables and their categorical values**

| Independent Variables | Levels |
|---|---|
| Age | Older (60+ years)<br>Younger (18–35 years) |
| Light tower type (mounting height 20 ft) | Metal halide<br>Balloon<br>LED |
| Orientation | Away (aimed away from travel lane at 135 degrees)<br>Towards (aimed towards travel lane at 45 degrees)<br>Perpendicular (aimed perpendicular to the travel lane at 90 degrees) |

*Dependent Variables*

**Detection Distance.** Detection distance was the distance at which the participants detected the worker in the work zone. Detection distance is a measure of how well a worker is visible under each light type and orientation. Higher detection distances indicate lower glare and better visibility.

**Speed.** The average speed of the participant vehicle in the work zone was also measured. It was hypothesized that the light tower types and orientations that had higher glare would result in participants slowing down in the work zone in order to drive safely and detect the worker.

**Perceptions of Visibility and Glare.** Participants rated their agreement with six statements using a custom questionnaire developed for this study that assessed visibility and glare using a Likert scale. Visibility was assessed by four statements (statements 1, 3, 4 and 6), and glare was assessed by two statements (statements 2 and 5).

## RESULTS

### Characteristics of Selected Work Zones

Data were collected from a total of 10 active nighttime work zones. The 10 active work zones consisted of five milling and paving operations, two bridge work operations, one trench drain installation, one road widening operation, and one on-ramp pavement operation. The locations of these work zone operations and the type of operations are shown in Table 2.

**Table 2. Locations and type of work zones**

| Location | Type of Operation | VDOT District |
|---|---|---|
| I-81 S | Bridge work | Bristol |
| I-81 N | Bridge work | Bristol |
| I-81 N | Milling and paving | Bristol |
| I-581 S | On-ramp | Salem |
| I-264 W | Milling and paving | Hampton Roads |
| I-64 W | Trench drain installation | Hampton Roads |
| I-64 E | Road widening | Richmond |
| I-64 W | Milling and paving | Richmond |
| VA-674 | Milling and paving (2) | Northern VA |

## Summary of Work Zone Characteristics

The most common type of portable light tower used in the work zones has four metal halide luminaires (Table 3). These were used at 6 of the 10 work zones where field measurements were conducted. These portable light towers were predominantly used for illuminating a static work area, such as with bridge work, trench drain installation, and road widening. At all the locations where this type of light tower was used, all four luminaires mounted on the tower were lit, except for the trench drain operation, where only one luminaire was lit.

Balloon light towers were commonly used in milling and paving operations and were always mounted on the pavers. Out of the five milling and paving operations where field measurements were conducted, balloon lights were used at three locations (see Table 3). At all three locations, the balloon lights were mounted on the pavers. At one location (I-264 W), the milling and paving machines utilized vehicle-mounted LED lights. The LEDs were attached to the body of the paver in such way that they illuminated the area in front of them.

The number of portable light towers used depended on the length of the work zone and the area of the work. Locations that covered larger areas had multiple light towers, whereas smaller work areas used a single light tower (see Table 3). Police vehicles with flashing blue lights were located at all the active work zones where field measurements were conducted except at two locations.

**Table 3. Characteristics of work zones observed in this study**

| Location | Type of Work | No. of Portable Light Towers | No. of Luminaires on Each Light Tower | Type | Name | Police Present? |
|---|---|---|---|---|---|---|
| I-81 S | Bridge work | 2 | 4 | Metal halide | Wacker Neuson LTN6 | Yes |
| I-81 N | Bridge work | 2 | 4 | Metal halide | Wacker Neuson LTN6 | Yes |
| I-81 N | Milling and paving | 2 | 1 | Balloon | Vehicle Mounted - Airstar 2000W | No |
| I-581 S | On-ramp work | 3 | 4 | Metal halide | Wacker Neuson LTN6 | Yes |
| I-264 W | Milling and paving | 2 | 4 | LED | Vehicle Mounted | Yes |
| I-64 W | Trench drain | 1 | 4 | Metal halide | Terex AL4000 | Yes |
| I-64 E | Road widening | 1 | 4 | Metal halide | Magnum | No |
| 1-64 W | Milling and paving | 2 | 2 | Balloon | Vehicle Mounted - Airstar 2000W | Yes |
| VA-674 | Milling and paving | 3 | 1 | Balloon | Vehicle Mounted - Powermoon 9000W | Yes |
| VA-674 | Milling and paving | 3 | 4 | Metal halide | Terex AL4000 | Yes |

## Lighting Performance Measurement

Light levels were measured in two specific orientations: (1) horizontal, and (2) vertical. These are shown in Table 4, Table 5, and Table 6.

**Table 4. Horizontal illuminance and luminance levels in traffic travel lane at work zones**

| Location | Type of Work | Horizontal Illuminance (lux) | | | | Luminance (cd/m$^2$) |
|---|---|---|---|---|---|---|
| | | Mean | *SD* | Max | Min | Mean |
| I-81 S | Bridge work | 23.58 | 52.12 | 265.99 | 0.04 | 27.51 |
| I-81N | Bridge work | 5.19 | 22.08 | 199.85 | 0.04 | 13.13 |
| I-81 N | Milling and paving | 0.77 | 3.10 | 63.19 | 0.04 | NA |
| I-581 S | On-ramp work | 6.52 | 78.16 | 14.15 | 0.04 | 5.88 |
| I-264 W | Milling and paving | 3.48 | 3.98 | 17.55 | 0.07 | 0.28 |
| I-64 W | Trench drain installation | 8.60 | 4.30 | 18.52 | 1.94 | 0.23 |
| I-64 E | Road widening | 2.40 | 3.18 | 17.64 | 0.07 | 2.19 |
| I-64 W | Milling and paving | 4.31 | 8.69 | 46.79 | 0.07 | 4.50 |
| VA-674 | Milling and paving | 29.65 | 52.15 | 293.86 | 1.38 | 0.74 |
| VA-674 | Milling and paving | 17.76 | 45.47 | 317.89 | 0.45 | 0.74 |

NA – not available because of equipment malfunction.

**Table 5. Horizontal illuminance and luminance levels in the work area at work zones**

| Location | Type of Work | Mean Horizontal Illuminance (lux) | Mean Luminance (cd/m$^2$) |
|---|---|---|---|
| I-81 S | Bridge work | 1420.34 | 90.42 |
| I-81 N | Bridge work | 955.15 | 60.81 |
| I-81 N | Milling and paving | NA | NA |
| I-581 S | On-ramp work | 379.54 | 60.41 |
| I-264 W | Milling and paving | 415.32 | 6.61 |
| I-64 W | Trench drain installation | 542.24 | 17.26 |
| I-64 E | Road widening | 1091.00 | 21.18 |
| 1-64 W | Milling and paving | 170.50 | 4.49 |
| VA-674 | Milling and paving | 165.50 | 5.40 |
| VA-674 | Milling and paving | 113.10 | 5.40 |

NA – not available due to equipment malfunction.

**Table 6. Vertical illuminance levels in traffic travel lane at work zones**

| Location | Type of Work | Vertical Illuminance (lux) | | | |
|---|---|---|---|---|---|
| | | Mean | *SD* | Max | Min |
| I-81 S | Bridge work | 22.68 | 31.34 | 122.20 | 0.04 |
| I-81N | Bridge work | 0.88 | 1.72 | 14.91 | 0.04 |
| I-81 N | Milling and paving | 8.77 | 7.74 | 134.77 | 0.04 |
| I-581 S | On-ramp work | 15.47 | 77.46 | 13.62 | 0.19 |
| I-264 W | Milling and paving | 7.73 | 8.42 | 90.22 | 0.04 |
| I-64 W | Trench drain installation | 4.34 | 4.33 | 24.15 | 0.53 |
| I-64 E | Road widening | 0.79 | 0.47 | 2.64 | 0.04 |
| I-64 W | Milling and paving | 3.89 | 4.83 | 24.32 | 0.04 |
| VA-674 | Milling and paving | 18.68 | 20.12 | 117.20 | 0.15 |
| VA-674 | Milling and paving | 15.32 | 29.15 | 281.43 | 0.07 |

*Vertical Illuminance in the Opposing Lane*

Improper aiming of the portable light towers could also introduce glare to drivers travelling in the opposing direction travel lanes as a direct result of higher vertical illuminance levels (Figure 4). This shows that care must be taken from the opposing lane's point of view when aiming the portable light towers in work zones when the median width is less than 11 m (~36 ft)

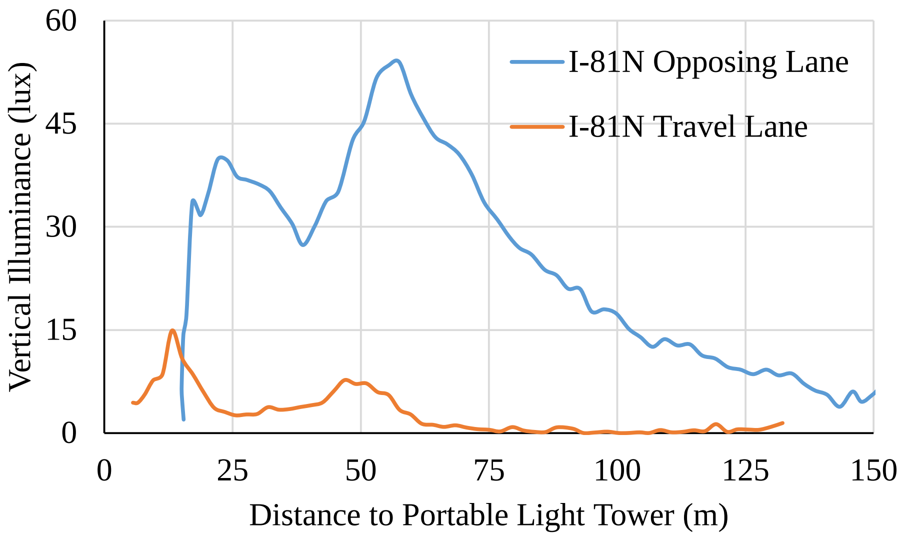


**Figure 4. Change in the vertical illuminance as vehicle gets closer to portable light tower when in the travel lane vs. the opposing lane.**

## Vehicle Speed in the Work Zones

Vehicle entry speeds, exit speeds, and vehicle counts were measured at six work zones. However, there were many issues with the placement of radar and camera systems in the work zones. First, due to the lane closures in active work zones, there is no place on either shoulder of the road to place the radar system without compromising the accuracy of the speed measurement. Second, to measure the effect of lighting from the light towers on driver behaviors, the radars have to be located very close to the light towers; however, in active work zones this could not be done without hindering the work being done. Moreover, in mobile operations such as milling and paving, the light towers located on the machines are constantly moving, making it impossible to place the radar systems in close proximity. Because of these issues, the radar systems were located at the beginning and end of the work zones. At the beginning, the radar systems were placed at the location of the police vehicle and the truck-mounted attenuator (TMA). A major issue with this location is that the change in speed of the vehicles entering the work zone could also be attributed to the presence of the police vehicle with flashing blue lights, which creates potential confounding effects. Another issue that could have a potentially confounding effect on driver behavior is traffic backing up at the work zones. This phenomenon was observed at one location (I-81 S Bridge work) in the field testing where vehicles were moving very slowly because of a traffic jam. These issues made it extremely hard to attribute the changes in speed or driver behavior to the lighting in work zones. Consequently, the research team collected speed data for only five work zones.

## Results and Discussion of Characterization of Lighting Performance of Common Luminaires and New Lighting Sources

### Horizontal Illuminance Characterization

The mean, standard deviation, maximum, and minimum of the horizontal illuminance levels in both the downhill and uphill directions are shown in Table 7. Horizontal illuminance levels in the travel lane greatly depended on the light tower type and its orientation. Illuminance levels for balloon light towers were similar in both uphill and downhill directions, and in all orientations. In general, horizontal illuminance levels were highest in the Perpendicular and Towards orientations and lowest in the Away orientation. The metal halide and the balloon light towers had higher illuminance levels than the LED light tower (Figure 5), which could be attributed to their wider light distributions.

**Table 7. Overall horizontal illuminance levels; the average of both the uphill and downhill directions**

| Type of Light Tower | Light Tower Orientation | Horizontal Illuminance (lux) | | | |
|---|---|---|---|---|---|
| | | Mean | *SD* | Max | Min |
| Balloon | NA | 1.76 | 6.60 | 63.17 | 0.02 |
| LED | Away | 0.64 | 0.43 | 5.23 | 0.04 |
| LED | Perpendicular | 0.89 | 1.82 | 20.63 | 0.07 |
| LED | Toward | 0.96 | 1.72 | 22.67 | 0.04 |
| Metal halide | Away | 1.06 | 3.60 | 54.05 | 0.04 |
| Metal halide | Perpendicular | 2.16 | 9.13 | 85.26 | 0.04 |
| Metal halide | Toward | 2.48 | 8.60 | 73.85 | 0.04 |

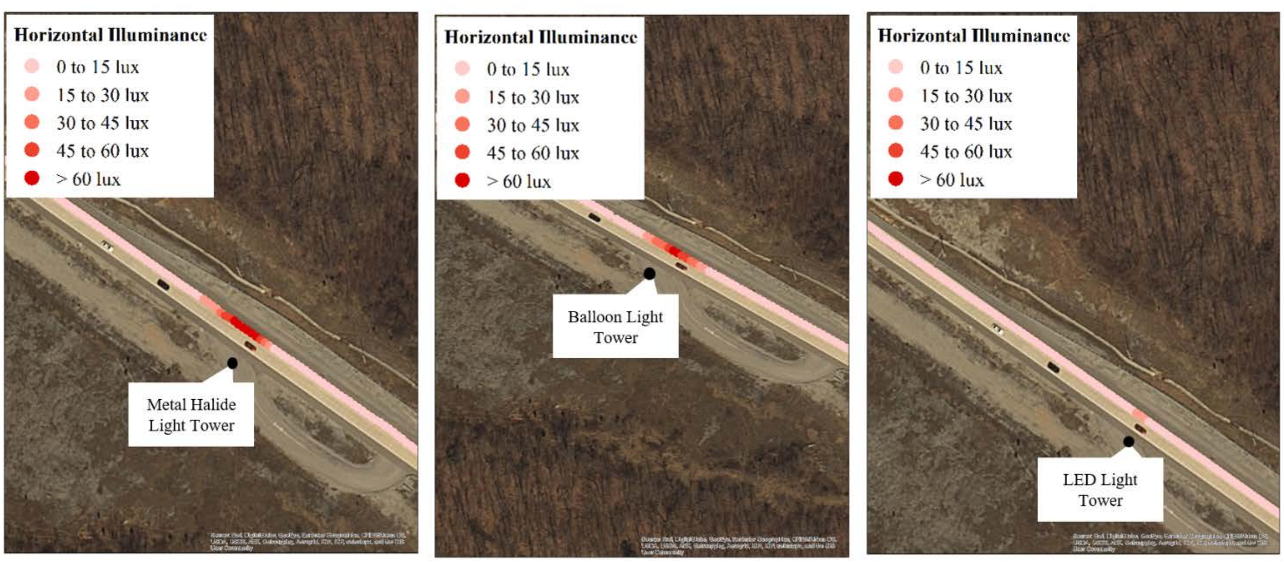


**Figure 5. Horizontal illuminance levels in the three portable light tower types in the Towards orientation.**

## Vertical Illuminance Characterization

The mean, standard deviation, maximum, and minimum of the vertical illuminance levels in both the downhill and uphill directions are shown in Table 8. Like horizontal illuminance levels, the vertical illuminance levels in the travel lane also greatly depended on the light tower type and its orientation. With balloon light towers, vertical illuminance levels were similar in both uphill and downhill directions, and in all orientations because of its circular light distribution pattern. In general, vertical illuminance levels were highest in the Towards orientations and lowest in the Away and Perpendicular orientations.

**Table 8. Overall vertical illuminance levels; the average of both the uphill and downhill directions**

| **Type of Light Tower** | **Light Tower Orientation** | **Vertical Illuminance (lux)** | | | |
|---|---|---|---|---|---|
| | | **Mean** | ***SD*** | **Max** | **Min** |
| Balloon | NA | 10.92 | 9.03 | 51.30 | 0.04 |
| LED | Away | 10.58 | 7.81 | 39.62 | 0.07 |
| LED | Perpendicular | 11.07 | 8.66 | 51.76 | 0.07 |
| LED | Towards | 10.19 | 7.93 | 43.60 | 0.04 |
| Metal halide | Away | 9.96 | 8.35 | 74.95 | 0.07 |
| Metal halide | Perpendicular | 7.50 | 8.92 | 67.09 | 0.07 |
| Metal halide | Towards | 12.46 | 13.65 | 89.56 | 0.07 |

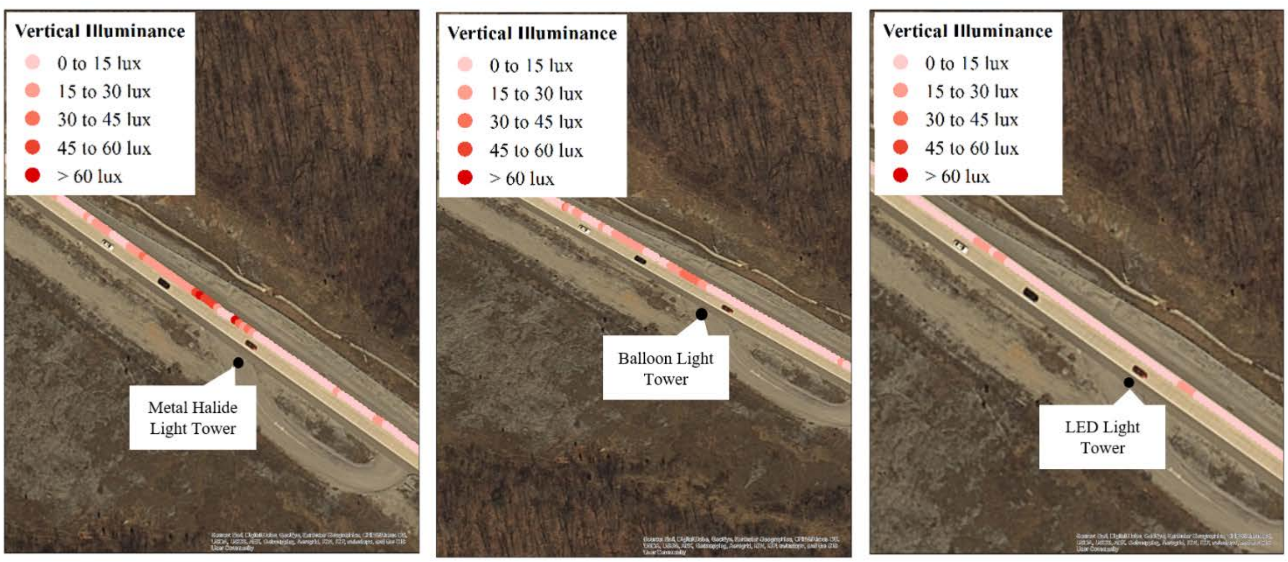


**Figure 6. Vertical illuminance levels in the three portable light tower types in the Towards orientation.**

## Critical Range for Vertical Illuminance

The mean vertical illuminance levels for all the light tower types in each orientation are shown in Table 9. The distribution of the vertical illuminance revealed that the increase in the vertical illuminance consistently occurs between a distance of 20 to 80 m from the light tower, irrespective of light tower type and orientation. In this critical range, the rapid increase in the vertical illuminance also results in increase in disability glare.

Table 9. Vertical illuminance levels in critical range (80 m to 20 m to the light tower)

| Type of Light Tower | Light Tower Orientation | Critical Range Mean Vertical Illuminance (lux) | | |
|---|---|---|---|---|
| | | Downhill | Uphill | Overall Mean |
| Balloon | NA | 19.58 | 15.58 | 17.58 |
| LED | Away | 6.98 | 9.67 | 8.33 |
| LED | Perpendicular | 10.03 | 8.01 | 9.02 |
| LED | Towards | 10.04 | 13.28 | 11.66 |
| Metal halide | Away | 10.73 | 9.40 | 10.07 |
| Metal halide | Perpendicular | 15.42 | 16.02 | 15.72 |
| Metal halide | Towards | 25.73 | 27.64 | 26.69 |

## Smart Road Field Testing Results

### Detection Distance Analysis

The combined effects of light type and light orientation on detection distance are shown in Figure 7. In all three orientations, detection distance differences between the metal halide and balloon light towers were not significant. Detection distances under the LED light tower were greatly affected by orientation. LED detection distances were shortest in the Towards *orientation* (*M* = 224.39 *m, SD* = 153.98 m*) and longest in the Perpendicular orientation (M* = 369.57 m, *SD* = 180.42 m).

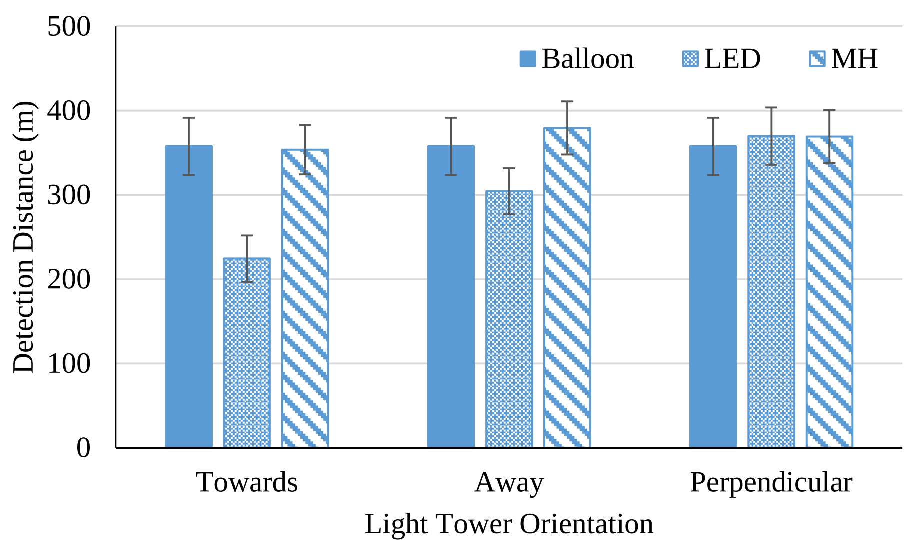


**Figure 7. Effect of light tower type and orientation on detection distance. Values are mean detection distances, and error bars represent standard errors.**

### Visibility – Questionnaire Analysis

The combined effect of light type and light orientation on ratings of visibility are shown in Figure 8. The mean Likert scale ratings of visibility were higher than "neutral" in the Away and Perpendicular orientations for all the light types. In the Towards orientation, only the balloon light type had mean Likert scale ratings greater than “neutral.”

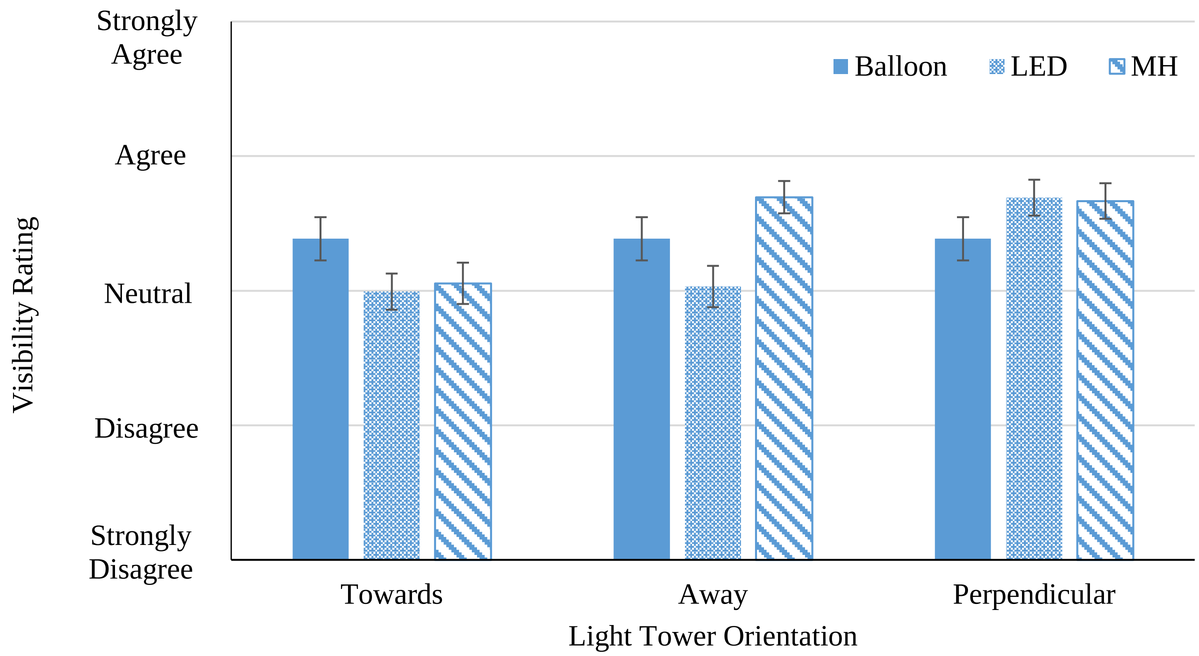


**Figure 8. Ratings of visibility in the light tower types. Higher ratings mean better visibility. Values are means of Likert scale composite scores, and error bars represent standard errors.**

### Glare – Questionnaire Analysis

The combined effect of light type and light orientation on ratings of visibility are shown in Figure 9. Glare ratings were dependent on both the light type and light orientation. The mean Likert scale ratings for glare were lower than “neutral” for the LED light tower in all three orientations. Mean glare ratings for the balloon light tower were greater than “neutral” in all three orientations. In the Towards orientation, both balloon and metal halide light towers had mean Likert scale ratings greater than “neutral.”

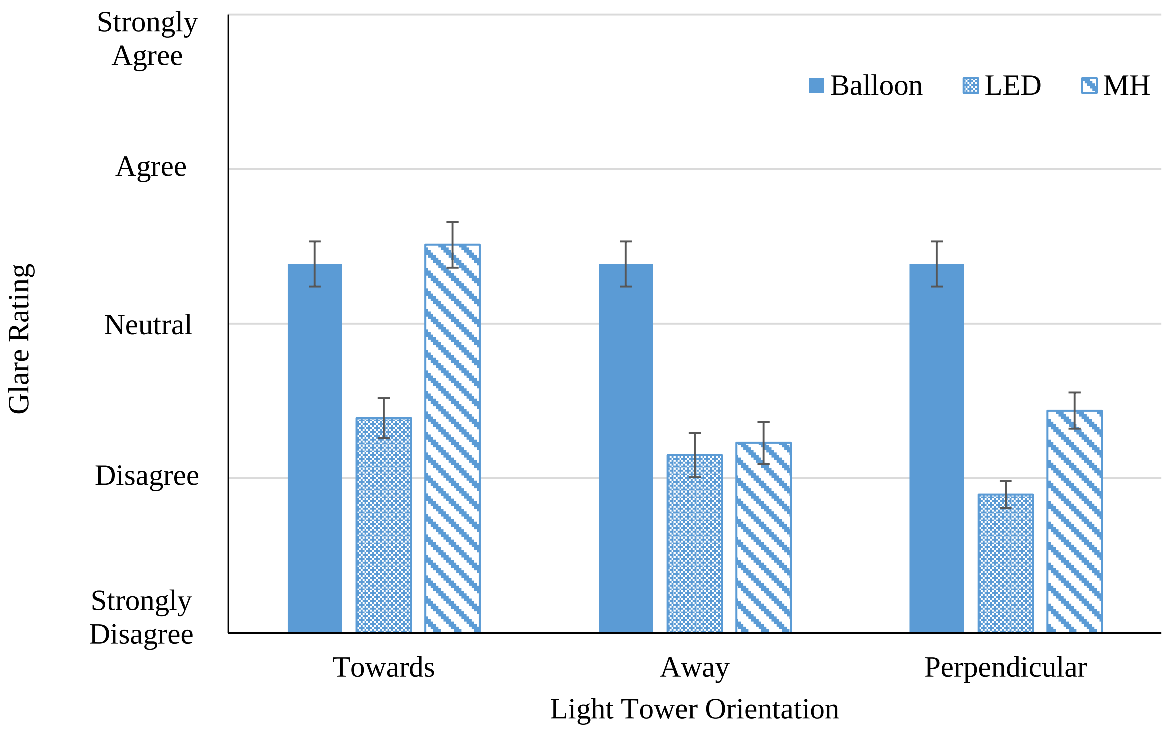


**Figure 9. Ratings of glare in the light tower types. Higher ratings are associated with higher glare. Values are means of Likert scale composite scores, and error bars represent standard errors.**

## Correlation Between Glare Rating and Vertical Illuminance in the Critical Range

The associations between mean vertical illuminance in the critical range and the composite ratings of glare ($r^2$ = 0.49, $p$ < 0.0001) exhibited significant positive correlations. This shows that increases in the vertical illuminance levels in the critical range result in higher glare ratings by the participants.

## Fitting the Generalized Logistic Function

The generalized logistic function fit indicated that the increase in the mean vertical illuminance significantly contributed to the increase in the perceived glare rating ($R^2$ = 0.96, *Adj*-$R^2$ = 0.96), as shown in Figure 10. The fitted final generalized logistic function is as follows:

$$MGR = 1 + \frac{5 - 1}{(1 + 1418.e^{-0.494.VE})}$$

MGR is mean glare rating, and VE is the mean vertical illuminance in the Critical Range.

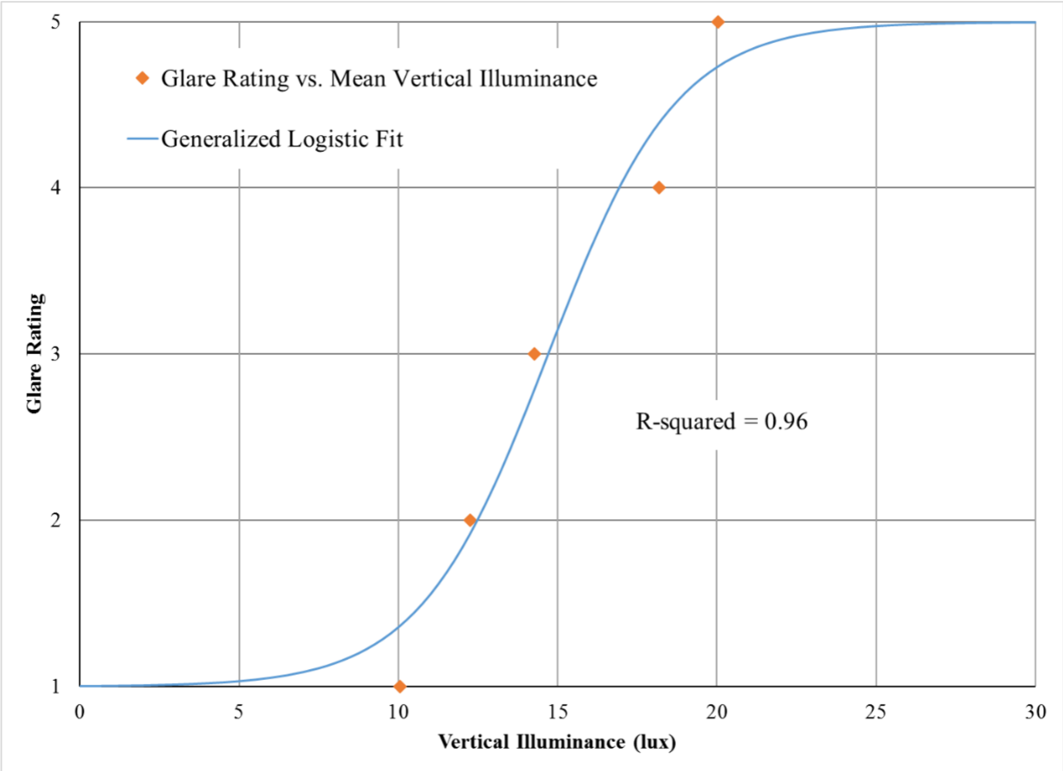


**Figure 10. Generalized logistic fit between perceived glare rating and mean vertical illuminance for each glare rating anchor in the critical range. Higher ratings are associated with higher glare.**

The mean vertical illuminance level at which the perceived glare rating was equal to 4 (or "Agree") was determined by the process of interpolation on the generalized logistic function. The mean vertical illuminance when the perceived glare rating was equal to 4 (or "Agree") was 17 lux (1.6 fc) (see Figure 11). This is maximum allowed mean vertical illuminance in the critical range on approach to the light tower in the work zone.

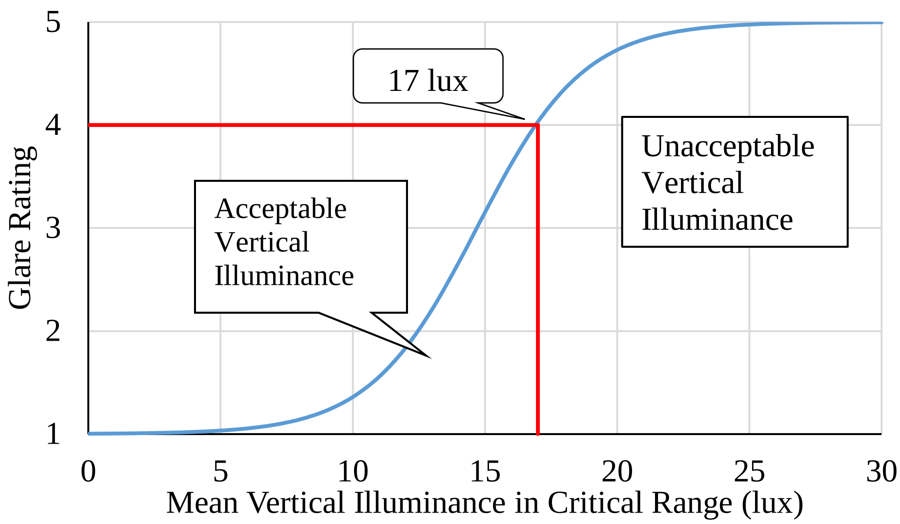


**Figure 11. Regions of acceptable and unacceptable mean vertical illuminance in the critical range based on the generalized logistic function. Higher ratings are associated with higher glare.**

## CONCLUSIONS

### On-Site Evaluations

- *The majority of the static nighttime work zones used metal halide portable light towers. Mobile operations like milling and paving used equipment-mounted balloon lights and LEDs.*

- *Horizontal illuminance levels in the work zones were affected by the number of light towers, locations of the light towers, and number of traffic lanes in the work zone. The measured horizontal illuminance levels in the work zones were much higher than recommended levels. Milling and paving operations that used equipment-mounted lights had lower illuminance levels than operations that used portable light towers.*

- *Vertical illuminance levels in the traffic lane were significantly affected by the aiming of the luminaires on the portable light towers. Luminaires aimed into the traffic travel lane produced higher vertical illuminance levels, which can result in disability and discomfort glare and consequently reduced visibility.*

### Illuminance Characterization in Portable Light Towers

- *The light tower type and orientation play a significant role in light distribution patterns. In general, both horizontal and vertical illuminances were highest for the metal halide and balloon light towers, especially in the Towards orientation.*

- *The increase in the vertical illuminance in the Towards orientation results in an increase in the discomfort glare for drivers approaching the work zone. These results are in line with* *the on-site evaluations conducted earlier. LED light towers overall had lower illuminance levels.*

- *Both metal halide and balloon light towers had wider light distribution patterns than the LED light tower.*

- *The results from this characterization study also show that vertical illuminance increases rapidly between a distance of 260 and 65 ft to the light tower. In this region the disability glare experienced by the driver also increases. This critical range was consistent across all the light tower types in each orientation. Measuring the vertical illuminance in this critical range could potentially serve as a measure of glare in the eyes of the drivers entering the work zone.*

## Smart Road Field Testing

- *The visual performance of the driver in a work zone was clearly influenced by the type and orientation of the light tower. An orientation aimed toward the driver resulted in lowering drivers' visual performance, both objectively and subjectively. This decrease in performance could be attributed to higher vertical illuminance. For the same orientations, metal Halide light tower and balloon light towers had higher visual performance than the LED light tower. LED light towers had lower glare ratings than the metal halide and the balloon light towers. The features of three light towers are shown in Figure 12.*


**Figure 12. Features of the three light tower types used in the Virginia Smart Road evaluation.**

- *To increase the drivers' visual performance and reduce glare in the work zone, efforts should be taken to aim the light towers in an active nighttime work zone away from the direction of traffic or perpendicular to it. In these orientations, all three light towers had similar visual performance measures.*

- *Balloon light towers had higher glare and higher visibility. This higher glare could be because of higher wattage (4000W) of the luminaire used in the Smart Road field test than those observed in work zones. In a typical nighttime work zone, contractors use two 1000 W balloon luminaires which offer lower glare than a single 4000W luminaire. In order to avoid the glare from using a higher wattage balloon luminaire, the light tower should be located on* *the shoulder and it should be mounted at height of at least 25 ft (~8 m). The increase in the height of the light tower will lower the veiling luminance, which in turn will reduce the glare.*

- *The increase in the mean vertical illuminance level in the critical range is associated with higher perceived ratings of glare, and at a mean vertical illuminance level of 17 lux (1.6 fc), the perceived glare transitions from low to high. The results of the study indicate that the maximum permissible level of mean vertical illuminance in the critical range is 17 lux (1.6 fc).*

## DRAFT SPECIFICATIONS OUTLINE FOR WORK ZONE LIGHTING

The following recommendations can made from the results of this study to reduce glare for drivers entering the work zone without affecting the visibility for the workers in the work zone.

### Work Zone Lighting Specifications

All the lighting in the work zone shall be designed, installed and operated to reduce glare for the traffic entering the work area and the workers in it. The contractor/engineer shall select, locate, aim and orient the lights so that the work area had the required level of illuminance while reducing glare for both workers and traffic. The contractor/engineer shall measure the illuminance levels prior to beginning the work and at each subsequent change in the location, aiming or orientation of the lighting. The contractor shall use a cosine corrected illuminance meter or similar calibrated photometer to measure the illuminance levels in the work area.

Desired horizontal illuminance levels vary depending upon the nature of the task involved. An average horizontal illuminance of 54 lux (5 fc) in the work area can be adequate for general activities. When the tasks involve using heavy and mobile construction equipment an average illuminance level of 108 lux (10 fc) should be in the work area. Tasks requiring high levels of precision and extreme care can require an average horizontal luminance of 216 lux or (20 fc) in the work area. These recommended minimum horizontal illuminance levels and categories for nighttime work zones on highways in Virginia could be adapted from the *Illumination Guidelines for Nighttime Highway Work* (Ellis et al., 2003) (see Table 9).

**Table 9. Recommended minimum illuminance levels and categories for nighttime highway construction and maintenance**

| Category | Recommended for |
|---|---|
| ***Category I*** *54 lx (5-foot candles)* | **Recommended for the general illumination in the work zone,** primarily from the safety point of view in the area where crew movement is expected or taking place. This category is also *for tasks requiring low accuracy*, involving slow-moving equipment, and having large-sized objects to be seen. |
| ***Category II*** *108 lx (10-foot candles)* | **Recommended for illumination on and around construction equipment** and the visual tasks associated with the equipment, such as resurfacing |
| ***Category III*** *216 lx (20-foot candles)* | **Recommended for tasks that present higher visual difficulty** and require increased attention from the observer, such as crack filling, critical connections, maintenance of electrical devices, or moving machinery. |

Source: Ellis et al., 2003.

The following requirements shall be met to reduce/avoid glare for traffic entering the work zone:

1. For the portable light towers, the angle between the beam axis and the driver's line of sight, shall always be greater than or equal to 90 degrees. Some of the recommended orientations are shown Figure 13. The work zone inspector shall explicitly ensure that the portable light towers are not aimed into the direction of traveling traffic.

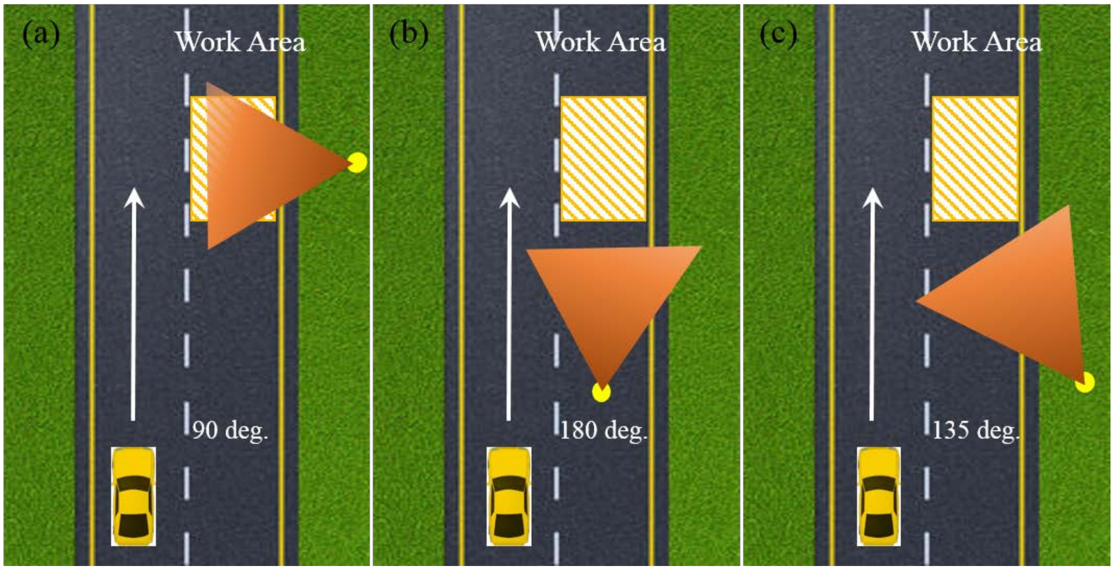


**Figure 13. Recommended orientations for the portable light towers with respect to the direction of traveling traffic.**

2. All luminaries on the light tower shall be aimed such that the center of the beam axis is no greater than 60 degrees from the vertical.

3. Glare for the oncoming traffic shall be measured using vertical illuminance. Vertical illuminance is defined as the amount of light incident on a vertical plane inside the windshield of a vehicle entering the work zone, measured at the driver eye level (height of 1.45 m from the ground), as illustrated in Figure 14 and Figure 15. This vertical illuminance shall be measured at a distance of 260, 200, 130, and 65 ft (80, 60, 40, and 20 m) from the portable light tower (see Figure 16). The arithmetic mean of the vertical illuminance at these four distances to the portable light tower shall not exceed 17 lux (1.6 fc). The vertical illuminance level shall be measured with the help of a cosine-corrected illuminance meter or a similar calibrated photometer. If the mean vertical illuminance level at the measured distances is greater than 17 lux (1.6 fc), then the portable light tower shall be reoriented, re-aimed or re-located and the vertical illuminance levels should be re-measured. This process shall continue until the mean vertical illuminance level is below the recommended value of 17 lux. The entire process of measuring the vertical illuminance shall be repeated if the orientation of the light tower is altered. For example, the vertical illuminance levels at a distance of 260, 200, 130, and 65 ft (80, 60, 40, and 20 m) from the portable light tower are 5, 10, 30 and 40 lux. Then the mean vertical illuminance in the critical range will be 21.25 lux, this value is higher than the acceptable level which is 17 lux (1.6 fc). The engineer then will re-aim/re-orient/relocate the portable light towers until the mean vertical illuminance value is less than 17 lux (1.6 fc). If the width of the median between the two directions of traffic flow is less than 36 ft (~11 m) then the mean vertical illuminance levels in the opposing traffic lane shall not exceed 17 lux (1.6 fc).

4. The mounting height of the portable light towers shall be greater than 20 ft (~6 m). Balloon type portable light towers of wattage greater than or equal to 4000W shall be located in the shoulder and be mounted at height of at least 25 ft (~8 m).

5. For lights and light towers mounted on vehicles the aiming shall depend on the type of light source. Light sources that could be aimed shall follow the same orientation guidelines like those of the portable light towers. Balloon light sources that produce diffused light in all directions should be mounted at least 20 ft in order to reduce glare for the oncoming traffic. For Vehicle mounted headlights care shall be taken while being used and if they exceed the vertical illuminance levels then the engineer shall provide shields, visors or louvers on light sources as necessary to reduce the vertical illuminance levels to the acceptable levels. Vehicle headlights shall not be used as light sources, especially when they are facing oncoming traffic.

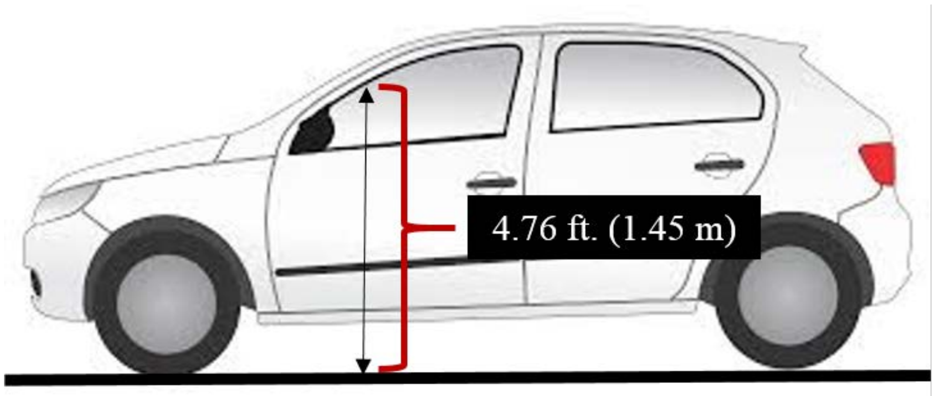


**Figure 14. Height at which the cosine-corrected illuminance meter should be measured inside the vehicle.**

**Figure 15. Mounting of the cosine-corrected illuminance meter on windshield to measure vertical illuminance levels.**

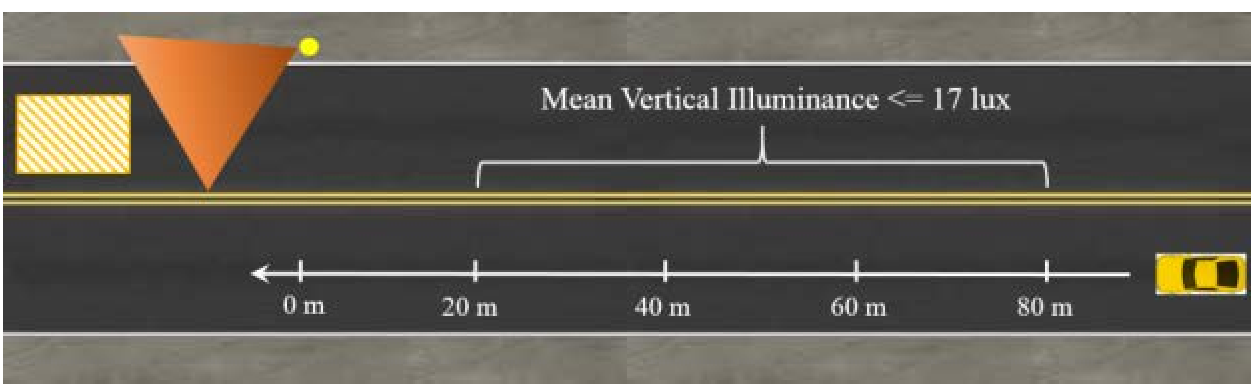


**Figure 16. Distances at which the vertical illuminance should be calculated to determine the mean vertical illuminance level in the critical range (65-260 ft = 20-80 m).**

## On-Site Lighting Evaluation Protocol

A modified work zone lighting plan, adopted from American Traffic Safety Services Association (ATSSA), is presented in Figure 17.

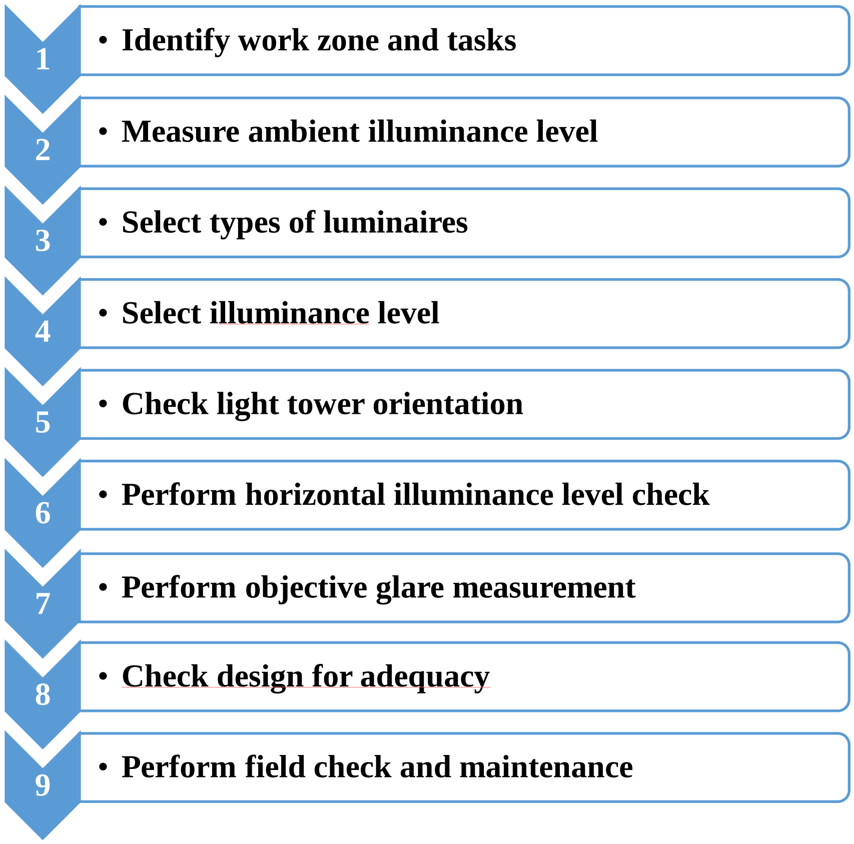


**Figure 17. Modified work zone lighting plan, adopted from ATTSA (2013).**

## RECOMMENDATIONS

1. *VDOT's Traffic Engineering Division with support from VDOT's Construction Division and Maintenance Division should implement the specifications presented in this report.*

## BENEFITS AND IMPLEMENTATION

### Benefits

The potential benefits of implementing the study recommendation include the following:

- easier-to-traverse work zones that limit the amount of nighttime glare affecting motorists, thereby improving travel flow and operations of the work zone
- increased safety for workers through improved visibility
- consistent lighting of nighttime operations
- easier-to-enforce requirements that can be used by inspection personnel

- improved safety of nighttime operations, with an expected decrease in work zone crashes, injuries, and fatalities.

### Implementation

VDOT's Traffic Engineering Division with support from VDOT's Construction Division and Maintenance Division will use the results of this study to develop a draft specification in the proper format. Once completed, VDOT's Traffic Engineering Division will initiate a statewide review of the draft specification. After the review process is completed, revisions will be made as appropriate. The draft specification will be adopted by VDOT approximately 18 months after the publication of this report and the specification will then be added to the *Virginia Work Area Protection Manual* and other appropriate VDOT documents.

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