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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

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16. Abstract:

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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

EXAMINATION OF THE CURRENT PRACTICE OF LIGHTING IN VIRGINIA: NIGHTTIME WORK ZONES AND IMPROVING SAFETY THROUGH THE DEVELOPMENT OF NIGHTTIME LIGHTING SPECIFICATIONS

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The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation. Any inclusion of manufacturer names, trade names, or trademarks is for identification purposes only and is not to be considered an endorsement.

Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ABSTRACT

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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 [VDOT], 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 (VDOT, 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) requires only 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), VDOT does not currently have any additional nighttime lighting requirements for work zone areas or equipment.

Literature Review

The research team built upon the results of the preliminary literature review conducted for this proposal to document current practices and advancements in work zone lighting. The team captured supplementary data, information, and resources using Transportation Research International Documentation and other literature scans for state and international studies and minutes from transportation industry meetings. Special attention was given to new lighting practices used in other fields that can be applied to the work zone scenario. New illumination technologies was documented and incorporated into the testing, as appropriate.

Background on Construction and Work Zone Safety

In 1956, the Federal-Aid Highway Act was implemented, leading to the development of the Interstate Highway System. Now, many of the roads and bridges developed during the era of the Federal-Aid Highway Act are decaying. Of major roads in the United States, 32% are in poor condition, and 40% of bridges are either structurally deficient or functionally obsolete. Of roads in Virginia, 47% are in poor or mediocre condition (American Society of Civil Engineers, 2014). Over the last 20 years, highway construction has shifted from creating new roads to maintaining existing ones (Al-Kaisy and Nassar, 2005).

The most-traveled roads are often in the worst condition, have the most wear, and require the most maintenance. The overlap of construction and heavy usage means road construction causes 10% to 24% of traffic congestion (Shane et al., 2012). Many agencies have shifted to night construction in an attempt to reduce traffic congestion, driver delays, disruption to local businesses, and fuel consumption (Ellis and Kumar, 1993). In 2001, about one-third of roadway construction occurred at night (Shane et al., 2012).

Performing construction at night has mixed results. Advantages of night construction include less driver delay (except for the trucking industry which often operates at night), less impact on business, more freedom for lane closures, longer possible work hours, less pollution, and fewer overall crashes. Disadvantages of night construction include poorer visibility, higher worker accident rates, higher traffic accident rates, noise disruption, possible quality problems, and light pollution (Al-Kaisy and Nassar, 2005; Elrahman, 2008). Despite the complexities involved in deciding whether the benefits of night construction are worth the risks, only half of states responding to a survey on night construction use a formal decision-making process (Al-Kaisy and Nassar, 2005).

Visibility is listed as the greatest disadvantage to performing construction at night (Al-Kaisy and Nassar, 2005), while other disadvantages, such as worker accident rates and construction quality problems, can be addressed by increasing visibility at the construction site. Nighttime work zone lighting is crucial to running efficient, safe work zones. Problems like traffic control, glare, and light pollution can also be addressed through the careful design of work zone lighting. If state departments of transportation (DOTs) were more familiar with work zone lighting standards driven by research, they could make more informed decisions on when and how to perform roadway construction at night.

This literature review covers the benefits and issues of performing road construction at night, and safety in work zones. It covers the current literature on work zone lighting, followed by a census of work zone lighting specifications at state DOTs.

Cost, Productivity, and Visibility in Nighttime Construction

The data regarding the comparative cost, quality of work, and productivity of nighttime versus daytime construction are mixed. One study in Florida found the cost of night construction to be less than daytime construction (Ellis and Kumar, 1993), but a later survey found that 76% of responding states felt nighttime construction was from 0% to 25% more expensive than daytime construction (Al-Kaisy and Nassar, 2005). The quality of work performed at night appears to be comparable to that performed during the day (Al-Kaisy and Nassar, 2005). Of the studies that examined nighttime productivity, one found that paving times at night was 10% lower than during the day (Lee et al., 2007); another found the two productivity levels to be equal (Ellis and Kumar, 1993), and another reported that 55.6% of the states performing construction at night thought night work was up to 25% slower than performing construction during the day (Al-Kaisy and Nassar, 2005).

The visibility-related problems inherent in performing construction at night appear to reduce the efficiency of nighttime construction (Al-Kaisy and Nassar, 2005; Lee et al., 2007). Those problems can be offset by the longer working hours possible at night and increased freedom in planning lane closures (Elrahman, 2008). The most efficient model for road construction appears to be the weekend model, where a roadway is closed for an entire weekend, and construction is performed day and night throughout the closure period (Arditi et al., 2007).

For night work to be effective, it can be assumed that work zone lighting must enable nighttime workers to have the same, or almost the same, productivity as their daytime counterparts. Glare and traffic routing would not be considerations in work zones where the road is closed because traffic would not be passing through. For more-common nighttime construction, though, when traffic passes by the work zone, increasing light levels to increase visibility for road workers could be at odds with preventing glare to oncoming traffic.

Safety in Work Zones

Work zones can be dangerous to both workers and passing drivers, as shown by accident and labor statistics (*Census of Fatal Occupational Injuries*, 2013; National Highway Traffic Safety Administration, 2014). Dangers to both populations are linked to lighting and visibility; some worker deaths could be attributed to poor visibility while operating equipment and machinery (National Institute of Occupation Safety and Health, 2006, 2011). Some driver deaths could possibly be attributed to either not seeing the work zone or to glare produced by work zone lighting. A review of accident report details, however, was outside the scope of this project.

Although the discussion below is separated into worker deaths and traffic accidents, they are not discrete occurrences. Some workers are struck by passing drivers, as reported by the U.S. Bureau of Labor Statistics (*Census of Fatal Occupational Injuries*, 2013). Other worker deaths are recorded as pedestrian fatalities during traffic accidents, as reported in the Fatality Accident Reporting System (National Highway Traffic Safety Administration, 2014).

Road-Worker Deaths

The U.S. Bureau of Labor Statistics reported 7,000 deaths in work zones between 2003 and 2010 (*Census of Fatal Occupational Injuries*, 2013). The time of day was not recorded, so the data are not restricted to nighttime work zones, but the statistics help to establish the overall magnitude of the problem. Of the 7,000 work zone fatalities, 962 were road workers. While overall workplace injuries decreased over that time period, the rate of road-worker deaths remained constant. Of the 962 road-worker deaths, 692 were transportation-related, with 442 deaths from vehicle and equipment strikes. Another 45 were from falls, 51 from falling objects, and 39 from electric shock (*Census of Fatal Occupational Injuries*, 2013). Increasing visibility at work zones has the potential to reduce the number of road-worker deaths at night. Better visibility could help drivers see road workers, and would help road workers better see each other, workplace hazards, and hazard warnings.

Motor Vehicle Crashes in Work Zones

A number of studies have attempted to compare the number of crashes at work zones at night to those during the day. One study found that in active and inactive work zones there are more crashes at night than during the day (Ullman et al., 2006). Another found that, after correcting for traffic volume and day length, there were five times as many work zone crashes at night than during the day (Arditi et al., 2007).

Work zones can be divided into three types based on the duration of the activity being performed: *construction* for work longer than three days, *maintenance* for work less than three days but longer than one hour, and *utility* for work less than one hour. When that distinction was made, Weng and Meng (2010) found that at construction-type work zones there were fewer crashes at night on illuminated roads than during the day. They also found that at maintenance-type work zones there were more crashes at night on illuminated roads than during the day. They speculated that their result could be because construction-type work zones are more likely to have retroreflective signs than maintenance-type work zones, increasing the visibility of the work zone to passing drivers and reducing the number of accidents (Weng and Meng, 2010).

VDOT (2006) examined the 4,618 motor vehicle crashes that occurred in work zones between 1999 and 2003. Of those crashes, 3,479 occurred between 6 a.m. and 7 p.m., and another 1,139 occurred between 7 p.m. and 6 a.m., hours that could have been in darkness depending on the time of year.

The Associated General Contractors of America (2014) performed a survey which found that 45% of construction company respondents reported having a motor vehicle crash at a work zone where they operate over the last 12 months. Forty-three percent reported that drivers or passengers were injured, 20% reported that workers were injured, and 60% reported that work zone crashes are a very serious problem compared to other work zone safety hazards. The best methods for reducing work zone crashes were stricter enforcement of existing laws (90% agreed) and greater police presence at work zones (85% agreed) (The Associated General Contractors of America, 2014). Research supports the surveyed contractors' belief that enforcement of laws, particularly speed limits, would reduce crashes in work zones. For example, Meng, Weng, and Qu (2009) found that reducing driver speed is the best way to reduce driver deaths in work zones. Proven ways to reduce speed are having a police vehicle present at the work zone (Summala et al., 1988), or placing red and blue (not amber) flashing lights at the work zone (Carrick and Washburn, 2012).

When using lighting to make work zones more visible to passing drivers, though, lighting designers should be aware of the moth effect. The moth effect is a small but measurable tendency in which drivers fail to maintain the lane and steer toward their point of visual fixation (Chatziastros et al., 2003; Readinger et al., 2002). Surrounding visual features, like lane markings and trees, create optical flow and help drivers maintain their position in the lane. When the road is devoid of visual cues, such as a straight road without lane markings on flat, open terrain, drivers are more likely to reorient toward the point of fixation (Chatziastros et al., 2003), and roadside accidents are more likely on roads with poor lane markings (Charles et al., 1990).

Recent and Ongoing Research in Work Zone Lighting

To get a snapshot of recent research in work zone lighting, six state DOT websites were surveyed for recent publications on the topic. To determine if they were performing ongoing research, employees at the DOTs and/or their research collaborators were contacted. Focus areas were if the states were considering new lighting technology, and if they were investigating glare control. State DOTs and collaborators were contacted in California, Colorado, Illinois, New York, and Texas. California, Texas, Illinois, and New York were chosen because they are large states and/or they have a history of transportation research. During the census of work zone lighting standards, Colorado was found to be in the process of evaluating new work zone lighting standards, so it was included in this group.

Colorado had researched other states' work lighting specifications and developed a draft standard specifically on night work zone lighting. The Colorado draft standard requires 5 fc of illumination for stationary work zones and separate lighting specifications for mobile equipment. There is also a requirement that lighting does not produce glare or light trespass, as well as a uniformity requirement. Contractors must submit a night work lighting plan and provide the engineer with a light meter for the lighting evaluation.

In 2003, a report under the auspices of the National Cooperative Highway Research Program (NCHRP) was published: *Illumination Guidelines for Nighttime Highway Work* (NCHRP Report 498) (Ellis et al., 2003). The objective of the research team was to develop guidelines regarding the minimum and maximum levels of illumination for a variety of nighttime work zone activities. The research team identified four influencing factors on nighttime illumination of work zones: human factors, environmental factors, task-related factors, and lighting factors. For the task-related factors, the most common tasks were identified for highway construction/maintenance activities performed at night. The tasks were grouped based on similar visual requirements and activities that are usually performed together. In addition to equipment attributes, three factors were considered: speed, physical characteristics, and response time. Illumination categories and levels were suggested for each task based on Illumination Engineering Society (IES) standards (illumination guidelines for non-highway activities), literature, and expert opinions.

In Illinois, research on work zone safety, including lighting, has been ongoing. A research group from The University of Illinois and Bradley University focused on glare reduction in work zones (El-Rayes et al., 2007). The team visited a number of nighttime work zones to evaluate glare-control methods, developed recommendations for glare control, and developed a model to calculate veiling luminance ratio in work zones. Their recommendations were to increase the height of light sources as much as possible, keep the aiming angle as close to zero degrees as possible, and follow their proposed method for measuring veiling luminance ratios. Members of the same team later studied the factors surrounding work zone crashes in Illinois (El-Rayes et al., 2013). They reported that crashes were more likely to happen at nighttime work zones without lighting than at those with lighting. They suggested work zone lighting be carefully designed to improve the visibility of the work zone, to reduce glare to drivers, and to improve driver alertness.

A group of researchers affiliated with Rensselaer Polytechnic Institute and the New York State DOT have researched lighting in work zones within the past 10 years. A 2006 study documented semi-permanent high-mast lighting in a long-term work zone. They stated that the system produced enough illuminance (100 lux) to perform the construction work, that it was probably safer because the lighting was brighter and more uniform than that of portable light towers, that repeatedly setting up portable light towers can cause injury, and that their generators create fumes and noise (Freyssinier et al., 2006). Ongoing research in New York includes a computation analysis of work zone lighting and visual performance. Researchers investigated whether some work zones might be over lit, creating glare for workers (Bullough et al., 2013). First, using the visual-performance model, researchers calculated that most workers were able to see even small objects when there was 10 lux of illuminance and 20 lux of glare (20,000 cd at 70 degrees above the vertical). Older workers required 30 lux of illuminance. They then tested various lighting configurations and had participants rate them. The results showed that, if glare were reduced, 10 to 20 lux of horizontal illuminance was sufficient for most work zone tasks. The researchers concluded that LED lighting with good optical control performed similarly to typical light towers using metal-halide lamps (Bullough et al., 2013).

The Texas DOT recently funded a report on work zone lighting that referenced solid-state, solar-powered LED lighting with a 12-ft mast height. The same report detailed several methods to reduce glare to motorists, including not allowing vehicle headlights to be aimed at oncoming traffic. It also recommended that an engineer evaluate the work zone for glare, including a drive through to check for glare to passing traffic (Finley et al., 2012). No ongoing work on work zone lighting is being performed in Texas as of the writing of this report.

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.

The survey began with an introduction describing the goal of the project and the goals of the survey, the eligibility requirements, and the participant's rights. All participation was voluntary and several steps were taken to protect participant privacy. The survey instrument and recruitment approach were reviewed and approved by the Virginia Tech Institutional Review Board (IRB). The survey was designed to document the following factors:

- planning of nighttime work zone lighting
- specifications used
- responsibility of developing lighting plans
- evaluation of lighting and glare on the work zone during projects
- frequency of evaluation of lighting and glare
- type of the lighting equipment used
- business model used (buy, rent, etc.)
- cost of the different types of lighting (initial cost, operational cost, and maintenance costs)
- glare characteristics of the different types of lighting
- strategies used to prevent or reduced glare
- pros and cons of each type of lighting
- major problems faced by companies regarding work zone lighting
- potential changes to specifications
- suggestions to improve work zone lighting and safety.

Several channels of survey distribution were evaluated by VDOT and the research team. Finally, VDOT recommended that the best way to reach the target audience was to ask professionals and industry organizations in Virginia to forward the survey to their members. The following organizations were asked to distribute the survey:

- Virginia Transportation Construction Association (VTCA)
- Virginia Asphalt Association (VAA)
- American Traffic Safety Services Association (ATSSA)
- Hampton Roads Utility & Heavy Contractors Association (HRUHCA)
- Virginia Ready-Mixed Concrete Association
- Old Dominion Highway Contractors Association (ODHCA)
- Heavy Construction Contractors Association (HCCA).

This type of approach has a major advantage: professional organizations, representing their members, are often the strongest advocates or opponents to changes in specifications. This type of distribution channel assured that their members were given the opportunity to provide input. VDOT personnel were confident that by asking professional organizations to reach their members, the answers would represent a demographic involved in nighttime work zone operations in Virginia and not mere spectators.

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.

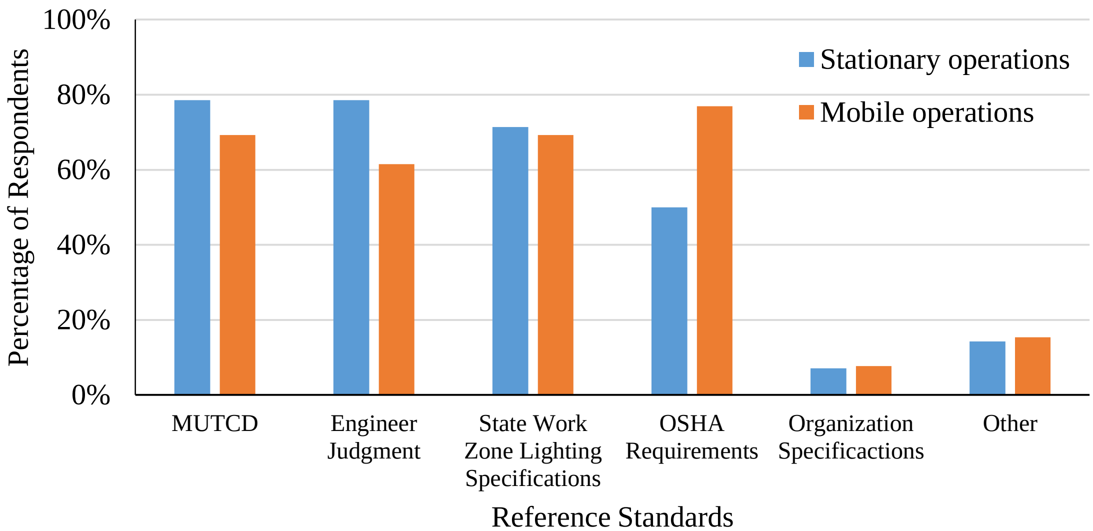

Figure 1. Reference standards used to select lighting specifications.

- 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.

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.

Work Zone Selection

In order to meet these objectives, the research team used data from the previously conducted state-of-practice survey to determine the types of work zones that extensively used portable light towers. In addition to the data from the state-of-practice survey, the research team also conducted an expert interview with a work zone inspector. From the survey and expert interview, it was determined that work zone operations involving extensive use of portable light towers are bridge work, on-ramp pavement work, trench drain installation, and milling and paving. In conjunction with VDOT, 10 active nighttime work zones were identified.

Equipment

The research team developed a new mobile light measuring system that is mounted on a trailer so that light levels could be measured close to the roadway surface. With this mobile light measuring system, a radar and a video camera system were used to collect data from work zones. The radar system was used to measure the speed of drivers approaching and exiting the work zone. The video camera system was used to count the number of vehicles traversing the work zone during the data collection period.

Trailer-Mounted Roadway Lighting Mobile Measurement System (TRLMMS)

A special Trailer-Mounted Roadway Lighting Mobile Measurement System (TRLMMS) was created by the Center for Infrastructure-Based Safety Systems (CIBSS) at the Virginia Tech Transportation Institute (VTTI) to measure illuminance levels on the roadway in a work zone.

The TRLMMS, which consisted of a specially designed “spider” apparatus containing four waterproof Minolta illuminance detector heads, was mounted onto the bed of a trailer (Figure 2c). Additionally, a vertically mounted illuminance meter was positioned in the vehicle windshield as a method to measure the vertical illuminance from the portable light towers in the work zone (Figure 2b). Vertical illuminance can be used as a measure of glare. The waterproof detector heads and windshield-mounted Minolta head were connected to separate Minolta T-10 bodies that sent data to the data collection computer positioned inside the vehicle.

A NovaTel Global Positioning System (GPS) was positioned at the center of the “spider” apparatus (Figure 2c). The GPS was connected to the data collection box, and the vehicle’s latitude and longitude position data were incorporated into the overall data file.

A specialized software program created in LabVIEW™ controlled each component of the TRLMMS. The software synchronized the entire hardware suite, and data collection rates were set at 20 Hz. The final output file used during the analysis contained GPS information (latitude, longitude, etc.), input box button presses, vehicle speed, vehicle distance, and the illuminance meter data from each of the five Minolta T-10s.

For collecting the lighting data, the TRLMMS system was hitched to a vehicle and was driven through the work zone travel lane (Figure 2a and Figure 2d). The number of passes of the TRLMMS system was equal to the number of the open travel lanes in the work zone. For the calculation of the lighting measurements, a mean value of all the passes was used.

Figure 2. TRLMMS developed at VTTI. (a) TRLMMS hitched to vehicle. (b) Illuminance meter that measures the vertical illuminance mounted to the windshield. (c) "Spider" apparatus with GPS unit in the center. (d) TRLMMS from behind with the headlamp barrier that eliminates the influence of the following vehicle's headlamps.

Radar and Video Camera System

The radar system consisted of a Smart Micro Systems (SMS) radar. This radar was extensively tested to ensure a superior level of data quality. The radar operated in the 24 GHz band. Its position accuracy was 0.5 m with a range from over 200 m to 0.5 m. Speed accuracy was better than 1%. A single radar was mounted on a pole and aimed into the lane of approaching traffic.

The video camera system consisted of a GoPro video camera, installed on the same pole as the radar system. This camera was selected because it was intended for outdoor use. The camera had a high-definition video of resolution 1920 by 1080 pixels and recorded video at 29 frames per second.

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 3). 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 3. 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 4a). This is the maximum angle recommended in NCHRP Report 498 (Ellis et al., 2003). 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 4b).

In the final orientation (the "Perpendicular" orientation), the light tower and luminaires were orientated 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 4c). For the metal halide and the LED light towers the angle between the vertical and center of the beam axis was 60 degrees.

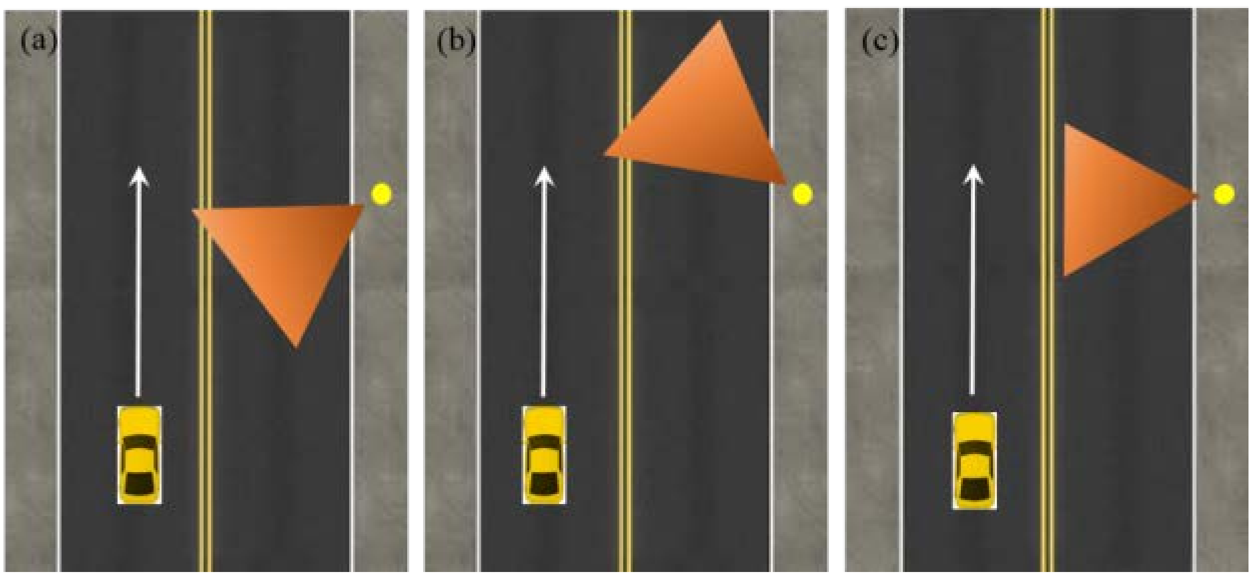

Figure 4. Light tower orientations used for illuminance characterization. (a) Towards oncoming traffic. (b) Away from oncoming traffic. (c) Perpendicular to traffic.

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. Each light tower in every orientation was also characterized for two travel directions on the Smart Road, downhill and uphill. In the downhill direction, the vehicle traveled in the left lane as if the lane closure were in the right lane. These conditions were reversed for uphill travel (right lane for travel; left lane closed), as illustrated in Figure 5. Since the data were collected in both the uphill and downhill directions, a cubic spline smoothing algorithm was performed to smooth the combined data from both directions. The smoothing spline was a knotted piecewise polynomial that responded very quickly to changes in the underlying form of the data. Thus it resulted in a data set that eliminated noise while still retaining the original characteristics. Another advantage of the smoothing spline techniques is that it does not require any distribution assumptions, unlike its parametric counterparts.

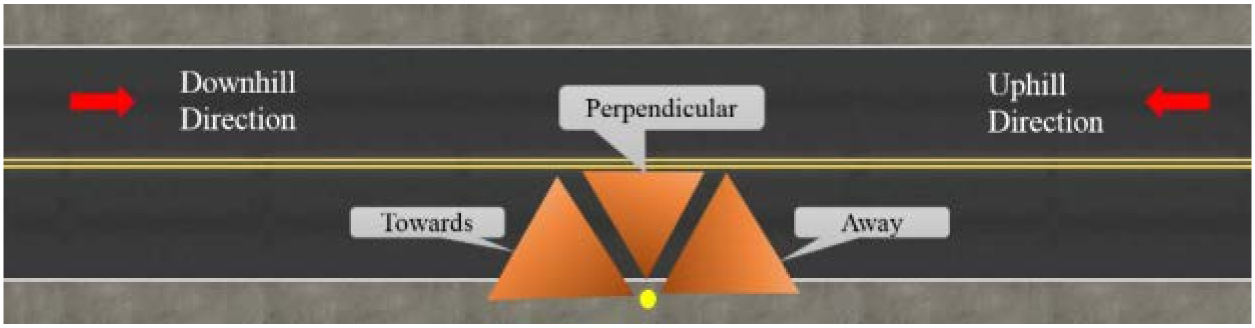

Figure 5. Vehicle travel directions with the three light tower orientations used for illuminance characterization on the Virginia Smart Road.

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.

To this end, three portable light towers: metal halide, balloon, and LED, were used. Metal halide and balloon portable light towers are currently being used in active nighttime work zones in Virginia. Metal halides are the most common types of portable light towers and are widely used for nighttime work zone operations. Balloon light towers are typically vehicle-mounted and exclusively used for milling and paving operations. In the on-site evaluation previously conducted, LEDs were used in only one milling and paving operations and were vehicle-mounted.

The research team evaluated each of the three light towers in three orientations, since the orientation of the luminaires significantly impacts the vertical illuminance and consequently the glare experienced by the driver. The three orientations were (1) towards traffic, (2) away from traffic, and (3) perpendicular to traffic.

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.

Methods

Participants

Twenty-four participants completed the study. Participants were recruited to form two age groups (younger and older), and each group was gender balanced. The older age group comprised participants who were age 60 or older (*M*ean = 63.9 years, *SD* = 3.1 years). The younger group comprised participants between 18 and 35 years old (*M*ean = 26.8 years, *SD* = 5.2

years). The two age groups were chosen to provide objective and subjective measures from a wide range of driving experiences and visual capabilities.

Experimental Design

A repeated measures experimental design was employed to evaluate the effects of portable light tower type and orientation on speed and objective and subjective measures of visual performance. Objective measures of visual performance were measured using the detection distance of a simulated worker while the participants drove through a simulated work zone on the Smart Road under several light tower types and orientations. The simulated work zone was set up on the straight section of the Smart Road. The simulated work zone was set up in such a way that the lane closure was in the right lane when traveling downhill and in the left lane when traveling uphill (see Figure 6). This enabled data collection in both directions, saved time, and reduced the number of runs. The simulated work zone resembled an active nighttime work zone on a limited access highway in Virginia with appropriate signage leading to the work zone and merge tapers (1,000 ft) in both directions (uphill and downhill).

The independent variables used in the study and their categorical values are summarized in Table 1, with additional details below. In each experimental session, participants enountered all three light tower types in all three orientations in both directions. The presentation order of the light towers and orientations was counterbalanced to reduce order-related confounding effects. Worker presentation was randomized with blanks (no worker present) as catch trails to discourage the participants from guessing.

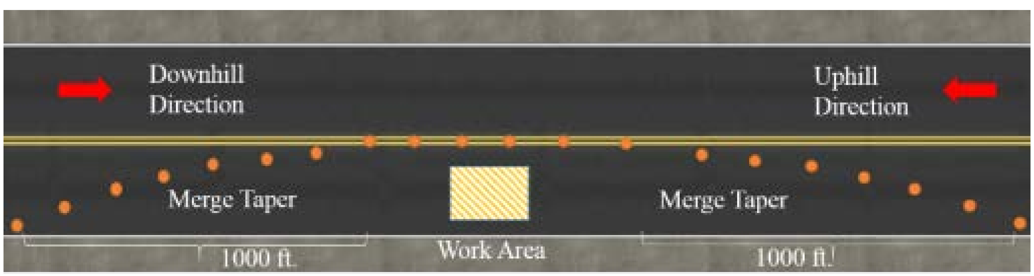

Figure 6. Simulated work zone on the Virginia Smart Road with merge tapers and travel directions.

Table 1. List of independent variables and their categorical values

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

Independent Variables

Light tower type and orientation were the same as those used in the Characterization of Lighting Performance of Common Luminaires and New Lighting Sources section.

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 (see the Appendix) 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).

Procedure

Two participants were recruited to participate in each experimental session. Upon arrival, participants were greeted by an experimenter and escorted to a conference room. Participants reviewed the informed consent form, and after all questions had been answered, the participants were asked to sign the informed consent form. Once the consent forms had been completed, the participants were asked to show the experimenter their valid driver's license.

Next, participants completed one pre-drive questionnaire, which collected demographic information and rated their comfort with nighttime driving. Participants then performed a basic visual acuity test. Participants were required to have at least 20/40 vision (with or without corrective lenses) to continue with the study. Those that did not meet this criterion were paid for the amount of time they participated and excluded from the remaining portions of the session.

Once the participants completed the paperwork, the experimenter read a brief overview of the driving portion of the study and answered any questions the participants may have had. Participants were then escorted to the test vehicle and orientated to the experimental vehicle. Model year 1999 and 2000 Ford Explorers served as experimental vehicles for this study and were instrumented with a data acquisition system (DAS). The DAS collected kinematic data from the vehicle's controller area network (CAN) system, including vehicle speed, differential GPS (DGPS) coordinates, four video images (driver's face, forward roadway, left side of roadway, and right side of roadway), audio from the driver, manual button presses, and other input from the in-vehicle experimenter. Low-beam headlamps were used during the study and were aimed before each experimental session.

Participants performed 8 laps in both uphill and downhill directions. Each lap involved driving uphill and downhill on the Smart Road and through a simulated work zone at the assigned speed limit for the study (55 mph). Participants encountered the metal halide and LED light towers in 3 orientations and the balloon light tower in both uphill and downhill directions which constituted 8 laps of driving on the Smart Road. The simulated work zone involved a lane closure. As the participants drove through the test area, they scanned for a simulated worker, who was dressed in retroreflective clothing along with a hard hat (see Figure 35). Each lap had a different type of a portable light tower in a specific orientation to the traffic lane. Participants indicated when they could first see the simulated worker by saying “worker” aloud. The in-vehicle experimenter then flagged the data stream with a button press when the participant detected the worker, which helped to determine the GPS coordinates at which the worker was detected. Worker’s locations’ GPS coordinates were predetermined. The GPS coordinates at detection and the location of the worker were used to determine the detection distance.

Once the first participant vehicle was clear of the test area, the in-vehicle experimenter notified the second participant vehicle via radio that they were clear to proceed. The first vehicle then parked in a turnaround and waited for the second vehicle. Once the second vehicle arrived at the second turnaround, the process was repeated driving in the other direction. The two vehicles continued in this fashion until all light tower configurations had been observed. At the end of every lap, participants were administered a questionnaire by the in-vehicle experimenter while they waited for the other vehicle. Overall, 16 questionnaires were rated by each participant.

At the end of 8 laps, participants were instructed by the experimenter to return to VTTI. In the event that multiple groups of participants were scheduled back-to-back, a third experimenter (the “greeter”) met the two in-vehicle experimenters and participants at the intersection with the Smart Road. The greeter would drop off the next set of participants and drive the two that just completed the study back to the building. Participants were paid $30 per hour for the time.

Figure 7. Simulated worker with retroreflective vest and trousers with a hard hat.

Analyses

Two linear mixed model (LMM) analyses were used to assess the (fixed) effects of light tower type and light tower orientation on detection distance and speed. In addition, six separate LMM analyses were used to assess the effect of light tower type on detection distance and speed in each of the three light tower orientations. Age and vehicle direction (uphill vs. downhill) were included as blocking factors. The level of significance was $p < 0.05$ for all statistical tests. Where relevant, post hoc analyses (pairwise comparisons) were performed using Tukey's honest significant difference (HSD) for main effects and simple effects testing for interaction effects.

For the questionnaires, composite Likert scores were calculated for each assessment area. A composite Likert score was the mean rating across multiple statements in each assessment area. These composite scores were used as the dependent measures. Separate LMMs were used to assess the effects of light tower type and light tower orientation on composite scores in each of the two assessment areas (visibility and glare). Like the detection distance analyses, six separate LMM analyses were used to assess the effect of light tower type on visibility and glare in each of the three light tower orientations. Age and vehicle direction (uphill vs. downhill) were included as blocking factors. For all statistical tests, the significance level was established at $p < 0.05$. Where relevant, post hoc pairwise comparisons were performed using Tukey's HSD for main effects, and simple effects testing was used to examine significant interaction effects. A particular light tower type and orientation was considered effective only when the mean visibility ratings were greater than 3 (i.e., "Agree" or "Strongly Agree") and mean glare ratings were less than 3 (i.e., "Disagree" or "Strongly Disagree").

Additionally, Pearson product-moment correlation coefficients were determined to assess the association between mean vertical illuminance in the critical range (from the characterization of illuminance levels on the Smart Road) and the composite score of perceived glare. Significance was established at $p < 0.05$. If this correlation was significant, a generalized logistic function was fitted between the rounded values of the composite Likert score of the glare rating and mean vertical illuminance levels in the critical range (from the Characterization of Illuminance Levels on the Smart Road task). This fitting helped in determining the vertical illuminance levels that resulted in higher glare ratings (i.e., participants "agreed" or "strongly agreed" that glare affected their visibility; Likert composite score > 3). A generalized logistic function is considered an appropriate function to describe the relationship between glare rating and vertical illuminance level because the glare is bound by a lower asymptote (lowest glare ratings) and a higher asymptote (highest glare ratings). No matter how high the vertical illuminance level increases, the glare ratings will not be higher than 5 ("strongly agree"), and at the lowest vertical illuminance levels, the glare rating will not be lower than 1 ("strongly disagree"). The generalized logistic function will have the following structure:

$$MGR = LGR + \frac{HGR - LGR}{(1 + b.e^{-a.VE})},$$

where MGR is the mean glare rating, LGR is the lowest glare rating ("1"), HGR is highest glare rating ("5"), VE is the mean vertical illuminance in the critical range, and *b* and *a* are regression parameters to be estimated by the curve fitting procedure. The MatLab® (ver. R2012b) toolbox *cftool()* was used to fit the data. The vertical illuminance level at which the perceived mean glare rating exceeds "4" or "Agree" was used as the highest permissible value allowed. Any increase beyond this value of vertical illuminance would result in a significant increase in perceived glare by the drivers entering the work zone.

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. Characteristics of the works zones and summary data s are presented in Table 3. In the following subsection, the lighting characteristics of each lighting tower will be elucidated.

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**

Table 3. Characteristics of work zones observed in this study

Location	Type of Work	Number of Portable Light Towers	Number 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

I-81 South – Bridge Work

The bridge work operation on I-81 south was illuminated by two portable metal halide light towers (see Figure 8). One of the light towers was aimed into the travel lane. Each light tower has four luminaires mounted on them. This work zone had police presence at the entrance near the beginning of the lane closure (right lane). This work zone had one open travel lane for traffic. This work zone had a high amount of traffic and it was backed up to approximately one mile before the work zone lane closure started. The horizontal and the vertical illuminance levels in this work area are shown in Figure 9.

Figure 8. Metal halide portable light towers on I-81 south bridge work.

Figure 9. Horizontal and vertical illuminance levels at the I-81 south bridge work.

I-81 North – Bridge Work

The bridge work operation on I-81 north was on the same bridge as the one before but in the south bound lanes. This work zone was also illuminated by two portable metal halide light towers and they were aimed away from the travel lane for traffic as shown in Figure 10. The vertical illuminance levels at this location were not as high as the previous location because of the way in which they were aimed. The illuminance levels in both orientations at this location are shown in Figure 11. This work zone also had police present at the beginning of the lane closure (left lane) for the work zone. This work zone had one open travel lane for traffic.

Figure 10. Metal halide light towers aimed away from the traffic at the I-81 north bridge work.

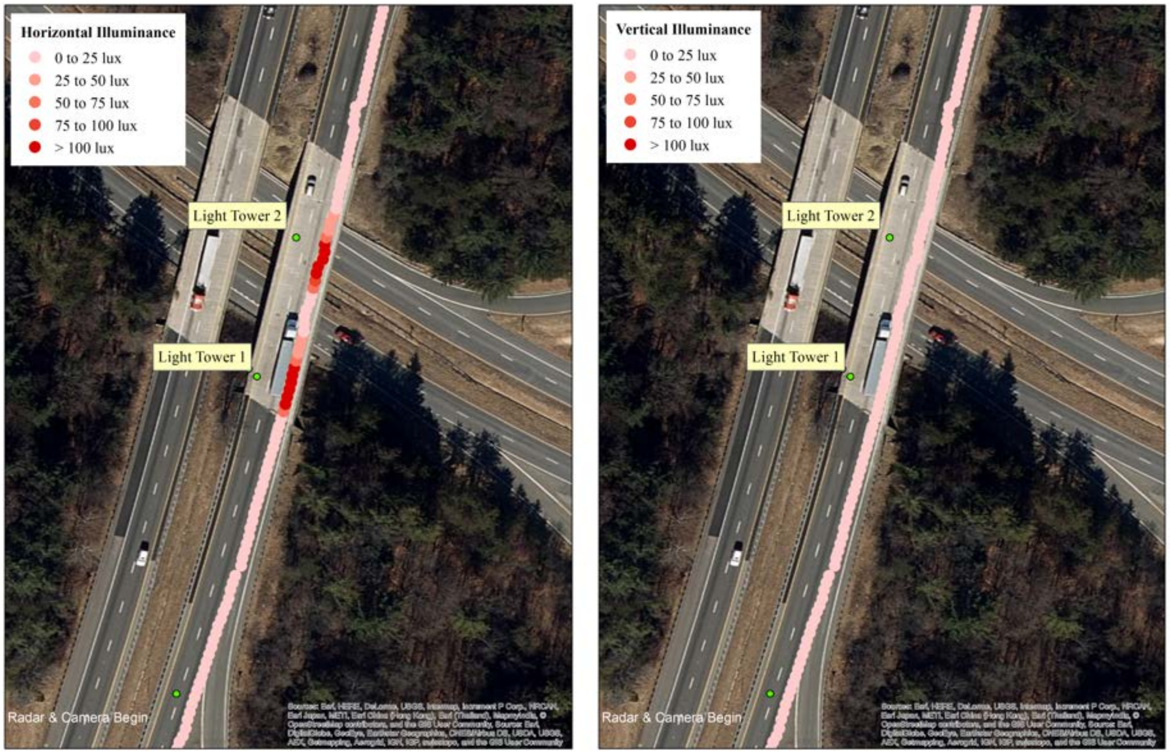

Figure 11. Horizontal and vertical illuminance levels at the bridge work on I-81 north.

I-81 North – Milling and Paving

The milling and paving operation on the I-81 north used equipment mounted balloon lights for the purpose of illuminating the work area. There were two balloon lights on the paver (see Figure 12). This work zone was considered as a mobile work zone as the paver which housed the lights was always moving. This work zone had one open travel lane (left lane) for traffic. The illuminance levels in the horizontal and vertical orientations are shown in Figure 13. This work zone did not have any police presence.

Figure 12. Balloon light towers at the I-81 north milling and paving work zone.

Figure 13. Horizontal and vertical illuminance levels at the milling and paving operation on I-81 north.

I-581 South – On-Ramp

The on-ramp construction operation on I-581 south was illuminated by four portable metal halide light towers and each of these light towers had four luminaires mounted on them. These portable light towers were aimed perpendicular to the traffic travel lanes as shown in Figure 14. The portable light towers used in this operation were also located beyond the guard rail. There was police presence at the entrance to the work zone. This work zone had two open travel lanes for traffic with the right-most lane closed. The horizontal and vertical illuminance levels at the work zone are shown in Figure 15.

Figure 14. Metal halide portable light towers at the I-581 south on-ramp work.

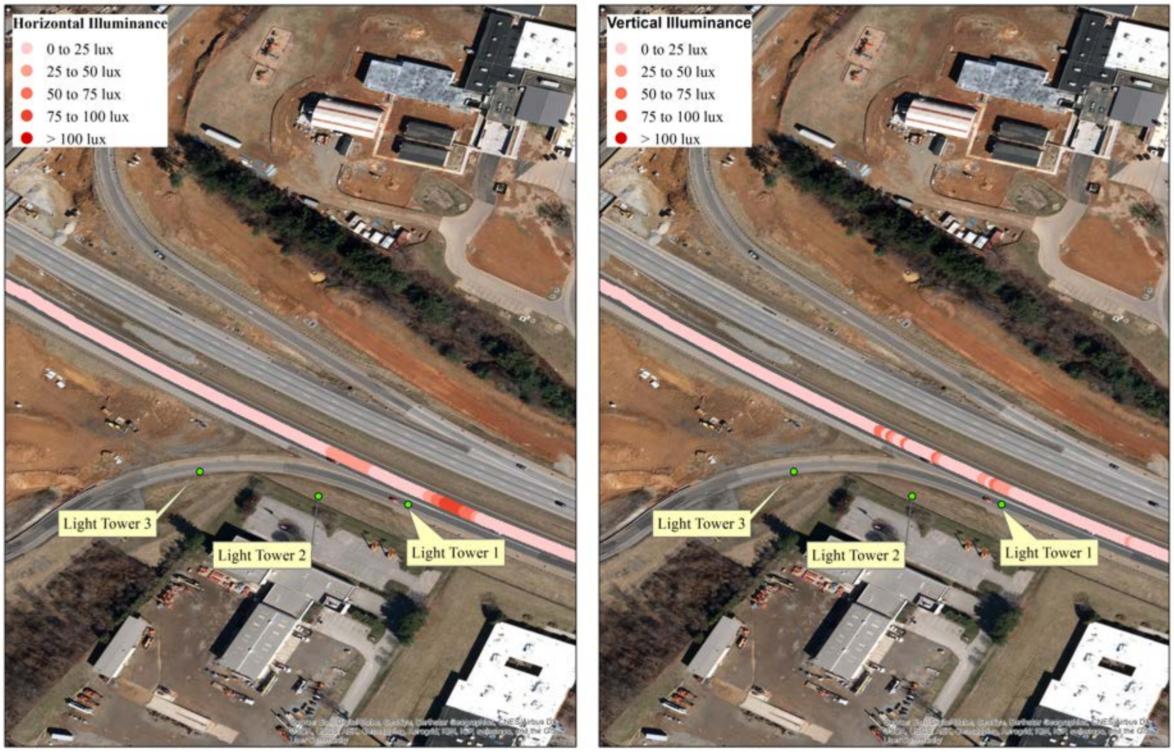

Figure 15. Horizontal and vertical illuminance levels at the on-ramp work on I-581 south.

I-264 West – Milling and Paving

The milling and paving operation on I-264 west was illuminated by equipment mounted led headlights (on rollers) and equipment mounted led luminaires on the pavers as shown in Figure 16. The roller and the pavers had four luminaires mounted on each. This work zone has police presence at the entrance to the lane closure (left lane closed). This work zone had one open travel lane for traffic. This was work zone was also located in an area which was illuminated by overhead roadway lighting. The horizontal and vertical illuminance levels at this work zone are shown in Figure 17.

Figure 16. Vehicle mounted LED lights being used to illuminate the work area in the milling and paving operation on I-264 west.

Figure 17. Horizontal and vertical illuminance levels at the milling and paving operation on I-264 west.

I-64 West – Trench Drain Installation

The trench drain installation on I-64 west was illuminated by one portable metal halide light tower, as shown in Figure 18. Even though this light tower had four luminaires mounted, only one was switched on. This work zone had one open travel lane for traffic (right lane), the left lane was closed. This work zone had police presence and also had roadway lighting present in the area. The horizontal and the vertical illuminance levels at this work zone are shown in Figure 19.

Figure 18. Metal halide light tower at the trench drain installation on I-64 west.

Figure 19. Horizontal and vertical illuminance levels at the trench drain installation on I-64 West.

Road Widening

The road widening operation was illuminated by one portable metal halide light tower (see Figure 20) and all the four luminaires on the light tower were switched on. There was no police presence at the entrance to work zone and there was no roadway lighting present. This work zone had one travel lone open for traffic (left-most lane). The horizontal and vertical illuminance levels in this work zone are shown in Figure 21.

Figure 20. Metal halide light tower at the road widening operation on I-64 east.

Figure 21. Horizontal and vertical illuminance levels at the road widening operation on I-64 east.

I-64 West – Milling and Paving

The milling and paving operation on I-64 west was illuminated by two balloon light towers mounted on the paver, as shown in Figure 22. This was also a mobile operation like the other milling and paving operations. This location had police presence at the entrance to the work zone (right lane was closed) and there was no roadway lighting present. There were two travel lanes for traffic at this work zone. One feature of this work zone was that work was being done a lane that was barricaded by concrete barriers. The horizontal and vertical illuminance levels at this location are shown in Figure 23.

Figure 22. Balloon light towers at the paving operation on I-64 west.

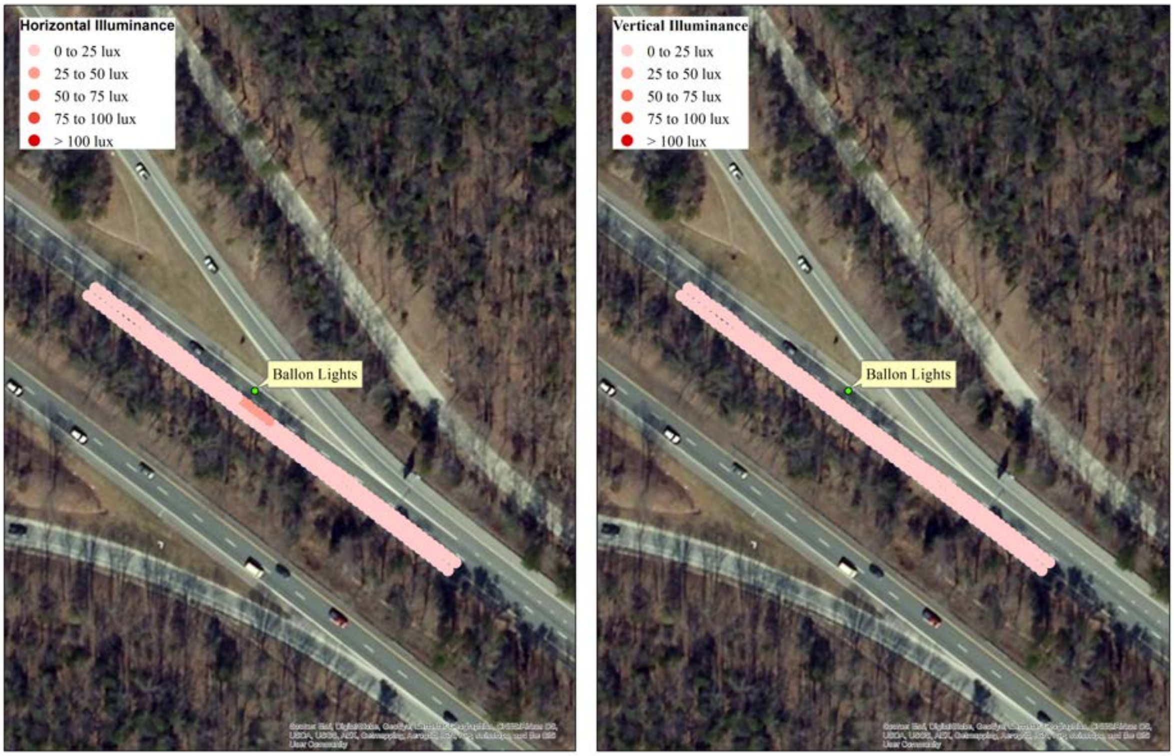

Figure 23. Horizontal and vertical illuminance levels at the milling and paving operation on I-64 west.

VA-674 – Milling and Paving

This milling and paving operation on VA-674 was interesting because it used a combination of both portable light towers and equipment mounted balloon lights for the purpose of illuminating the work area, as shown in Figure 24. The paver had three balloon light towers mounted on it and the portable light tower had four luminaires mounted on it. This work zone had police presence at the entrance and there was roadway lighting present. This work zone only had one open travel lane for traffic. The horizontal and the vertical illuminance levels for this work zone are shown in Figure 25.

Figure 24. Balloon light towers on the paver (right) used in conjunction with the metal halide portable light tower (left) on VA-674.

Figure 25. Horizontal and vertical illuminance levels at the milling and paving operation on VA-674.

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 (Figure 26).

Figure 26. Metal halide portable light towers. (a) All four luminaires powered on at bridge work (I-81 N). (b) One luminaire powered on at a trench drain installation (I-64 W).

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 (see Figure 27b).

Figure 27. (a) Balloon light towers. (b) LEDs mounted on pavers and rollers.

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.

Lighting Performance Measurement

Light levels were measured in two specific orientations: (1) horizontal and (2) vertical. Horizontal illuminance is defined as the amount of light incident on a horizontal surface, and was measured by the four illuminance heads on the "spider" apparatus in both the work areas and the traffic travel lanes.

Vertical illuminance is defined as the amount of light incident on a vertical surface, and was measured with the illuminance meter mounted on the windshield, facing outwards. Vertical illuminance level was only measured in the traffic travel lanes. Since the vertical illuminance quantified the amount of light entering the windshield, it served as a measure of glare. Very high amounts of vertical illuminance could produce glare in the eyes of the drivers and is not desirable. Luminance was measured by a handheld LS-110 photometer.

Horizontal Illuminance

The mean, standard deviation, and minimum and maximum horizontal illuminance levels in the traffic lanes of the work zones are shown in Table 4. Horizontal illuminance levels in the work zones depended on the number of portable light towers used, length of the work zone, and the distance of the light tower from the travel lane. For example, when the portable light towers were located in a closed lane on a two-lane highway, the average and maximum horizontal illuminance levels were high (I-81 S bridge work). Conversely, when the portable light tower was located in the shoulder of the highway for a three-lane highway with two lanes closed, the average and maximum horizontal illuminance levels were lower (I-64 E road widening) as shown in Figure 28 and Figure 29.

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.

Figure 28. Horizontal illuminance levels at two work zones with differences based on number of lanes and light towers.

Figure 29. Horizontal illuminance level in the travel lane as a result of location of portable light tower and number of light towers. (a) Higher horizontal illuminance levels in travel lane than in (b) with fewer light towers and more lanes.

Milling and paving operations that had light towers mounted on the equipment without any additional portable light towers had the lowest horizontal illuminance levels (I-81 N, I-264 W, I-64 W), as shown in Figure 7. However, milling and paving operations that had a combination of portable light towers and equipment-mounted light towers had the highest horizontal illuminance levels (for example, VA-674), as shown in Figure 30.

Figure 30. Horizontal illuminance in milling and paving operations.

The mean horizontal illuminance and luminance levels in the work areas of the work zones are shown in Table 4. Horizontal illuminance levels in the work areas of all the work zones were higher than 108 lux, which is the minimum recommended value in NCHRP Report 498 (Ellis et al., 2003), as shown in Table 5. In some of the work zones, the measured illuminance level was 10 times more than recommended (I-81 S bridge work and I-64 E road widening).

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.

Vertical Illuminance

A summary of the vertical illuminance measurements in the travel lanes for all work zones is shown in Table 6. Vertical illuminance levels were greatly affected by the orientation of the luminaires on the portable light towers. Work zones where the luminaires on the light towers were aimed into the traffic lane had relatively high vertical illuminance levels. For example, in the bridge work at I-81 S the luminaires on the portable light towers were aimed into the traffic lane, which resulted in high amounts of vertical illuminance. Conversely, on I-81 N bridgework, the luminaires on the light towers were aimed away from the traffic lane, which resulted in lower vertical illuminance levels, as shown in Figure 31, Figure 32 and Figure 33. The light tower used in the road widening work zone on I-64 E was also aimed away from the traffic which resulted in very lower mean vertical illuminance (see Table 6 and Figure 29b).

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

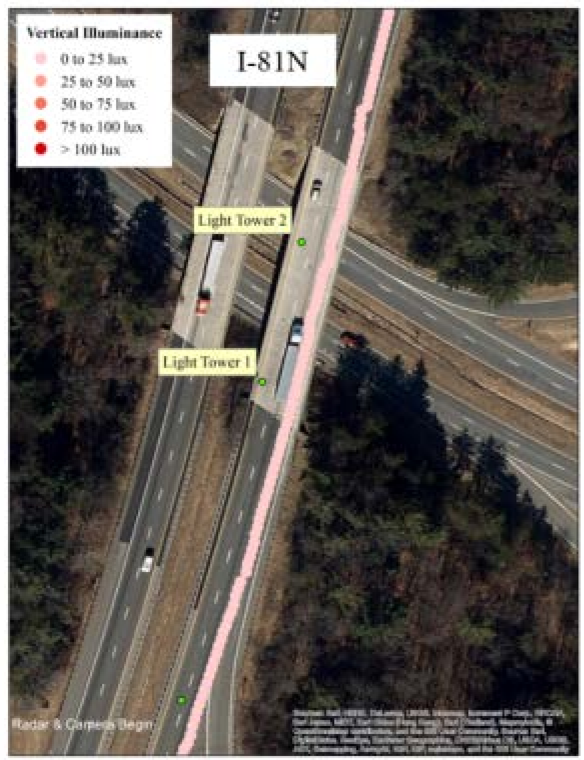

Figure 31. Vertical illuminance levels in the work zones significantly affected by aiming of the light towers.

Figure 32. Aiming of the luminaires on portable light towers and resulting significant changes in the vertical illuminance levels in the work zone. Red arrows= direction of traffic flow. (a) Light tower aimed toward traffic, resulting in higher mean and maximum vertical illuminance levels (*M* = 22.68 lux and Max = 122.2 lux). (b) Luminaires aimed away from the traffic, resulting in lower mean and maximum illuminance levels (*M* = 0.88 lux, Max = 14.91 lux).

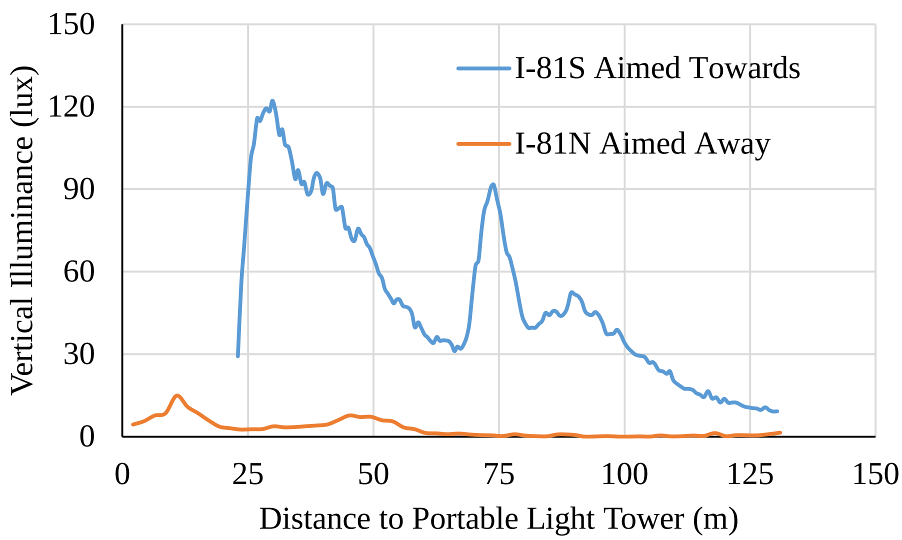

Figure 33. Change in the vertical illuminance as vehicle gets closer to portable light tower when aimed towards and away from the traffic travel direction.

The increase seen in the vertical illuminance when the light tower is aimed into the traffic also increases the disability glare in the eyes of the driver. Threshold increment (TI) is a measure of disability glare, and it is defined as the percentage increase in threshold luminance due to the addition of the glare sources (i.e., the light tower in this situation). Threshold increment can be calculated by the following equation:

$$TI = 60.275.\frac{L_v}{L^{0.862}}$$

where L_v is the veiling luminance which can be calculated by the following equation:

$$L_v = \frac{k.E_{gl}}{\theta^n}$$

where k is a multiplier that is dependent on age and is given by the following equation:

$$k = 9.05\,.\left(1 + \left(\frac{Age}{66.4}\right)^4\right)$$

E_{gl} is the illuminance of the glare source

θ is the angle of the glare source from the line of sight

n is an exponent that can vary with the angle of the glare source and is given by the following equation:

$$n = 2.3 - 0.07 * log\theta\ for\ 0.2^o < \theta = \ 2^o$$
$$n = 2\ for\ \theta > \ 2^o$$

Figure 34 clearly shows that when the light tower is aimed into the traffic the threshold increment is higher (higher disability glare) than when the light tower is aimed away from the traffic.

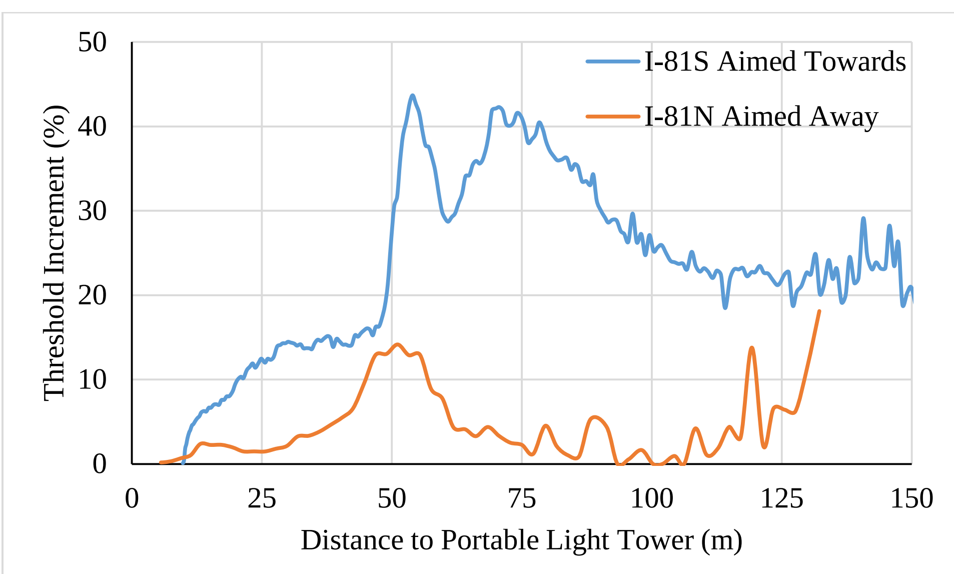

Figure 34. Change in the threshold increment as vehicle gets closer to portable light tower when aimed towards and away from the traffic travel direction.

In milling and paving operations, work zones that only used equipment-mounted balloon lights had lower vertical illuminance levels (e.g., I-81 N milling and paving) than those work zones that used a combination of balloon light towers and portable light towers as shown in Figure 35. In general, milling and paving operations had lower vertical illuminance levels than operations that used portable light towers. Vehicle (pavers, rollers, millers, etc.) headlights (see Figure 36 and Figure 37) that also serve to illuminate the work area are typically mounted at lower heights and aimed to illuminate the work area in front of them had lower mean vertical illuminance levels than portable light towers.

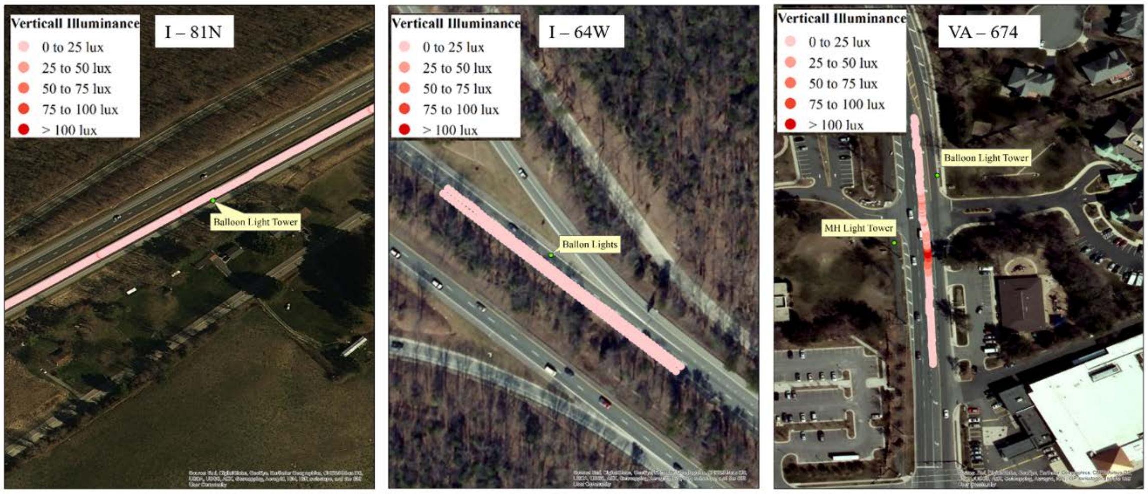

Figure 35. Comparison of vertical illuminance levels in milling and paving operations using equipment-mounted and portable light towers.

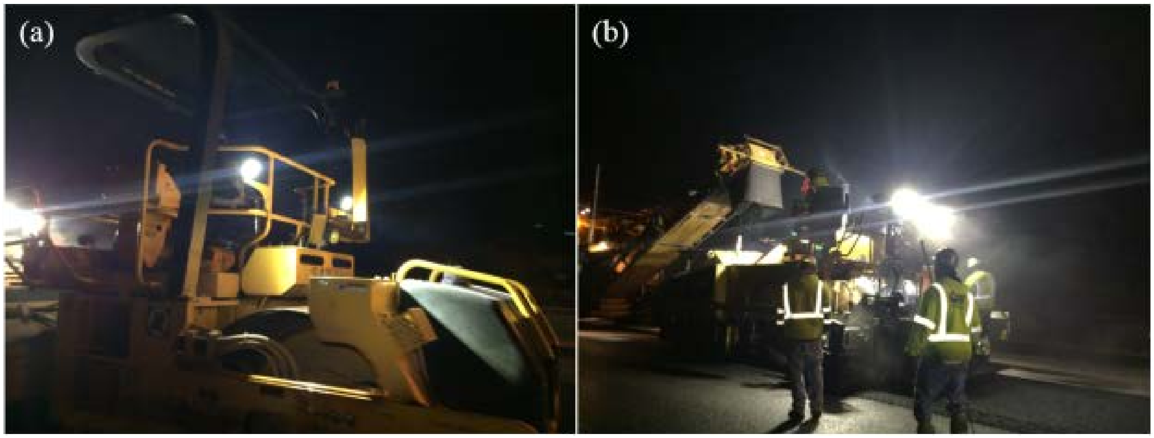

Figure 36. Vehicle mounted headlights (LED) resulting in lower vertical illuminance levels than portable light towers.

There were also differences in the distribution of vertical illuminance levels in the milling and paving operations that used different varieties of equipment-mounted luminaires. Equipment-mounted balloon lights had uniform increases in vertical illuminance levels, whereas LEDs had sharp spikes in vertical illuminance levels as the vehicle approached the light source as shown in Figure 13.

Figure 37. Differences in the distribution of vertical illuminance levels in equipment-mounted balloon vs. LED luminaires.

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. The research team encountered two locations where could have happened; they were the bridge work on I-81 north and the road widening operation on I-64 east. The vertical illuminance levels at the I-81 north location were higher than those at the I-64 east location because of a combination of higher number of lanes, a wider median and lower number of portable light towers at the latter, as shown in Figure 38. At the bridge work on I-81 north a sharp increase in the vertical illuminance was indeed observed but there increases were not as high as those that were observed when in travel lane when the light towers were aimed into the traffic. However, it is important to mention that the vertical illuminance levels in opposing lane were higher than those measured in travel lane for the I-81 north location Figure 39. 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).

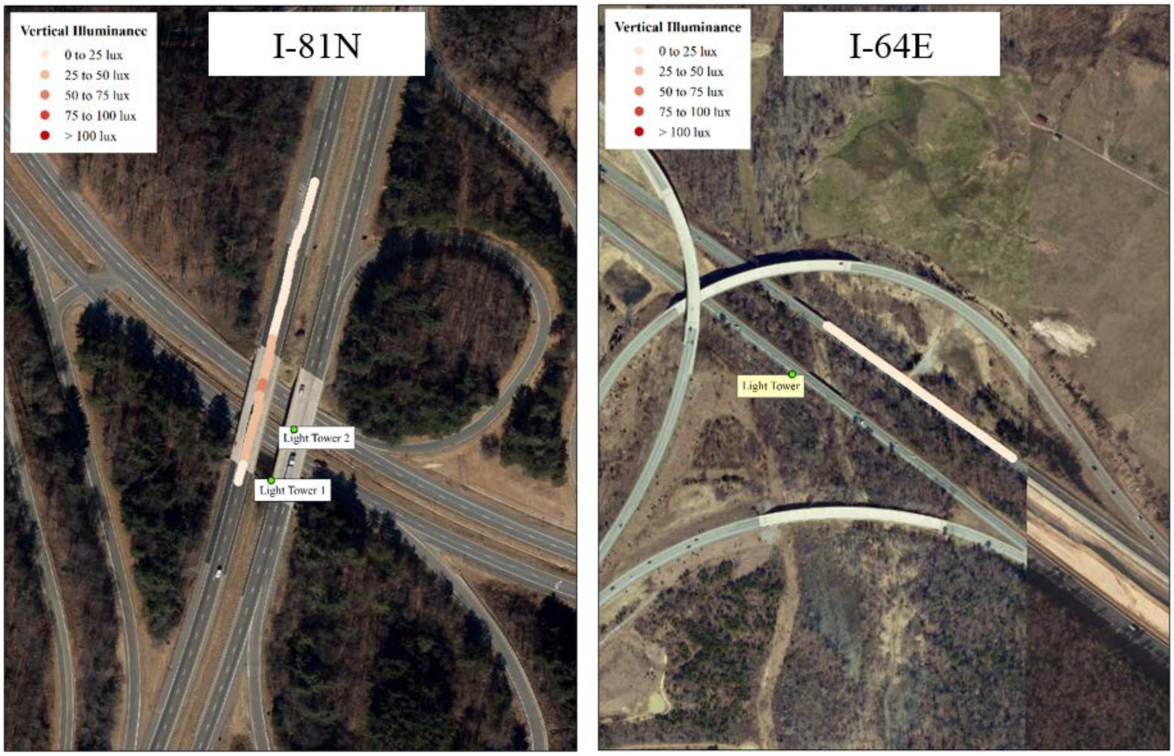

Figure 38. Vertical illuminance levels in the opposing lanes of the location of the portable light towers.

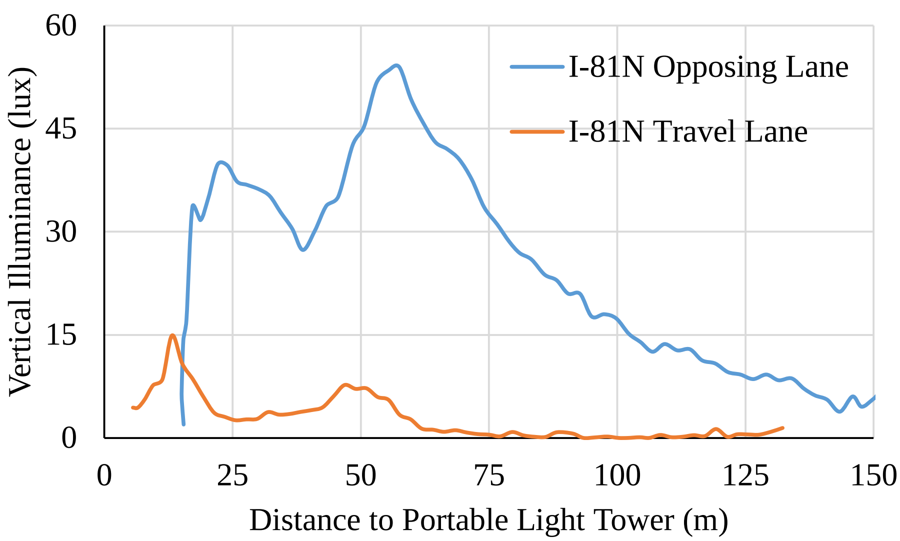

Figure 39. Change in the vertical illuminance as vehicle gets closer to portable light tower when in the travel lane vs. the opposing lane.

Vehicle Speed in the Work Zones

Vehicle entry speeds, exit speeds, and vehicle counts were measured at six work zones (Table 7). Results from the light measurement and radar system has shown that increase in both the average horizontal and vertical illuminance level is associated with a decrease in the average speed of the vehicles at the entry to the work zone, as shown in Figure 40 and Figure 41.

Table 7. Summary traffic count and speed data collected from the work zones

Location	Type of Work	Traffic Count	Average Speed (mph)	
			Entry	Exit
I-81 S	Bridge work	425	13.56	10.62
I-81 N	Bridge work	367	43.79	59.81
I-81 N	Milling and Paving	180	NA	13.84
I-581 S	On-ramp work	500	51.02	49.89
I-264 W	Milling and Paving	434	49.61	NA
I-64 W	Trench drain installation	593	36.79	NA

NA – not available due to equipment malfunction.

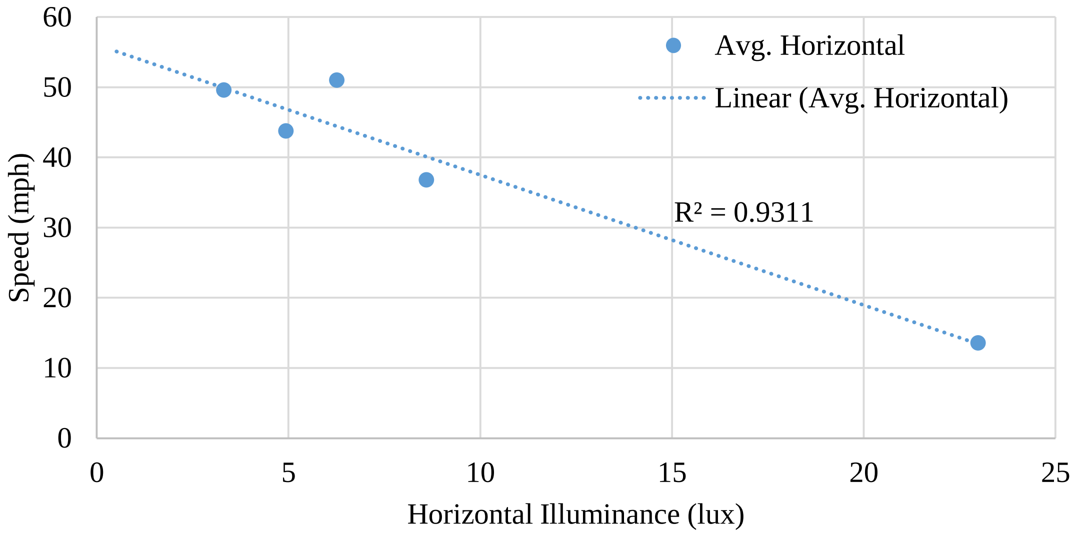

Figure 40. Relationship between average speed and average horizontal illuminance level in the work zones.

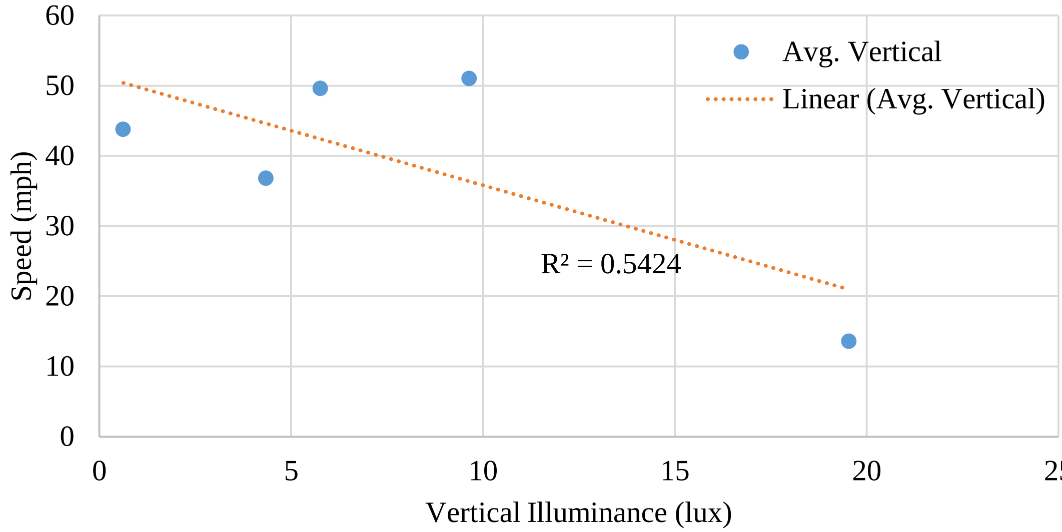

Figure 41. Relationship between average speed and average vertical illuminance level in the work.

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 8. 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 42), which could be attributed to their wider light distributions. The wider distributions of the metal halide and balloon light towers can be clearly observed in Figure 43, Figure 44, and Figure 45, where the increase in the horizontal illuminance level starts farther from the light tower than the LED light tower. The LED light tower had a narrower beam distribution pattern with sharper cutoffs. These wider distributions of metal halide and balloon light towers could potentially illuminate larger areas around the work zone and could result in increased perception of visibility. Because the LED light tower has sharper cutoffs, it does not illuminate areas beyond the work area, which could adversely affect perceptions of visibility. However, such hypotheses need to be tested before drawing conclusions.

Table 8. 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

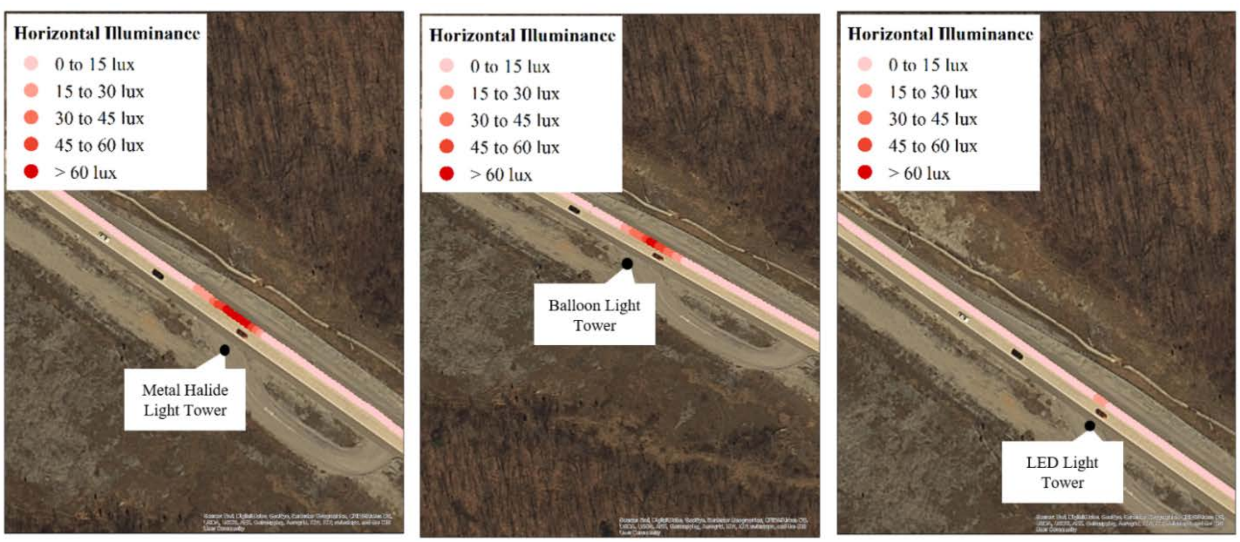

Figure 42. Horizontal illuminance levels in the three portable light tower types in the Towards orientation.

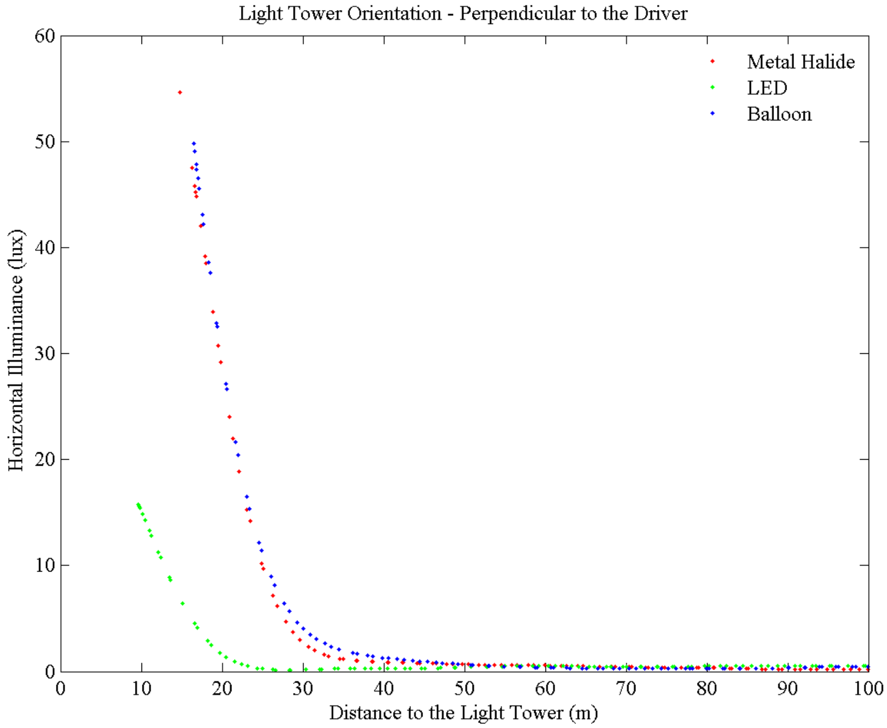

Figure 43. Change in horizontal illuminance level with distance to the light tower in the Perpendicular orientation.

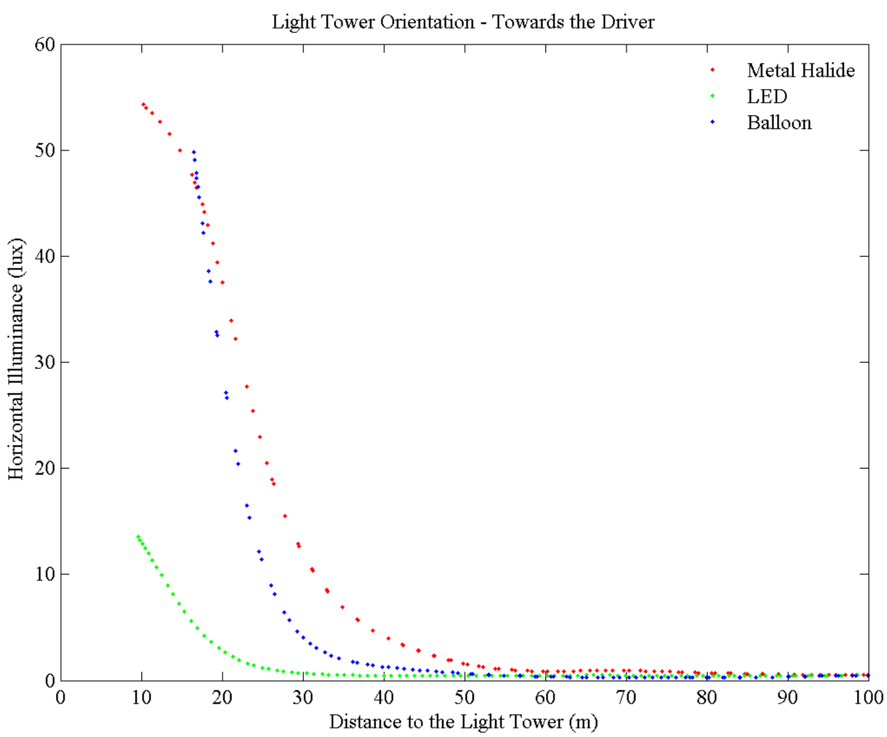

Figure 44. Change in horizontal illuminance level with distance to the light tower in the Towards orientation.

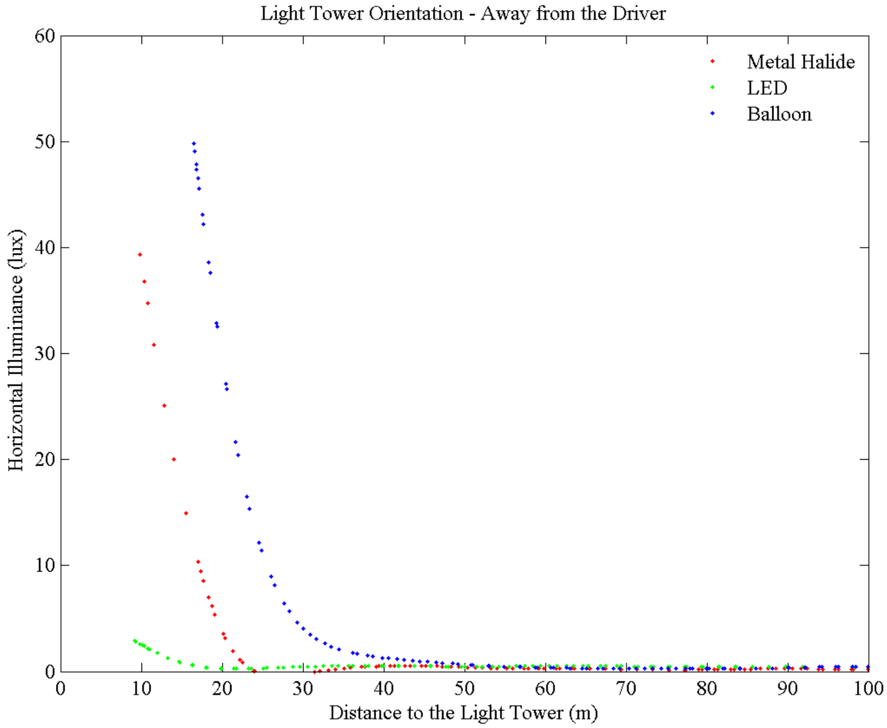

Figure 45. Change in horizontal illuminance level with distance to the light tower in the Away orientation.

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 9. 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. Metal halide and the balloon light towers had higher illuminance levels than the LED light tower. Vertical illuminance levels reached higher levels in the metal halide and balloon light towers than in the LED light tower, especially in the Towards orientation, which can be clearly observed in Figure 46, Figure 47, Figure 48, and Figure 49.

Table 9. 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 46. Vertical illuminance levels in the three portable light tower types in the Towards orientation.

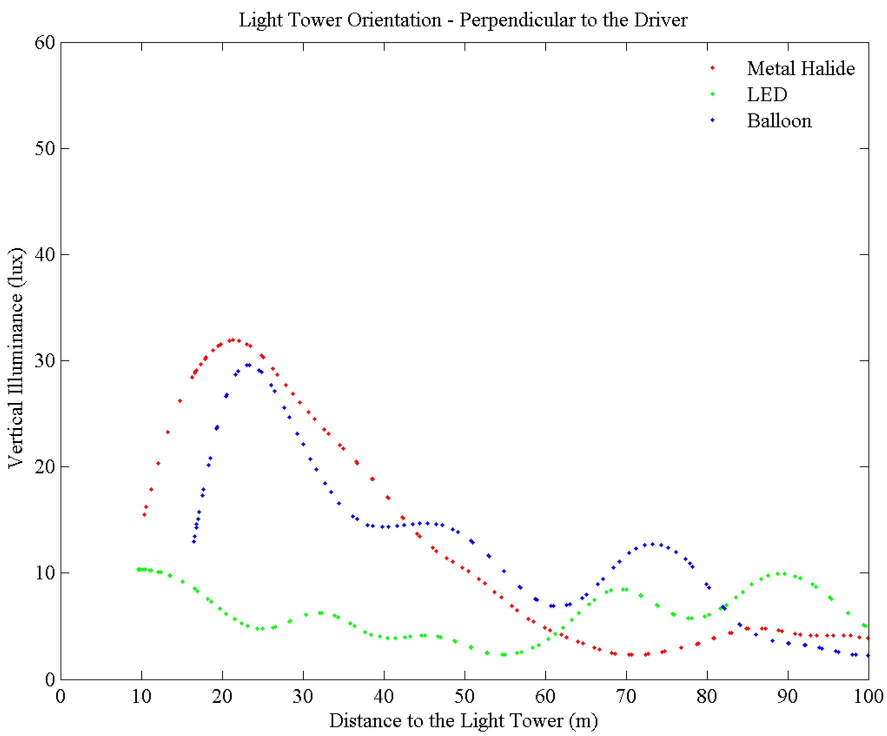

Figure 47. Change in vertical illuminance level with distance to the light tower in the Perpendicular orientation.

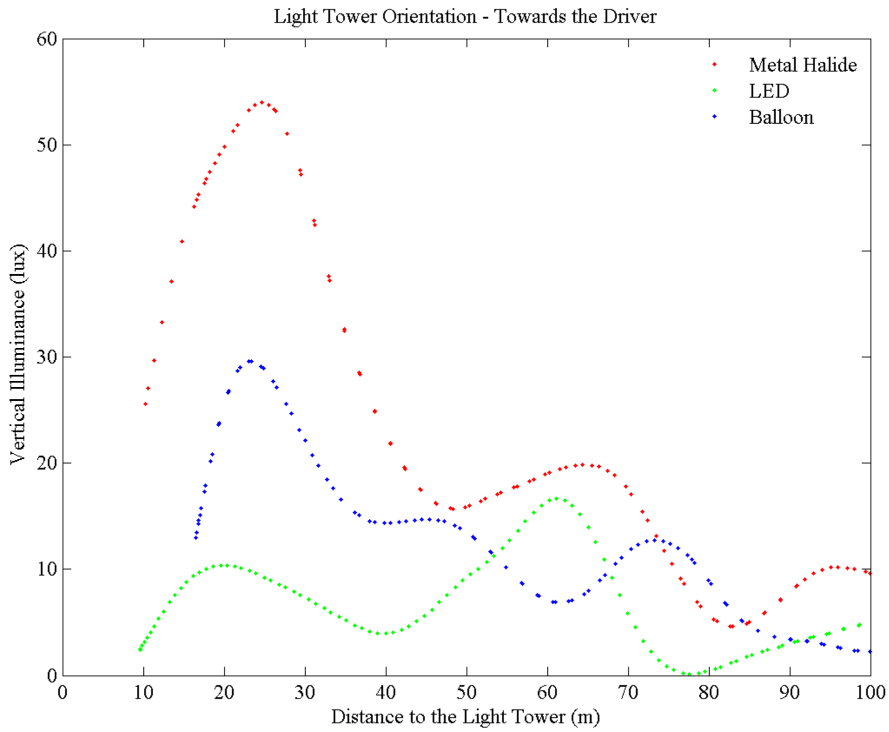

Figure 48. Change in vertical illuminance level with distance to the light tower in the Towards orientation.

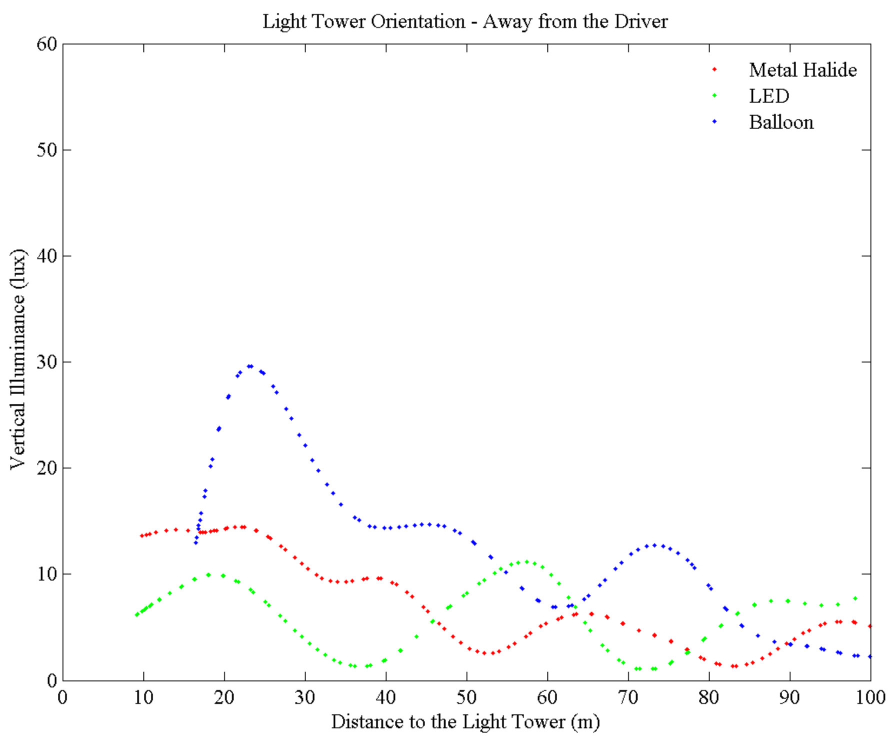

Figure 49. Change in vertical illuminance level with distance to the light tower in the Away orientation.

The higher vertical illuminances in metal halide and balloon light towers could result in increased disability and discomfort glare as one approaches the light tower, especially in the Towards orientation. The metal halide light tower had higher threshold increment values in the Towards orientation than in the Away and Perpendicular orientations, as shown in Figure 50. Threshold increment was lowest in the Away orientation for the metal halide light towers.

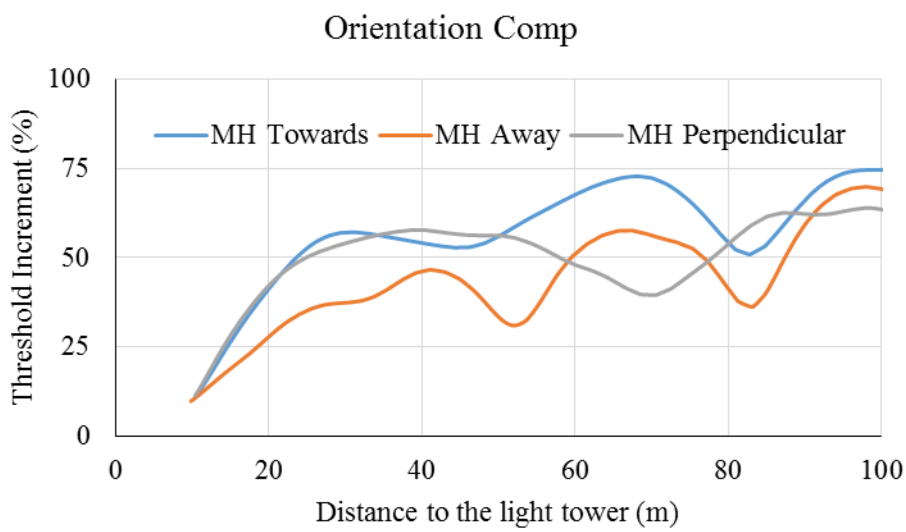

Figure 50. Change in threshold increment for the metal halide (MH) light tower in the three different orientations.

Critical Range for Vertical Illuminance

Various distances to the light towers and the vertical illuminances associated with them for each of the three light towers in all orientations were analyzed to determine the range of distances to the light tower where the vertical illuminance increased rapidly. This rapid increase in the vertical illuminance could potentially create conditions of glare (disability and discomfort) for drivers entering the work zone.

Table 10. Vertical illuminance levels in critical range (260 to 65 ft 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

The mean vertical illuminance levels for all the light tower types in each orientation are shown in Table 10. From Figure 51, Figure 52, and Figure 53, it is clearly evident that the increase in the vertical illuminance consistently occurs between a distance of 65 to 260 ft (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. The increase in disability glare (threshold increment) for the metal halide and LED portable light tower is illustrated in Figure 50 and Figure 54, where the threshold increment starts to increases from a distance of 260 ft (80 m) to the light tower.

In general, the vertical illuminance levels in the critical range are higher than those reported above, as the critical range is closer to the light tower. In the critical range, for the metal halide and balloon light towers the vertical illuminance levels in the Towards orientation were higher than in the other orientations. Overall, metal halide in the Towards orientation had the highest mean vertical illuminance level in the critical range followed by the balloon light tower.

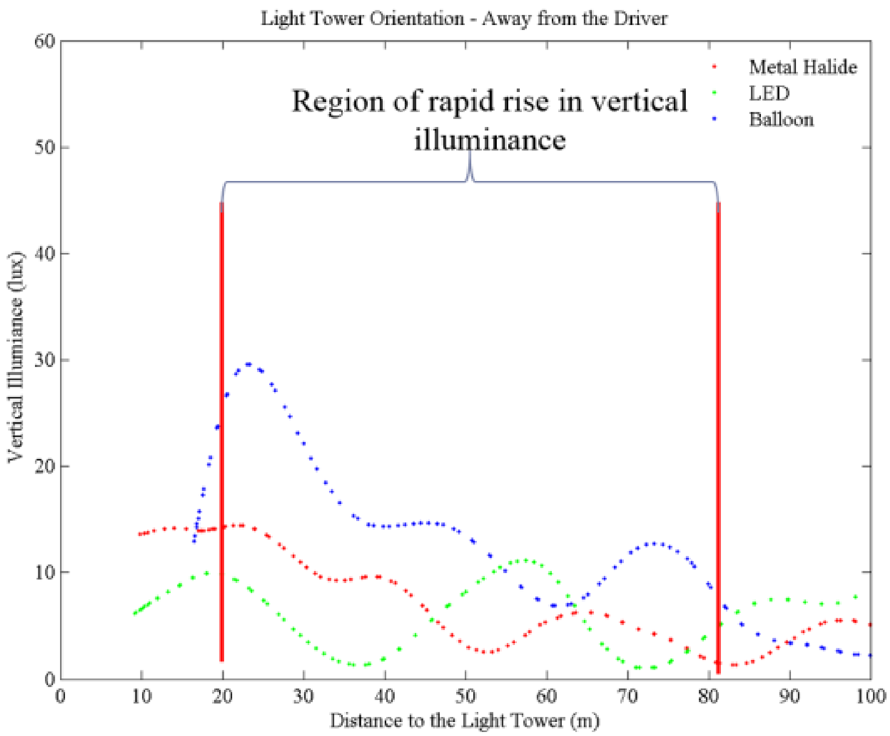

Figure 51. Critical range of vertical illuminance levels for the three light towers in the Away orientation.

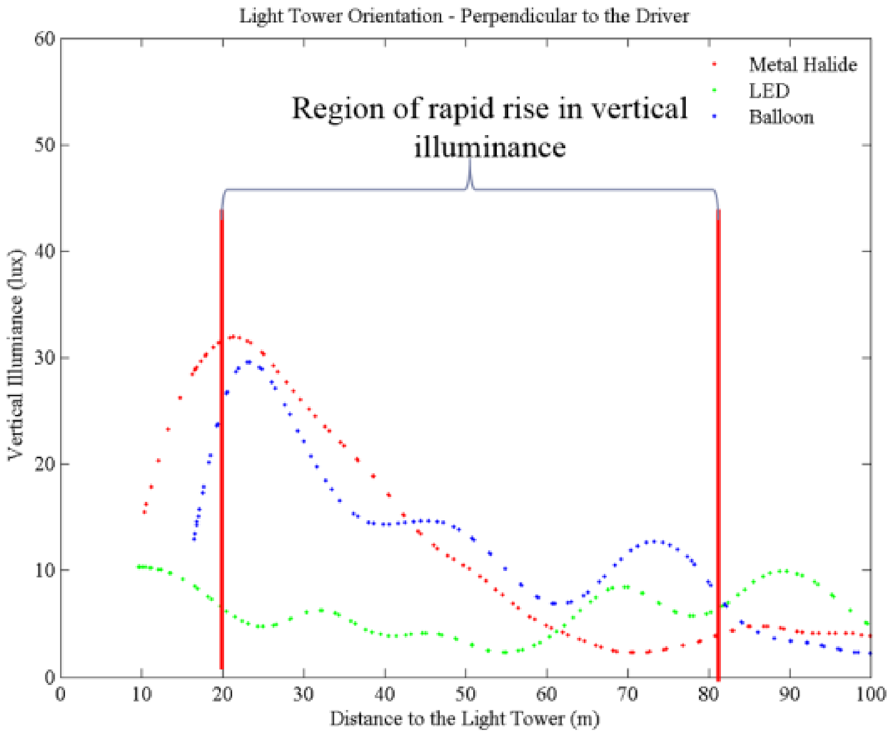

Figure 52. Critical range of vertical illuminance levels for the three light towers in the Away orientation.

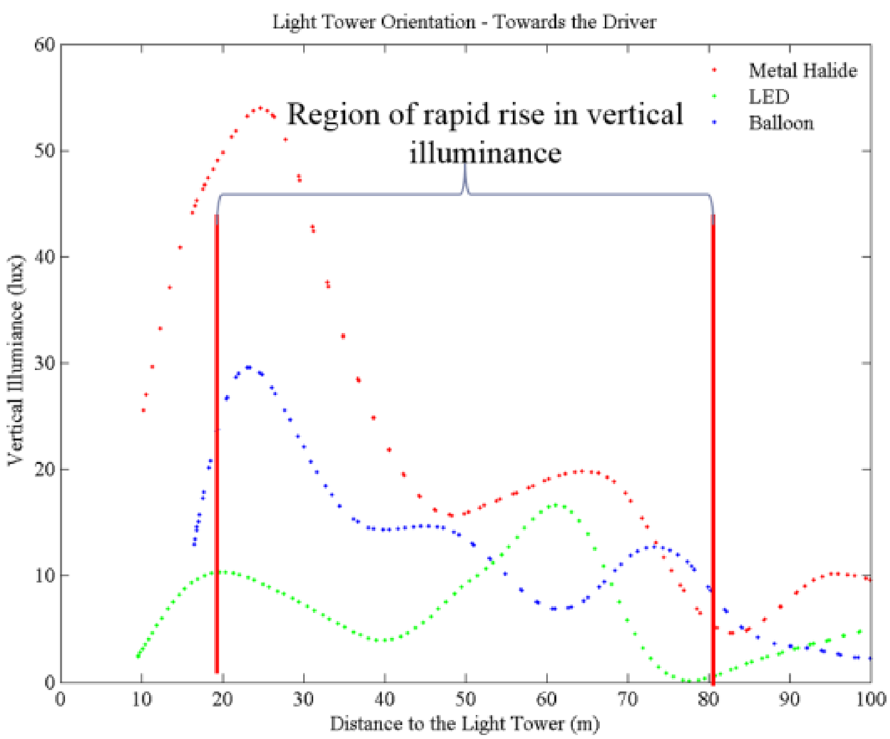

Figure 53. Critical range of vertical illuminance levels for the three light towers in the Towards orientation.

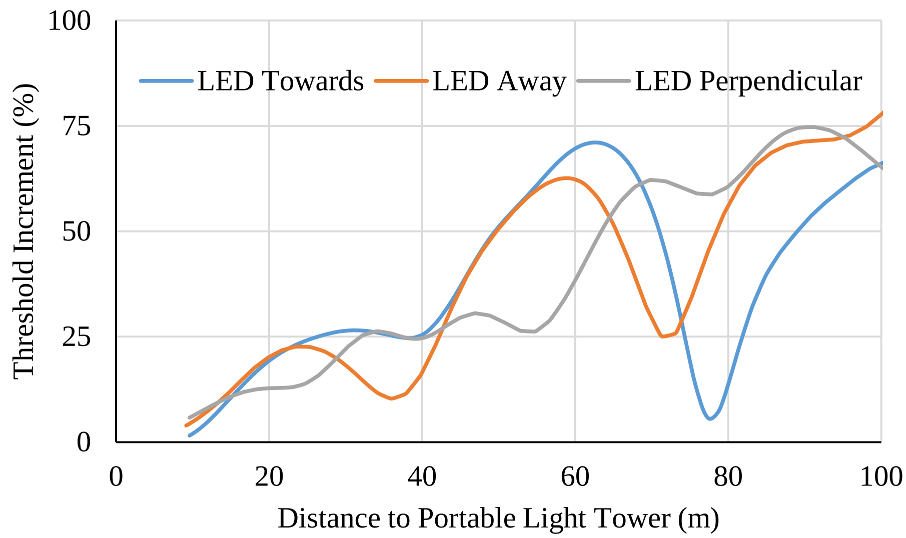

Figure 54. Changes in the threshold increment (disability glare) with distance to the LED light tower.

Smart Road Field Testing Results

Detection Distance Analysis

LMM results are summarized in Table 11. All the main effects were significant, as well as one two-way interaction involving light type and light orientation.

The combined effects of light type and light orientation on detection distance are shown in Figure 55. 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). To further analyze this interaction, differences between the three light types within each orientation were considered. This analysis is described in following section. Older drivers (*M* = 283.50 m, *SD* = 169.66 m) had significantly shorter detection distances compared to younger participants (*M*= 394.5 m, SD = 171.76 m). Detection distances were significantly longer when traveling in the uphill direction (*M* = 353.04 m, *SD* = 208.29 m) than in the downhill direction (*M* = 323.03 m, *SD* = 144.76 m).

Table 11. Statistical results from LMM analysis of detection distance

Effect	*F*	*p*
Age	**4.37**	**0.0484**
Light Type	**10.44**	**0.0019**
Age*Light Type	1.53	0.22
Light Orientation	**4.92**	**0.0084**
Age*Light Orientation	0.91	0.4048
Light Orientation*Light Type	**4.3**	**0.0153**
Age*Light Orientation*Light Type	0.26	0.7685
Vehicle Direction	**4.21**	**0.0425**
Age*Vehicle Direction	1.09	0.2979
Light Type*Vehicle Direction	1.56	0.2135
Age*Light Type*Vehicle Direction	0.59	0.4445
Light Orientation*Vehicle Direction	0.6	0.5485
Age*Light Orientation*Vehicle Direction	2.58	0.0788
Light Orientation*Light Type*Vehicle Direction	1.05	0.3507
Age*Light Type*Light Orientation*Vehicle Direction	0.61	0.5472

Significant effects are highlighted in bold text.

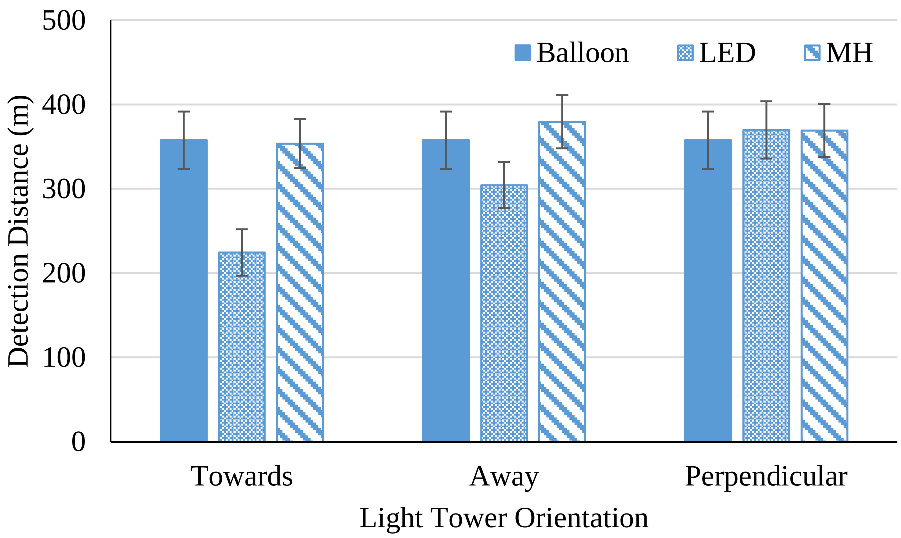

Figure 55. Effect of light tower type and orientation on detection distance. Values are mean detection distances, and error bars represent standard errors.

Effect of Light Type in Each Orientation

LMM results for each of the three orientations are summarized in Table 12. In the Perpendicular orientation, only the main effect of age was significant, with younger participants having longer detection distances than older participants. In the Towards orientation, the main effect of light type was significant and the two-way interaction between light type and vehicle direction was significant. Simple effects of light type were significant across both directions with metal halide and balloon light towers having significantly longer detection distances than the LED light tower (Figure 56). Simple effects also revealed that the differences between vehicle direction within each light type were not significant.

In the Away orientation, the main effect of light type was significant, with the metal halide light tower having a significantly longer detection distance than the LED light tower but not the balloon light tower (Figure 57). A two-way interaction involving age and vehicle direction was also significant.

Table 12. Statistical results from LMM analysis of detection distance in the three orientations. Significant effects highlighted in bold text.

Effect	Perpendicular		Towards		Away	
	F	*p*	*F*	*p*	*F*	*p*
Age	**5.18**	**0.0324**	**2.35**	**0.1397**	**2.68**	**0.1164**
Light Type	**0.83**	**0.4429**	**8.6**	**0.0006**	**6.58**	**0.0031**
Age*Light Type	**1.33**	**0.2725**	**0.64**	**0.5339**	**0.59**	**0.5604**
Vehicle Direction	**1.3**	**0.2613**	**1.58**	**0.2135**	**1.88**	**0.1774**
Age*Vehicle Direction	**0.64**	**0.4287**	**0.52**	**0.4727**	4.12	0.0483
Light Type*Vehicle Direction	**0.55**	**0.5809**	3.87	0.0282	**1.61**	**0.2077**
Age*Light Type*Vehicle Direction	**0.01**	**0.9907**	**1.44**	**0.2473**	**0.35**	**0.7028**

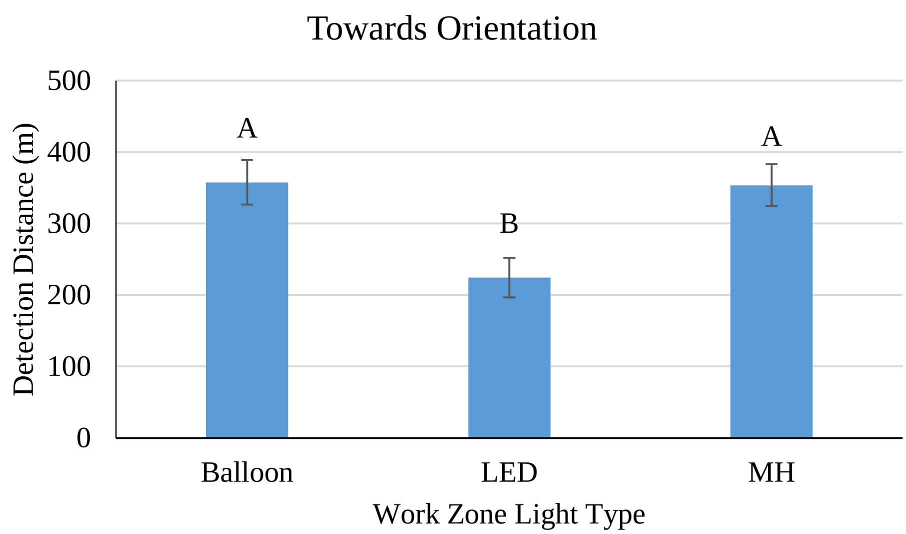

Figure 56. Effect of light tower type on detection distance for the Towards orientation. Values are mean detection distances, and error bars represent standard errors. Uppercase letters represent significant post hoc comparisons between light types.

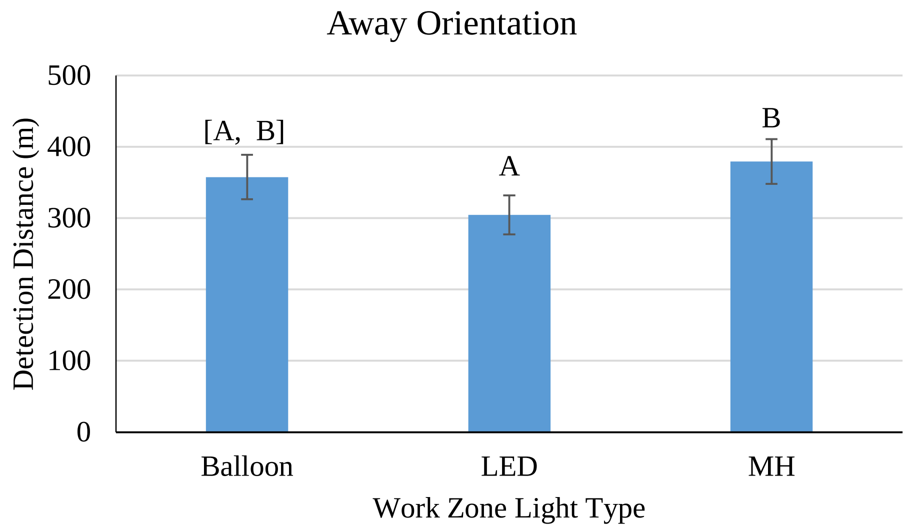

Figure 57. Effect of light tower type on detection distance for the Away orientation. Values are mean detection distances, and error bars represent standard errors. Uppercase letters represent significant post hoc comparisons between light types.

Speed Analysis

LMM results for the speed analysis are summarized in Table 13. Only the main effects of age and vehicle direction were significant. Light type approached significance, with p = .0517. The differences between the three light types within each orientation are examined in the following section (Figure 58). Overall uphill speeds (mean = 51.08 mph; SD = 1.31 mph) were significantly lower than downhill speeds (mean = 55.84 mph; SD = 1.29 mph).

Table 13. Statistical results from LMM analysis of speed

Effect	***F***	***p***
Age	**4.86**	**0.0383**
Light Type	**3.92**	**0.0517**
Age*Light Type	**0.49**	**0.488**
Light Orientation	**2.7**	**0.0696**
Age*Light Orientation	**0.41**	**0.6673**
Light Orientation*Light Type	**1.74**	**0.1784**
Age*Light Orientation*Light Type	**0.92**	**0.3994**
Vehicle Direction	**269.22**	**<.0001**
Age*Vehicle Direction	**3.29**	**0.0722**
Light Type*Vehicle Direction	**0.5**	**0.481**
Age*Light Type*Vehicle Direction	**0.02**	**0.8861**
Light Orientation*Vehicle Direction	**0.31**	**0.7316**
Age*Light Orientation*Vehicle Direction	**0.09**	**0.914**
Light Orientation*Light Type*Vehicle Direction	**1.82**	**0.1652**
Age*Light Type*Light Orientation*Vehicle Direction	**0.01**	**0.993**

Significant effects are highlighted in bold text.

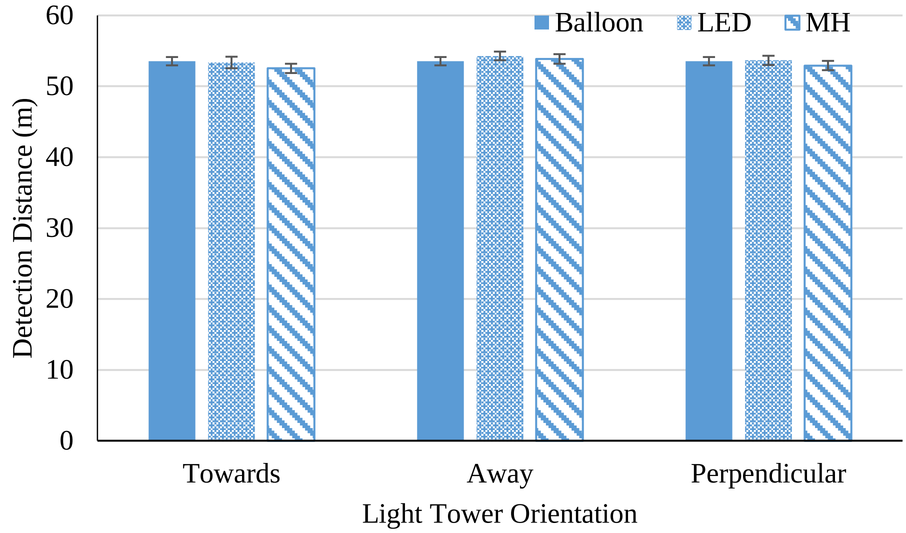

Figure 58. Effect of light tower type and orientation on detection distance. Values are mean detection distances, and error bars represent standard errors.

Visibility – Questionnaire Analysis

The LMM results of the Likert scale composite score of visibility are summarized in Table 14. Only the main effect of light orientation and a two-way interaction involving light type and light orientation were significant.

The combined effect of light type and light orientation on ratings of visibility are shown in Figure 59. 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." To further analyze this interaction, differences between the three light types within each orientation were considered. This analysis is described in following section.

Table 14. Statistical results from LMM analysis of the effects of light tower and light orientation on composite scores of visibility

Effect	*F*	*p*
Age	0	0.9892
Light Type	2.03	0.1582
Age*Light Type	0.76	0.3845
Light Orientation	**9.51**	**0.0001**
Age*Light Orientation	0.67	0.5152
Light Orientation*Light Type	**5.45**	**0.0048**
Age*Light Orientation*Light Type	0.42	0.6593
Vehicle Direction	0.78	0.3774
Age*Vehicle Direction	0.33	0.5656
Light Type*Vehicle Direction	0.04	0.8396
Age*Light Type*Vehicle Direction	0.19	0.6648
Light Orientation*Vehicle Direction	2.61	0.0757
Age*Light Orientation*Vehicle Direction	0.97	0.3793
Light Orientation*Light Type*Vehicle Direction	0.04	0.9565
Age*Light Type*Light Orientation*Vehicle Direction	0.47	0.6241

Significant effects are highlighted in bold.

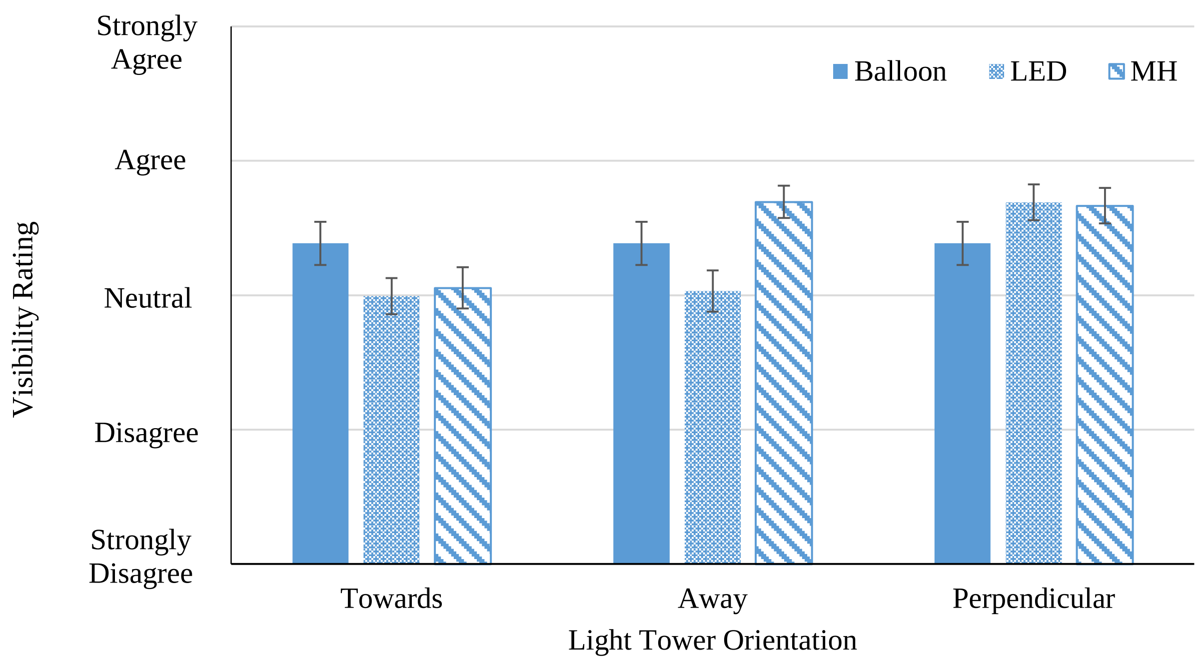

Figure 59. Ratings of visibility in the light tower types. Higher ratings mean better visibility. Values are means of Likert scale composite scores, and error bars represent standard errors.

Effect of Light Type in Each Orientation

In the Perpendicular and Towards orientations, the effect of light type on Likert scale ratings of visibility was not significant (Table 15). The effect of light type was only significant in the Away orientation. In this orientation, only the ratings between metal halide and LED light towers were significantly different from each other, with the metal halide having higher ratings of mean visibility than the LED (Figure 60).

Table 15. Statistical results from LMM analysis of the effects of light tower and light orientation on composite scores of visibility for Perpendicular orientation.

Effect	Perpendicular		Towards		Away	
	F	***p***	***F***	***p***	***F***	***p***
Age	0.32	0.5745	0.24	0.6309	0.01	0.9225
Light Type	1.7	0.187	1.44	0.2407	**4.49**	**0.0132**
Age*Light Type	1.37	0.2591	0.06	0.9397	0.34	0.7113
Vehicle Direction	**9.11**	**0.0038**	0.22	0.6411	0.11	0.7457
Age*Vehicle Direction	0.5	0.4836	1.4	0.2399	0.73	0.3957
Light Type*Vehicle Direction	0.16	0.8502	0.74	0.4782	0.67	0.5125
Age*Light Type*Vehicle Direction	0.3	0.7451	1.24	0.295	0.08	0.92

Significant effects are highlighted in bold.

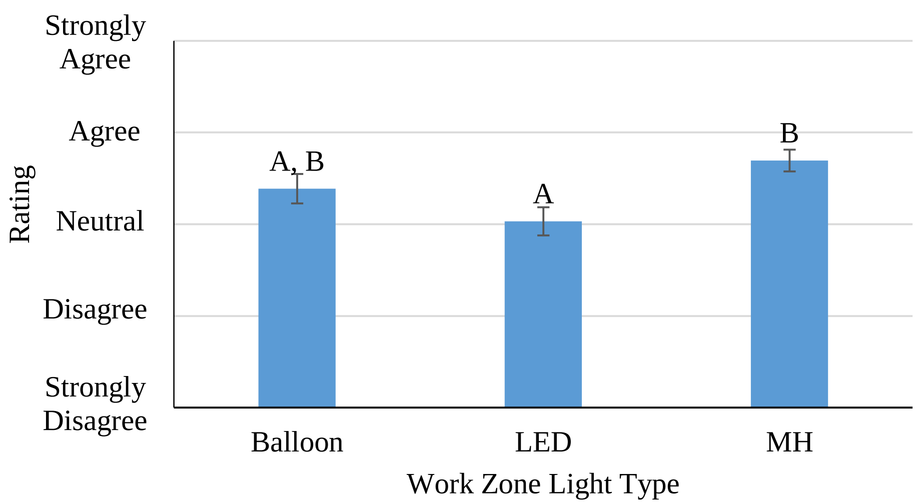

Figure 60. Ratings of visibility for the three light tower types in the Away orientation. Higher ratings are associated with better visibility. Values are means of Likert scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on significant (p < 0.05) paired comparisons between light tower types.

Glare – Questionnaire Analysis

The LMM results of the Likert scale composite scores of glare are summarized in Table 16. The main effect of light type and light orientation and a two-way interaction involving them were significant.

The combined effect of light type and light orientation on ratings of visibility are shown in Figure 61. 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." To further analyze this interaction, differences between the three light types within each orientation were considered. This analysis is described in following section.

Table 16. Statistical results from LMM analysis of the effects of light tower and light orientation on composite scores of glare

Effect	*F*	*p*
Age	0.54	0.4688
Light Type	**26.21**	**<.0001**
Age*Light Type	0.03	0.865
Light Orientation	**24.61**	**<.0001**
Age*Light Orientation	1.06	0.3492
Light Orientation*Light Type	**9.49**	**0.0001**
Age*Light Orientation*Light Type	0.03	0.9709
Vehicle Direction	0.1	0.7493
Age*Vehicle Direction	0.33	0.5658
Light Type*Vehicle Direction	0.48	0.4895
Age*Light Type*Vehicle Direction	2.23	0.1377
Light Orientation*Vehicle Direction	0.65	0.5242
Age*Light Orientation*Vehicle Direction	0.21	0.8144
Light Orientation*Light Type*Vehicle Direction	0.11	0.894
Age*Light Type*Light Orientation*Vehicle Direction	0.25	0.7797

Significant effects are highlighted in bold.

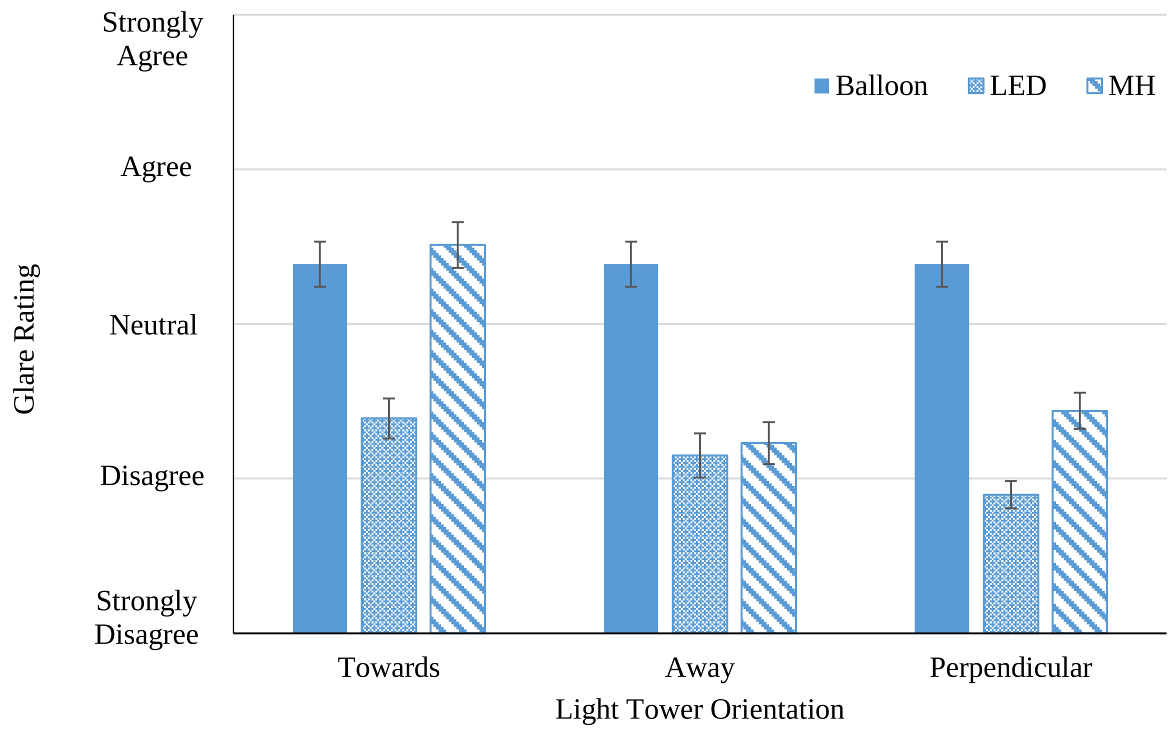

Figure 61. Ratings of glare in the light tower types. Higher ratings are associated with higher glare. Values are means of Likert scale composite scores, and error bars represent standard errors.

Effect of Light Type in Each Orientation

The main effect of light type was significant in every orientation as shown in Table 17. In the Perpendicular orientation, the glare ratings between all three light types were significantly different from one another, with the balloon light tower having the highest glare rating, and the LED light tower having the lowest glare rating (Figure 62).

In the Towards orientation, the glare ratings between balloon and LED light towers and LED and metal halide light towers were significantly different. In this orientation, metal halide light towers had the highest mean glare ratings, and the LED light tower had the lowest (Figure 63).

In the Away orientation, the glare ratings between balloon and LED light towers and balloon and metal halide light towers were significantly different. In this orientation, balloon light towers had the highest mean glare ratings and the LED light tower had the lowest (Figure 64).

Table 17. Statistical results from LMM analysis of the effects of light tower and light orientation on composite scores of glare for Perpendicular orientation

	Perpendicular		Towards		Away	
Effect	***F***	***p***	***F***	***p***	***F***	***p***
Age	**1.18**	**0.2848**	**0.01**	**0.9099**	**0.59**	**0.4504**
Light Type	**34.92**	**<.0001**	**22.1**	**<.0001**	**20.96**	**<.0001**
Age*Light Type	**0.18**	**0.836**	**0.51**	**0.5989**	**0.15**	**0.8604**
Vehicle Direction	**1.46**	**0.2314**	**0.65**	**0.4242**	**0**	**0.9568**
Age*Vehicle Direction	**0.08**	**0.7833**	**0.39**	**0.533**	**0.18**	**0.6737**
Light Type*Vehicle Direction	**0.27**	**0.7605**	**0.36**	**0.7007**	**0.14**	**0.8715**
Age*Light Type*Vehicle Direction	**1.32**	**0.2722**	**0.96**	**0.388**	**1.18**	**0.3126**

Significant effects are highlighted in bold.

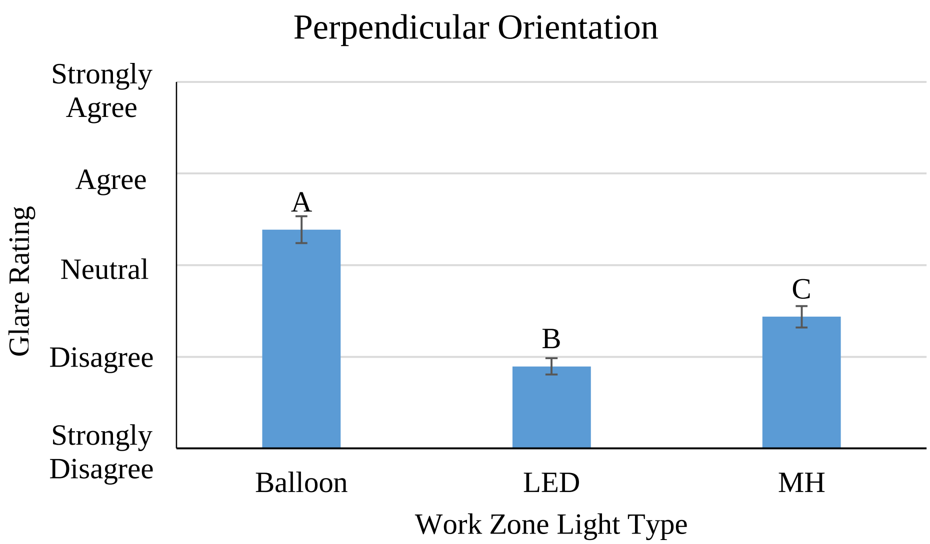

Figure 62. Ratings of glare for the three light tower types in the Perpendicular orientation. Higher ratings are associated with higher glare. Values are means of Likert scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on significant (p < 0.05) paired comparisons between light tower types.

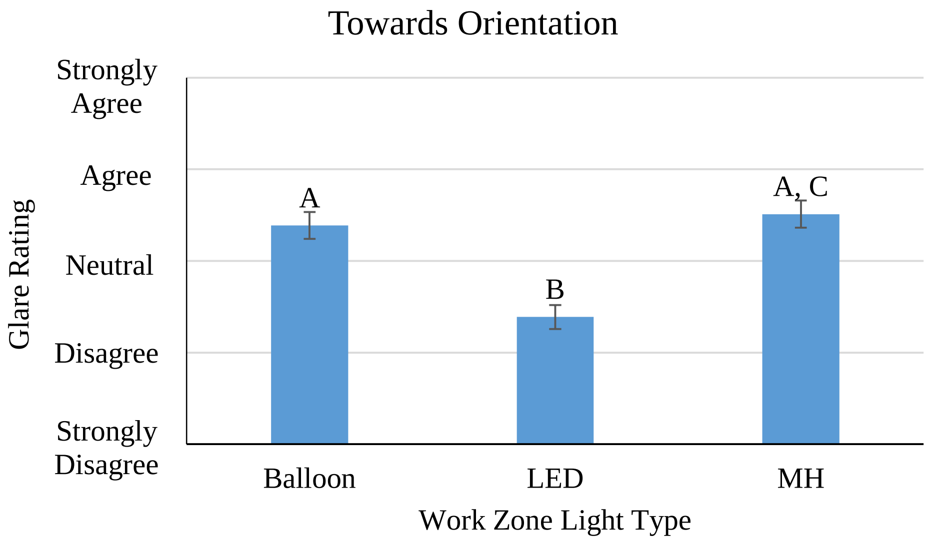

Figure 63. Ratings of glare for the three light tower types in the Towards orientation. Higher ratings are associated with higher glare. Values are means of Likert scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on significant (p < 0.05) paired comparisons between light tower types.

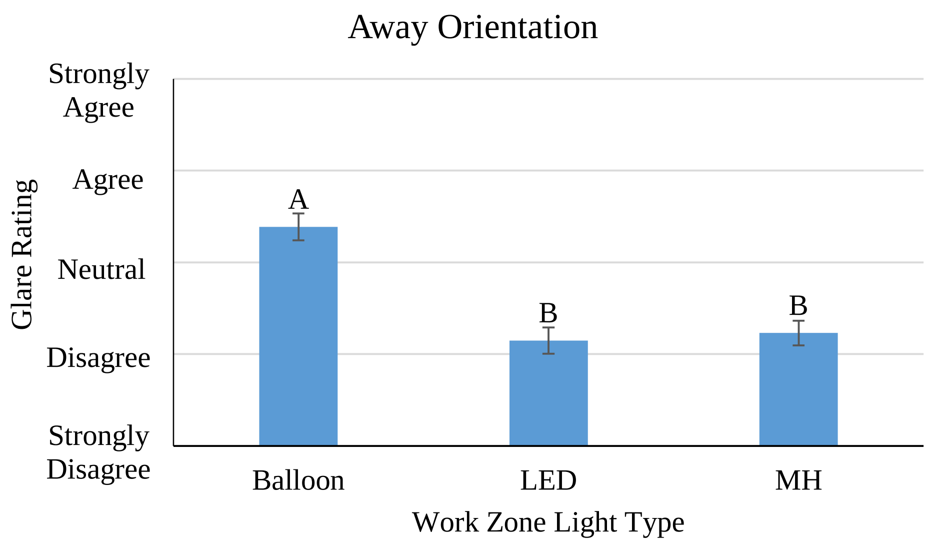

Figure 64. Ratings of glare for the three light tower types in the Away orientation. Higher ratings are associated with higher glare. Values are means of Likert scale composite scores, and error bars represent standard errors. Upper case letters indicate groupings based on significant (p < 0.05) paired comparisons between light tower types.

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 (see Figure 65). This shows that increases in the vertical illuminance levels in the critical range result in higher glare ratings by the participants.

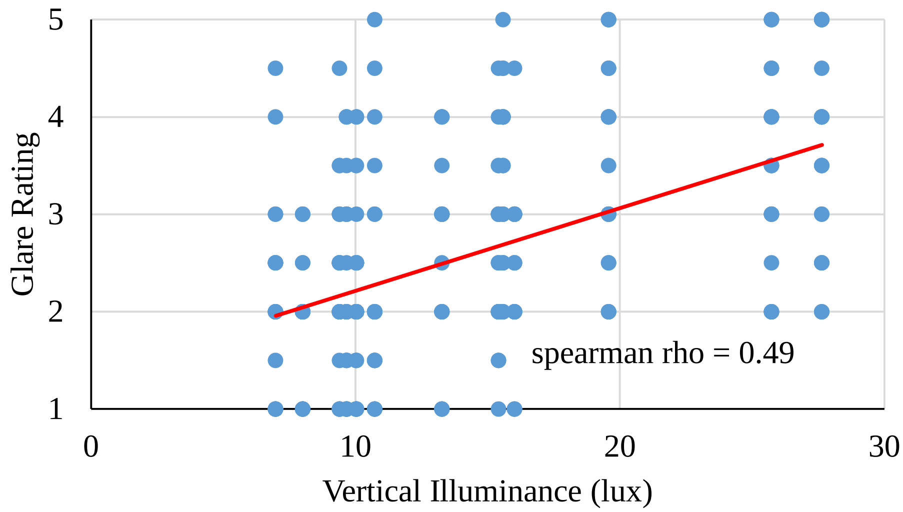

Figure 65. Association between perceived glare ratings and mean vertical illuminance in the critical range (80 m to 20 m to the light tower). Higher ratings are associated with higher glare.

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 66. 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.

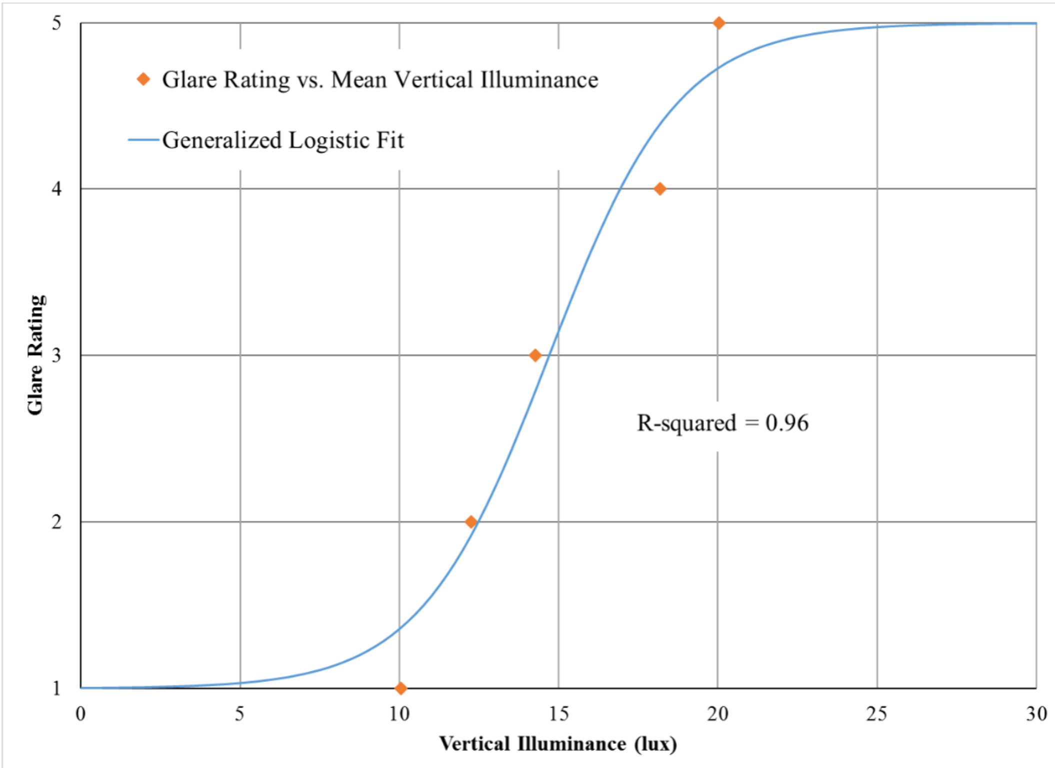

Figure 66. Generalized logistic fit between perceived glare rating and mean vertical illuminance for each glare rating anchor in the critical range. Higher ratings are associated with higher glare.

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 (see Figure 67). This is maximum allowed mean vertical illuminance in the critical range on approach to the light tower in the work zone.

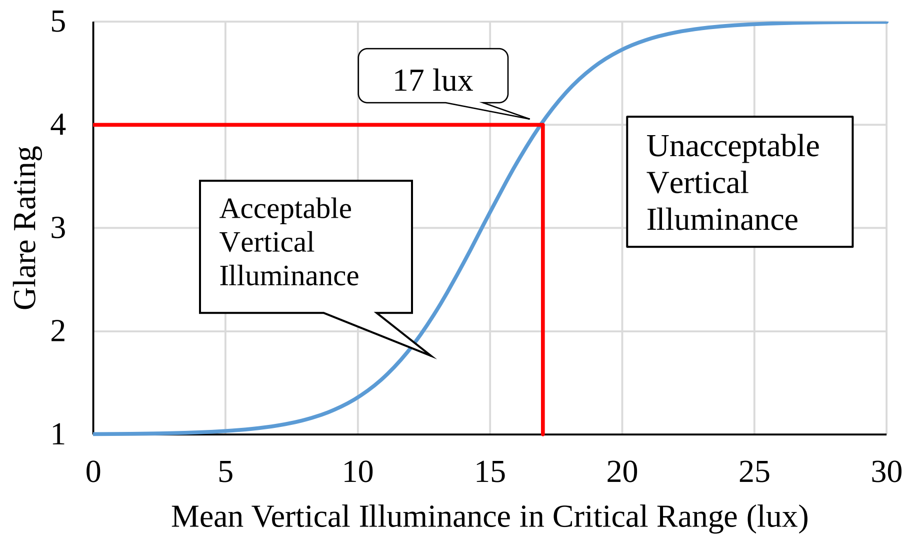

Figure 67. Regions of acceptable and unacceptable mean vertical illuminance in the critical range based on the generalized logistic function. Higher ratings are associated with higher glare.

DISCUSSION

Smart Road Field Testing

The goals of the Smart Road field testing were to understand the effect of light tower type and orientation on driver visual performance, speed, and perceptions of visibility and glare. Five major findings were evident.

1. Objective measures of visual performance were significantly impacted by both light tower type and orientation.

2. Speed was not majorly influenced by light tower type and orientation.

3. Perceptions of visibility were significantly affected by light tower type and orientation.

4. Perceptions of glare were also significantly affected by light tower type and orientation.

5. The perceived glare ratings were significantly correlated with mean vertical illuminance in the critical range and the relationship between them is accurately defined by a generalized logistic function.

Regarding the effects of light tower orientation, three converging results show that the Towards orientation results in lowering visual performance. First, the mean detection distances were lower in the Towards orientation than in either the Perpendicular or Away orientations. Second, the mean visibility ratings were the lowest for the Towards orientation. Third, the mean glare ratings were also the highest in the Towards orientation. This shows that great care must be taken to not aim the light towers toward the direction of traffic flow. In order to optimize drivers' visual performance, the light towers should be aimed away from approaching traffic or perpendicular to it. In these two orientations, the visual performance measures between the three types of light towers were very similar to one another.

Lower visual performance in the Towards orientation could be attributed to the higher vertical illuminance level attained as a result of aiming the lighting tower toward a driver approaching the work zone. Vertical illuminance could be a double-edged sword when it comes to visual performance in work zones. Increasing the vertical illuminance could result in increasing the visual performance, but after a certain level any increase in vertical illuminance will negatively affect visual performance by increasing disability glare and reducing visibility. Future research should determine where this transition takes place so that vertical illuminance specifications can be developed for work zones.

Overall, metal halide light towers had the longest detection distances and highest ratings of visibility. Conversely, metal halide also had higher ratings of glare, especially in the Towards orientation. Detection distances and visibility ratings in the balloon light tower were comparable to those with the metal halide light tower. Interestingly the balloon light tower had the highest ratings of glare. The LED light tower had the lowest detection distances, the lowest visibility ratings, and the lowest glare ratings. The paradoxical result in the detection distance, visibility, and glare ratings could be attributed to light distribution patterns. Metal halide and balloon light towers illuminated a much larger area than the LED light tower, which resulted in the simulated worker being detected farther away. For these two light towers, the simulated worker was detected (greater than 985 ft [300 m]) prior to the onset of disability glare, which started at a distance of about 260 ft [80 m] (critical range) to the light tower. The smaller area illuminated by the LED light tower and the lower vertical illuminance levels in the critical range could have resulted in lowering the visual performance without really affecting the glare perception. However, the metal halide and balloon light towers had higher vertical illuminance levels in the critical range (thereby higher disability and discomfort glare), which could have resulted in higher glare ratings.

An important point to note is that even though the LED tower had the shortest mean detection distance, it was still greater than the stopping sight distance at 55 mph (500 ft [152.4 m]). This shows that all three light towers enabled detection of the worker in the test work zone from a safe stopping distance. This also indicates that detections took place before the participants experienced disability glare.

An increase in vertical illuminance levels in the critical range was associated with significantly higher perceptions of perceived glare ratings or discomfort glare. Further, the relationship between perceived glare rating and the mean vertical illuminance in the critical range could be accurately defined by a generalized logistic function. This function was used to determine the boundary at which the vertical illuminance level transitions from acceptable to unacceptable, resulting in higher perceptions of glare. This transition occurred at a mean vertical illuminance level of 17 lux. In order to lower the perceive ratings of glare, the mean vertical illuminance should be maintained below 17 lux in the critical range (260 to 65 ft [80 m to 20 m] to the light tower).

The speed at which the participants drove the vehicle was not significantly influenced by light tower type or orientation. This could be attributed to drivers being aware that they were in a simulated work zone with an in-vehicle experimenter watching their driving. In general, older drivers had shorter detection distances than younger drivers and this could be attributed to the loss in visual acuity due to aging.

DRAFT SPECIFICATIONS OUTLINE FOR WORK ZONE LIGHTING

The following recommendations were 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 has 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. A minimum 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, a minimum 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 a minimum 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 NCHRP Report 498 (Ellis et al., 2003) (see Table 18).

Table 18. 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: NCHRP Report 498, 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 in Figure 68. The work zone inspector shall explicitly ensure that the portable light towers are not aimed into the direction of traveling traffic.

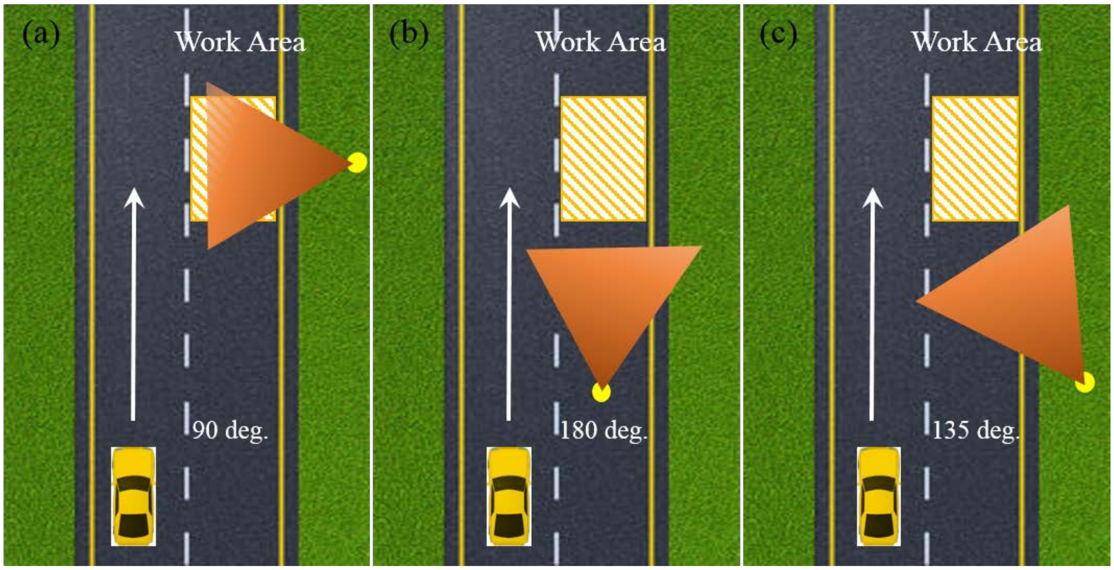

Figure 68. Recommended orientations for the portable light towers with respect to the direction of traveling traffic.

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 4.76 ft (~1.45 m) from the ground), as illustrated in Figures 69 and 70. 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 71). The arithmetic mean of the vertical illuminance at these four distances to the portable light tower shall not exceed 17 lux. 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 (1.6 fc). 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 (0.46, 0.93, 2.79 and 3.72 fc). Then the mean vertical illuminance in the critical range will be 21.25 lux (1.97 fc), this value is higher than the acceptable level which is 17 lux (1.6 fc). The contractor/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 on 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 lights 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.

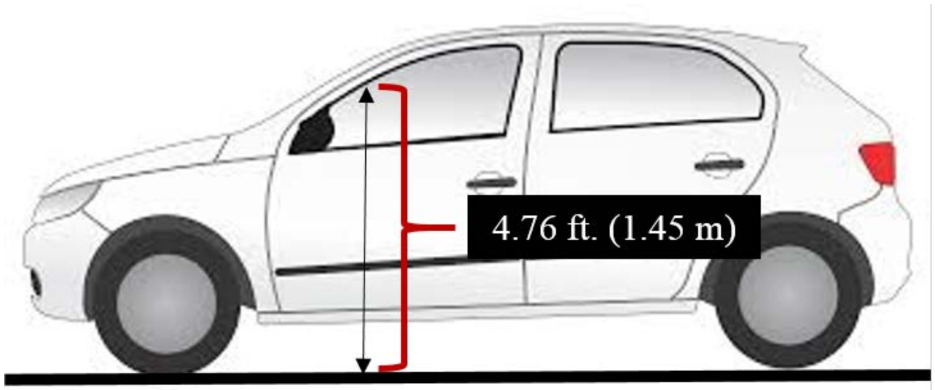

Figure 69. Height at which the cosine-corrected illuminance meter should be measured inside the vehicle.

Figure 70. Mounting of the cosine-corrected illuminance meter on windshield to measure vertical illuminance levels.

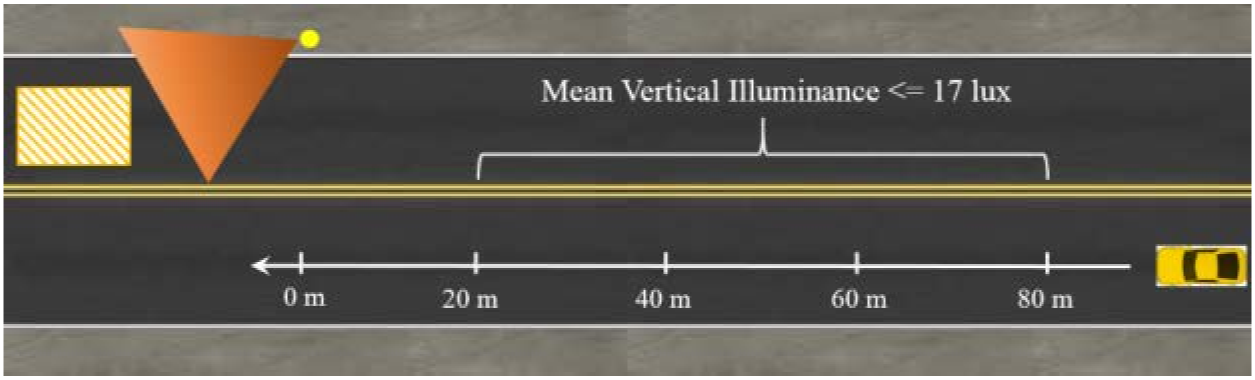

Figure 71. Distances at which the vertical illuminance should be calculated to determine the mean vertical illuminance level in the critical range (65-260 ft = 20-80 m).

On-site Lighting Evaluation Protocol

A modified work zone lighting plan, adopted from American Traffic Safety Services Association (ATSSA), is presented as shown in Figure 72.

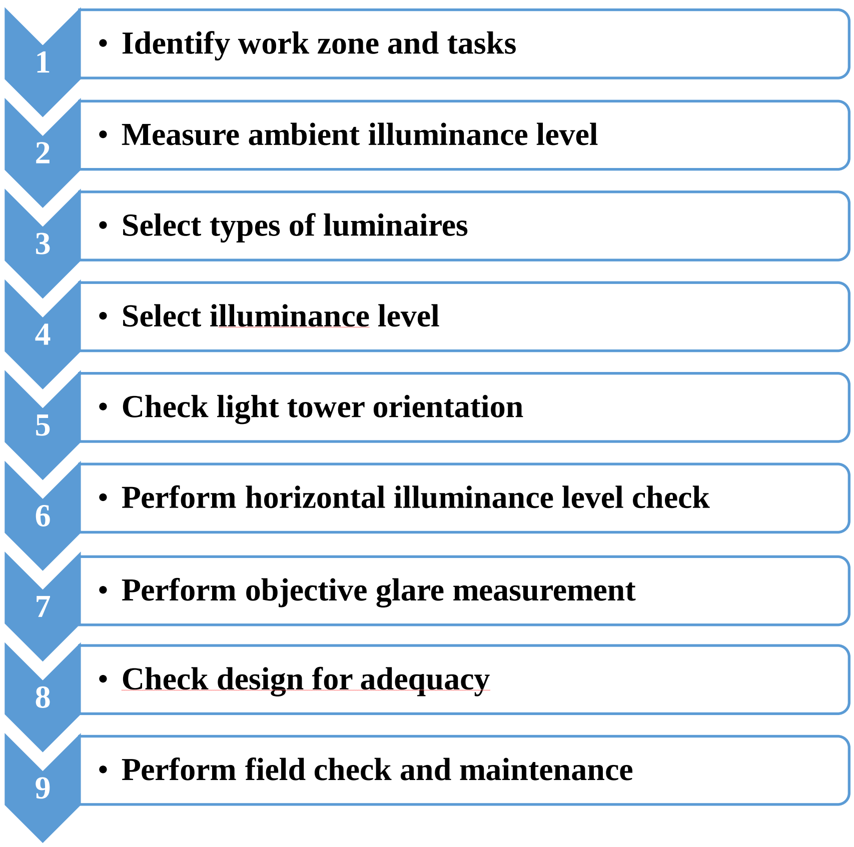

Figure 72. Modified work zone lighting plan, adopted from ATTSA (2013).

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 73.*

Figure 73. 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).*

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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APPENDIX

VISIBILITY AND GLARE QUESTIONNAIRE

Post-Scenario Questionnaire

Participant Number: Lighting Type: Lighting Orientation: Direction:

1. The current lighting helped me detect the worker from a safe distance

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

2. The current lighting caused glare while driving through the work zone

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

3. In the current lighting , it was very easy to drive through the work zone

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

4. The current lighting was helpful in increasing the visibility of the worker

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

5. Glare from lighting affected my ability to detect the worker

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

6. Current lighting was helpful in increasing the work zone visibility and the workers in it

1	2	3	4	5
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree