The Effect of Nighttime Lighting Systems on Workers' Visibility and Safety

Final Report
December 2025

SWZDI
Smart Work Zone Deployment Initiative

Sponsored by
Smart Work Zone Deployment Initiative
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About the Smart Work Zone Deployment Initiative

The Smart Work Zone Deployment Initiative (SWZDI) is a transportation pooled fund that supports research investigations into better ways to improve the safety and efficiency of traffic operations and highway work in work zones. The primary objective is to promote and support research and outreach activities that focus on innovative policies, processes, tools, and products that enhance the implementation, safety, and mobility impacts of work zones.

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16. Abstract

Nighttime work zones pose increased risks for both drivers and workers due to the challenge of ensuring adequate visibility while minimizing glare. Current lighting practices vary widely across public agencies, often resulting in excessive illumination and poor glare control. This study evaluated the performance of nighttime lighting systems through two phases: (1) an industry survey and (2) a controlled field experiment along with a qualitative task assessment and analysis. The survey, with 116 responses, identified persistent issues related to glare and uneven light coverage, primarily attributed to improper lighting configurations rather than insufficient light output. The field study tested 126 lighting setups using LED and halogen lighting sources set at varying mounting heights, aiming angles, and rotation angles. Measurements included horizontal and vertical illuminance, pavement luminance, and veiling luminance ratio (VLR). Results showed that the lighting setups—rotation angle and mounting height—had the greatest impact on visibility and glare. Optimal configurations (rotation: 40°–50°, height: 12–13 ft, aiming angle: 20°–40°) could provide better visibility and minimize harmful glare in the vicinity of nighttime work zones. This report provides recommendations for optimal lighting configurations, offering agencies practical guidance to improve safety and visibility in nighttime work zones.

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EXECUTIVE SUMMARY

Nighttime work zones pose increased risks to both workers and drivers due to the potential for hazardous glare caused by construction lighting. While lighting is essential for visibility, excessive or poorly controlled illumination can compromise safety. Current lighting practices vary significantly across states, and field observations reveal that many work zones suffer from over-illumination and inadequate glare control.

This project addressed these challenges by evaluating visibility and glare from the perspectives of both drivers and construction workers. The research culminated in practical guidelines that specify optimal parameters for the mounting height, aiming angle, and rotation angle of light towers—helping agencies and contractors reduce glare and enhance worker visibility and safety during nighttime operations.

The study was conducted in two phases:

1. **Industry Survey**: A survey of 116 professionals (79 complete responses) captured current practices and identified persistent issues. While most respondents expressed general satisfaction with existing systems, they highlighted recurring problems with glare and uneven light coverage—primarily attributed to improper aiming and rotation angles rather than insufficient light output.

2. **Controlled Field Study**: A series of field lighting tests were conducted at the University of Nebraska–Lincoln's Midwest Roadside Safety Facility. This phase tested 126 lighting configurations using portable light towers equipped with LED and halogen fixtures. Variables included mounting heights of 12, 13, and 14 ft; aiming angles of 10°, 20°, and 40°; and rotation angles ranging from 20° to 160°. Measurements included horizontal and vertical illuminance, pavement luminance, and veiling luminance ratio (VLR), alongside qualitative assessments such as plan reading and tape measure legibility. Results were evaluated against recommended illuminance levels (40 to 480 lux) and VLR thresholds (≤0.3 preferred, ≤0.4 marginal).

Key findings indicate that lighting configuration—particularly rotation angle and mounting height—significantly influences glare and illuminance distribution. Rotation angles between 90° and 160° (perpendicular to or toward traffic) often resulted in excessive or insufficient lighting. In contrast, optimal configurations were identified with rotation angles of 40° to 50°, mounting heights of 12 to 13 ft, and aiming angles of 20° to 40°, which consistently provided safe and effective lighting conditions.

This report offers evidence-based recommendations for nighttime lighting setups in work zones, equipping public agencies and contractors with practical guidelines to improve safety and visibility for both workers and drivers.

INTRODUCTION

Nighttime work zones present unique safety challenges for both roadway workers and motorists. The inherent risks of driving are amplified after dark; the nighttime fatality rate on US roadways is three times higher than the daytime rate (FHWA 2025). Between 2011 and 2020, 1,260 workers were killed in road construction zones—an average of 126 fatalities per year. Visibility has been the top priority for all lighting system designs in nighttime work zones; however, to ensure worker visibility, many work zones are paradoxically over-illuminated, which can create harmful levels of glare (IDOT n.d., Wu and Garber 2017). This glare is a critical safety hazard, defined by the Illuminating Engineering Society (IES) in terms of the several forms it can take. Disability glare impairs the ability to see detail by scattering light within the eye, creating a visual haze that reduces contrast (FHWA 2012). Discomfort glare causes annoyance or pain, which can lead to fatigue and distraction (FHWA 2012). The most extreme form, blinding glare, is so intense that for a period after the source is removed, no visual perception is possible (Schorsch n.d.).

All forms of glare can negatively affect the visual performance of workers on foot and motorists traveling through construction areas, ultimately impacting overall work zone safety. The impact can be severe; one study found that under conditions of significant glare, the average detection distance for an object on the roadway dropped to just 37 ft, with 45% of participants failing to see the object at all before passing it (Carlson et al. 2013).

Existing lighting design guidelines and technical reports, such as those from the IES, provide general recommendations but remain in need of supplemental information to address specific safety concerns. For instance, field studies have found that measured illuminance levels in many work zones are much higher than IES-recommended levels, indicating a gap between guidelines and practice (Wu and Garber 2017). Current practices do not sufficiently evaluate the comparative impacts of different lighting sources, orientations, and configurations on visibility and glare. More critical than the overall amount of light is its direction; research has consistently shown that the aiming of portable light towers is a decisive factor in generating glare (Wu and Garber 2017). A systematic assessment of these factors is essential to improve safety outcomes in nighttime work zones.

To achieve this systematic assessment, this research conducted an experimental evaluation of two types of light sources—LED light towers and halogen light towers—under multiple orientations and light configurations (mounting height, aiming angle, and rotation angle). The study addressed three key factors:

- Type of light source and associated luminance characteristics
- Relative positioning and orientation of light towers with respect to motorists and workers
- Measurement of glare index and illuminance level using quantitative (illuminance meters) and qualitative (observer assessment) methods

The field test was conducted at the University of Nebraska–Lincoln's Midwest Roadside Safety Facility (MwRSF) at a controlled experimental site that replicated nighttime work zone environments. Data collection followed standardized procedures for measuring illuminance, luminance, and glare intensity at multiple grid points within the test site. Results were compared against established standards and guidelines to identify effective lighting practices that maximize visibility while minimizing harmful glare.

The outcomes of this study are expected to contribute to safer nighttime construction operations by providing evidence-based recommendations for lighting system design and implementation. These findings are intended to provide practical guidance to state departments of transportation (DOTs) and relevant industry stakeholders in support of nighttime work zone safety.

The remainder of this report is organized as follows:

- The following chapter provides a comprehensive literature review of existing guidelines and studies on nighttime work zone illumination and glare.
- The third chapter details the research methodology, covering both the nighttime lighting survey and the field test design.
- The fourth chapter presents the results of the survey and the results and analysis of the field experiment, including the various lighting arrangements and analytical methods used.
- The final two chapters present the overall conclusions and provide actionable recommendations for improving nighttime work zone lighting practices.

LITERATURE REVIEW

Lighting Design and Nighttime Work Zone Safety

Existing research has established a strong correlation between traffic accidents in nighttime work zones and challenges related to visibility and inadequate lighting design. Wood (2020) articulated the foundational principle that effective nighttime lighting must provide sufficient illuminance while simultaneously avoiding discomfort or disability glare for drivers, noting that the effects of glare on pedestrian detection can be more detrimental than reduced visual acuity alone. Experimental studies have clarified the mechanisms by which poor lighting elevates accident risk. Bhagavathula and Gibbons (2017) found that improper lighting configurations—including low luminaire mounting heights and light sources aimed directly into drivers' lines of sight—significantly reduced pedestrian detection distances, lowered visibility ratings, and intensified glare perception, thereby increasing collision risk. These experimental findings have been corroborated by analyses of real-world accident data. Nafakh et al. (2022), for example, examined accident records from Indiana and identified a significant correlation between both insufficient lighting and excessive glare and an increased incidence of worker-vehicle accidents, particularly where sight distance was limited or where drivers transitioned between brightly lit and dark areas.

In response to these identified hazards, researchers have developed comprehensive design strategies for work zone lighting. Finley et al. (2013) and Gambatese and Jafarnejad (2018) demonstrated that well-designed systems can simultaneously meet the visibility needs of both motorists and workers, reducing accident rates and occupational injuries. Their recommendations include using luminaires with elevated mounting heights, increasing the use of diffused lighting, and incorporating shielding devices to minimize glare while enhancing light uniformity. Field investigations have provided empirical validation for these principles. Bhagavathula et al. (2017), in an examination of lighting practices in Virginia, identified direct links between worker fatalities or injuries and inadequate visibility or improper luminaire placement, leading the authors to advocate for more rigorous lighting standards that optimize tilt angles, light source selection, and light tower configuration. Further advancing this work, Davila (2022) used controlled field testing to demonstrate that distributed, multi-source lighting layouts improve uniformity and reduce shadow areas, thereby helping drivers maintain continuous identification of worker locations.

State DOT Lighting Standards and Practices

Based on a systematic review of state-level standards and practices for nighttime work zone lighting across the United States, the research team identified several approaches that are currently in use and divided these approaches into two main categories. The first category includes states where the state DOT has developed its own specific standards, while the second includes states that lack state DOT-developed standards and instead reference general provisions from sources such as the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA 2009, FHWA 2013). Among the state DOT-established standards, a clear distinction exists: one subset provides specific numerical values for work zone lighting equipment and illuminance levels, while the other subset offers lighting arrangement practices or guidance within manuals and specifications without establishing concrete numerical parameters (FHWA 2013, Vecellio and McCarthy 2006). Detailed nighttime work zone lighting standard or practices for each state DOT are presented in Appendix A.

Among states with specific numerical requirements for nighttime work zone lighting, several agencies directly specify illuminance thresholds and critical equipment parameters. For example, the California Department of Transportation (Caltrans) requires 10 foot-candles (fc) for nighttime operations (Caltrans 2021). The Florida Department of Transportation (FDOT) specifies 5 fc (Vecellio and McCarthy 2006, FHWA 2013). The Georgia Department of Transportation (GDOT) connects equipment specifications to performance requirements, requiring 20 fc in work areas, with each light tower providing ≥50,000 lumens (lm) (approximately 460,000 lm in total) and mobile lighting systems delivering 22,000 to 50,000 lm (Vecellio and McCarthy 2006, FHWA 2013). The Illinois Department of Transportation (IDOT) establishes minimum requirements of ≥5 fc for work areas and ≥10 fc for flagger zones (FHWA 2013). The Missouri Department of Transportation (MoDOT) distinguishes between work areas requiring 5 fc and flagger/designated planning locations requiring 0.6 fc (FHWA 2013). The New Jersey Department of Transportation (NJDOT) uses task-based illuminance expressed in lux with uniformity ratios (≤5:1), specifying 100 lux for equipment operations and 200 lux for specific tasks (Vecellio and McCarthy 2006, FHWA 2013). The North Carolina Department of Transportation (NCDOT) provides detailed specifications, including luminous flux, illuminance, and mounting height requirements (light towers: 50,000 to 460,000 lm achieving 20 fc; mobile lighting: 22,000 to 50,000 lm achieving 10 fc; installation at 13 ft) (FHWA 2013, NCDOT 2018). Equipment-level requirements are also common. The Rhode Island Department of Transportation (RIDOT) specifies 250 W metal-halide fixtures for paving/compaction vehicles (Vecellio and McCarthy 2006); the Iowa Department of Transportation (Iowa DOT) requires specific boom angles of 88° to 92° and mounting heights of ≥17 ft for trailer-mounted LEDs (Iowa DOT 2016, Iowa DOT 2017); and the Kansas Department of Transportation (KDOT) requires full cutoff LEDs (KDOT 2015). Additional states directly adopt National Cooperative Highway Research Program (NCHRP) three-tier maintained illuminance levels of 59/108/215 lux with maximum uniformity ratios of 10:1. Examples include the Texas Department of Transportation (TxDOT) and the Delaware Department of Transportation (DelDOT) (NCHRP 2002, Finley et al. 2012, DelDOT 2009). The Alabama Department of Transportation (ALDOT) adds illuminance requirements with glare control provisions (average 50 lux, precision tasks 216 lux, with prohibition of disabling glare) (Vecellio and McCarthy 2006).

A large portion of states maintain nighttime work zone standards without specifying concrete numerical data (24 out of 51 jurisdictions). Within this category, DOTs typically establish nighttime lighting and glare reduction requirements in state-level work zone manuals and specifications, list typical task scenarios (such as paving, sawing, and flagging operations), and reference or align with MUTCD/IES concepts, but they do not publish unified state-level numerical thresholds. Instead, project teams or design professionals determine optimal parameters based on site-specific conditions. Representative states include Oregon, Virginia, Washington, Ohio, Louisiana, Maine, Maryland, Massachusetts, Mississippi, Montana, Nevada, New Hampshire, New Mexico, South Carolina, South Dakota, Tennessee, Utah, Vermont, West Virginia, Wyoming, Hawaii, Kentucky, Oklahoma, and Michigan (FHWA 2013). These documents focus on visibility and glare control principles and procedures but maintain advisory language regarding task illuminance, uniformity, or installation parameters.

The remaining approximately 27% of states rely solely on general provisions from state work zone design manuals and/or MUTCD guidelines without establishing independent state-level numerical standards. Representative jurisdictions include Alaska, Arizona, Arkansas, Colorado, Connecticut, Idaho, Indiana, Minnesota, Nebraska, Pennsylvania, Wisconsin, New York, North Dakota, and the District of Columbia. This approach maintains consistency with national-level terminology and procedures while leaving numerical indicators and equipment parameters undefined (FHWA 2013, FHWA 2009).

International Illuminance Standards and Guidelines

The photometric evaluation of nighttime work zone lighting involves assessing multiple parameters that directly impact the safety of both drivers and workers. Although international standards all stress the importance of photometric evaluation, large methodological differences exist between the major frameworks. The IES' recommended practice, ANSI/IES RP-8-22, establishes vertical illuminance as the main metric for evaluating driver visibility, as this represents the light that reaches a driver's eyes from the work zone. Vertical illuminance measurements are typically taken at 1.45 m above the road surface to simulate the eye level of drivers in passenger cars. For assessing worker safety, horizontal illuminance at ground level is the main metric for task visibility and obstacle detection (ANSI/IES RP-8-22). This measurement directly relates to a worker's ability to perform tasks safely and move through the work environment.

Evaluating disability glare is a very important safety factor in work zone lighting design. The veiling luminance ratio (VLR), which is calculated by dividing the veiling luminance by the average pavement luminance, gives a numerical measure of how severe the glare is. The IES recommends maximum VLRs of 0.3 for freeways and expressways and 0.4 for collector and local roads. Any values that go above these limits indicate unacceptable levels of disability glare.

However, the IES and International Commission on Illumination (CIE) standards apply these photometric evaluations in different ways. The IES method places the observer 1.45 m above the pavement and at a changing longitudinal position 83.07 m from the measurement point. In contrast, the CIE method uses a fixed position at a 1.5 m height and a 60 m distance from the road curb. These differences in positioning show that the two standards use different approaches to simulate real-world viewing conditions (CIE 112-1994).

The method for calculating veiling luminance is also very different. The IES standard calculates veiling luminance at the same points where pavement luminance is measured without using optical filters, which provides direct measurements of glare. The CIE standard, on the other hand, requires special filters during testing to better simulate how glare physically affects the eye. The standards also differ in uniformity. While the IES evaluates longitudinal uniformity using simple maximum-to-minimum ratios, the CIE includes veiling luminance effects in its uniformity calculations. Additionally, the CIE standard includes surround ratio metrics to evaluate lighting effects in the peripheral area, a parameter that does not exist in the IES framework.

Summary of Nighttime Work Zone Lighting Research

Past research on nighttime work zone safety has shown a clear link between lighting design and accident risk. However, important gaps in knowledge still exist. Studies by Wood (2020) and Bhagavathula and Gibbons (2017) showed that bad lighting setups, like low mounting heights and wrong aiming angles, reduce visibility and increase crash risk. Despite this, most research has evaluated lighting mainly from the driver's point of view using veiling luminance ratios. Researchers have not focused enough on defining the specific visibility needs of workers. They also have not developed assessment methods that evaluate the glare effect on the driver's perception and discomfort illuminance on the worker's visibility at the same time.

A review of state DOT practices shows that regulations are inconsistent and that there are no unified standards that can be used as guidelines for nighttime lighting arrangements. Out of 51 jurisdictions, only a handful of state DOTs provide specific numerical requirements, which range from 10 fc in California to 0.6 fc in Missouri for different zones. Meanwhile, 27% of jurisdictions only use the general rules from the MUTCD. In addition, 24 states only provide advice without any measurable requirements. This leaves the decision of the best lighting setup to the construction workers at each construction site. The lack of consistency makes nighttime work more difficult for contractors and can also make work conditions less safe because the lighting is set up differently from one place to another.

A comparison of international standards shows further differences in methods, and these differences make it even harder to create a single, unified standard. The IES and CIE frameworks have major differences in key areas, including observer positioning (83.07 versus 60 m), methods for calculating veiling luminance, and approaches to evaluating uniformity. These differences, along with the lack of detailed field studies that test many setups under controlled conditions, show a clear need for more systematic research. This research is required to create evidence-based parameters that can be used in a wide variety of work zone situations.

METHODOLOGY

This research was motivated by the critical need to enhance nighttime work zone safety through optimized lighting design configurations that improve visibility for both drivers and workers while minimizing glare-related hazards. The increasing frequency of nighttime construction activities and associated accident rates necessitated a comprehensive investigation into current practices and the effectiveness of various lighting arrangements. Therefore, this study first conducted a comprehensive survey of contractors, state DOT inspectors, and maintenance crews regarding current nighttime work zone lighting arrangement practices, then proceeded to experimental field testing that evaluated visibility and glare conditions from both the driver's and worker's perspectives in controlled test environments, followed by an analysis of the collected data.

Survey Design and Implementation

The survey was designed to gather feedback and feelings from industry professionals regarding their experiences with nighttime work zone lighting systems. The target population included contractors, state DOT inspectors, and maintenance crews, representing diverse perspectives from operational implementation to regulatory compliance and hands-on experience. The survey instrument consisted of 10 questions organized around a logical progression from current lighting practices to comfort assessment to problem identification and solution development. Detailed survey question can be seen in Appendix B.

The survey began by documenting current lighting practices through two foundational questions. Question 1 assessed satisfaction with different lighting technologies (balloon lights, light towers, halo lights, vehicle headlights) using five-point scales from “extremely uncomfortable” to “extremely comfortable.” Question 2 identified the most common light source orientations using visual diagrams (Figure 1). Three overhead diagrams showed light positioning relative to traffic flow: toward oncoming traffic, away from traffic, and perpendicular to traffic. These visual aids eliminated interpretation errors and enabled precise identification of current practices.

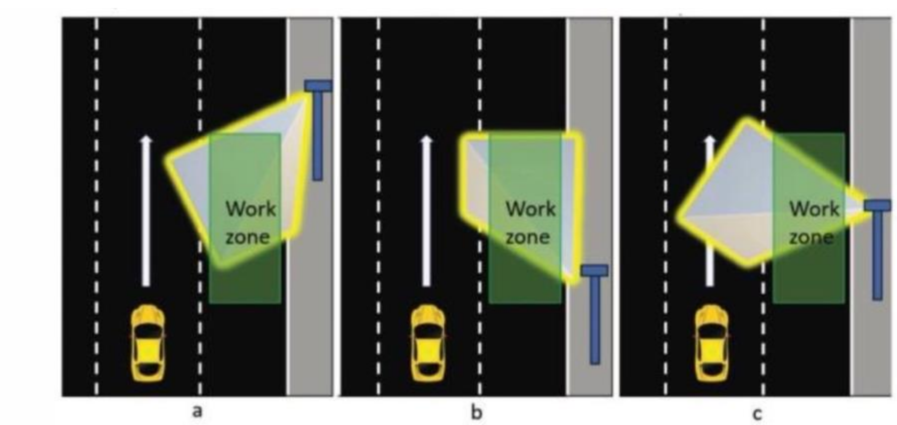


Figure 1. Light source orientation in survey

Questions 3 and 4 evaluated the relationship between lighting adequacy and worker comfort. Question 3 used frequency scales (never to always) to assess safety incidents attributed to inadequate lighting. Question 4 employed the same five-point comfort scale as Question 1 to quantify lighting comfort levels during nighttime work operations.

Question 5 included an open text field where respondents provided detailed explanations of specific discomfort sources. This qualitative component captured nuanced feedback that quantitative scales could not address. Questions 6 and 7 systematically evaluated glare issues. Question 6 assessed how often glare affected the visibility of construction equipment and workers. Question 7 used a comprehensive matrix to evaluate glare likelihood from six lighting system parameters: luminaire aiming angle, lighting intensity, mounted height, rotation angle, lighting source, and distance from light source. Each parameter was rated on a five-point likelihood scale from "unlikely to cause glare" to "extremely likely to cause glare."

Questions 8 and 9 focused on improvement strategies. Question 8 evaluated perceptions of flashing vehicle lights using a five-point effectiveness scale. Question 9 used multiple-selection checkboxes for seven predefined improvement measures (adjusting equipment placement, using glare shields, reducing brightness, providing warning signs, increasing overall brightness, ensuring consistent lighting levels) plus an open text option for additional suggestions.

Question 10 assessed whether respondents had access to lighting standards or guidelines. Those answering affirmatively were provided with a secure upload link to share their reference materials. This feature enabled the collection of actual guidance documents currently in use across different organizations.

Field Testing Protocol

This project used field experiments to measure photometric parameters and evaluate lighting performance from the perspectives of both drivers and workers. Based on the ANSI/IES RP-8-22 guidelines (IES 2022), three key parameters were measured: horizontal illuminance for assessing worker task performance, and pavement luminance and vertical illuminance at the driver's eye level for glare analysis. For the driver's perspective, the research team calculated a glare index by measuring pavement luminance and vertical illuminance. For the worker's perspective, as indicated by the Federal Highway Administration (FHWA) lighting handbook (FHWA 2023), ground horizontal illuminance can be used to assess brightness in a nighttime work zone; the research team performed this assessment from the worker's perspective.

Testing Site and Setup

The field experiments were conducted at the University of Nebraska–Lincoln's MwRSF, which provided a controlled nighttime testing environment. For systematic testing, this study rented two types of portable light towers with different light sources from Sunbelt Rentals: LED modules and metal halide. These represent the mainstream lighting technologies currently used in nighttime construction. Table 1 summarizes the detailed technical specifications of the portable light towers used in the tests, including light source type, power configuration, and mounting height range. This table provides the technical basis for the equipment selection and shows the differences between LED and metal halide technologies in terms of power density and operational flexibility.

Table 1. Portable light tower specifications

Equipment Type	Light Source Type	Power Configuration	Mounting Height Range
LED Light Tower	LED Modules	4×230 W	3.7–4.3 m
Halogen Light Tower	Metal Halide	4×1000 W	3.7–4.3 m

This study investigated the site lighting conditions for each lighting source under various configurations of mounting height, rotation angle, and aiming angle, and evaluated them from both the driver's and worker's perspectives. In the lighting configurations, the aiming angle refers to the angle between the luminaire's light beam axis and the horizontal plane, which is the upward or downward tilt of the light head relative to the ground. The rotation angle refers to the angle of the light beam's rotation in the horizontal plane relative to the direction of traffic flow (IES 2022). Table 2 lists the complete combination of factors used in the experimental design, totaling 126 configurations. Figure 2 shows an example of the aiming and rotation angles for a light tower; the red arrow indicates the direction of traffic flow.

Table 2. Test configuration factor matrix

Factor	Levels
Light Source Type	LED; Halogen
Mounting Height	12 ft, 13 ft; 14 ft
Aiming Angle	10°; 20°; 40°
Rotation Angle	20°; 40°; 50°; 90°; 130°; 140°; 160°

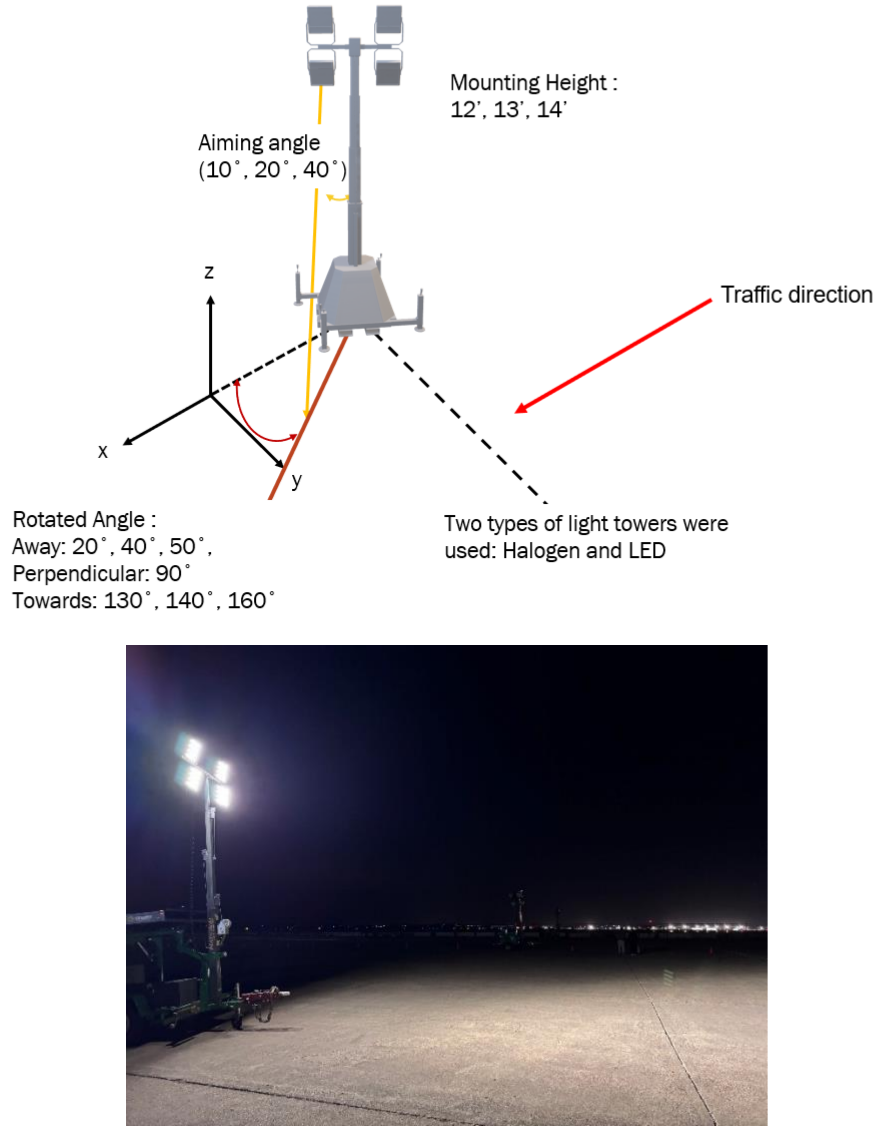


Figure 2. Light tower configurations

Nighttime Work Zone Illuminance Levels Assessment

The research team set up a single lane at MwRSF. For each light tower configuration, measurements were taken at 7 points marked by safety cones, with cones placed at 15 ft (4.6 m) intervals. Figure 3 shows the three site layouts for a light tower positioned "away from traffic" (rotation angle less than 90°), "perpendicular to traffic" (rotation angle equal to 90°), and "towards traffic" (rotation angle greater than 90°). For the away-from-traffic configuration, the team started from the front of the light tower and collected data every 15 ft, for a total of 7 measurement points over a 90 ft stretch. The same measurement rule applies to the other two lighting arrangements.

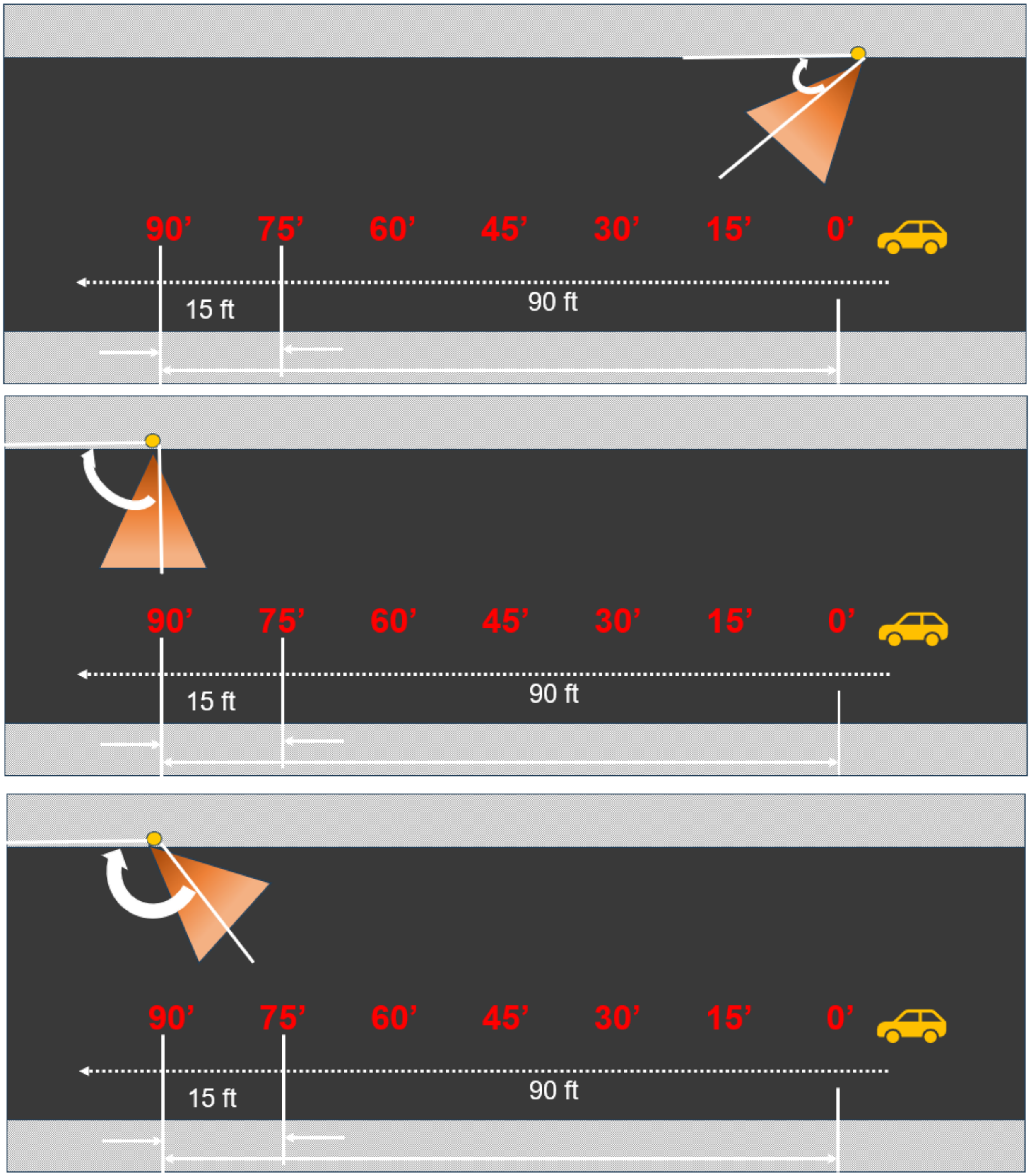


Figure 3. Three lighting arrangements: away from traffic (top), perpendicular to traffic (middle), toward traffic (bottom)

Table 3 details the specifications of the measurement equipment used in this study, including the model, manufacturer, and its application in this study.

Table 3. Measurement equipment specifications

Measurement Type	Equipment Model	Manufacturer	Application Perspective
Pavement Luminance	LS-150 Luminance Meter	Konica Minolta	Driver's Perspective
Vertical Illuminance	Illuminance Meter T-10A	Konica Minolta	Driver's Perspective
Horizontal Illuminance	Illuminance Meter T-10A	Konica Minolta	Worker's Perspective

Following the guidance in ANSI/IES RP-8-22 Chapter 19, Temporary and Work Area Lighting, the following measurements (IES 2022) were taken from the worker's perspective: horizontal illuminance measurement. An illuminance meter (T-10A) was placed on the ground at the worker's standing position with the sensor facing upward to capture the amount of light falling on a horizontal surface. This simulates the lighting conditions for a worker standing in the work area and helps evaluate the overall adequacy of illumination.

These conditions are directly related to a worker's ability to identify ground obstacles, tools, materials, and construction equipment, which is important for preventing accidents such as collisions, traps, and slips.

The measured horizontal illuminance data were evaluated against the classification standard for nighttime construction lighting established by FHWA (2023). Table 4 details the recommended horizontal illuminance levels for different types of nighttime construction tasks. This classification system is based on extensive field research and safety incident analysis and fully considers factors such as task complexity, precision requirements, and safety risks.

Table 4. Recommended illuminance levels for highway worker task areas

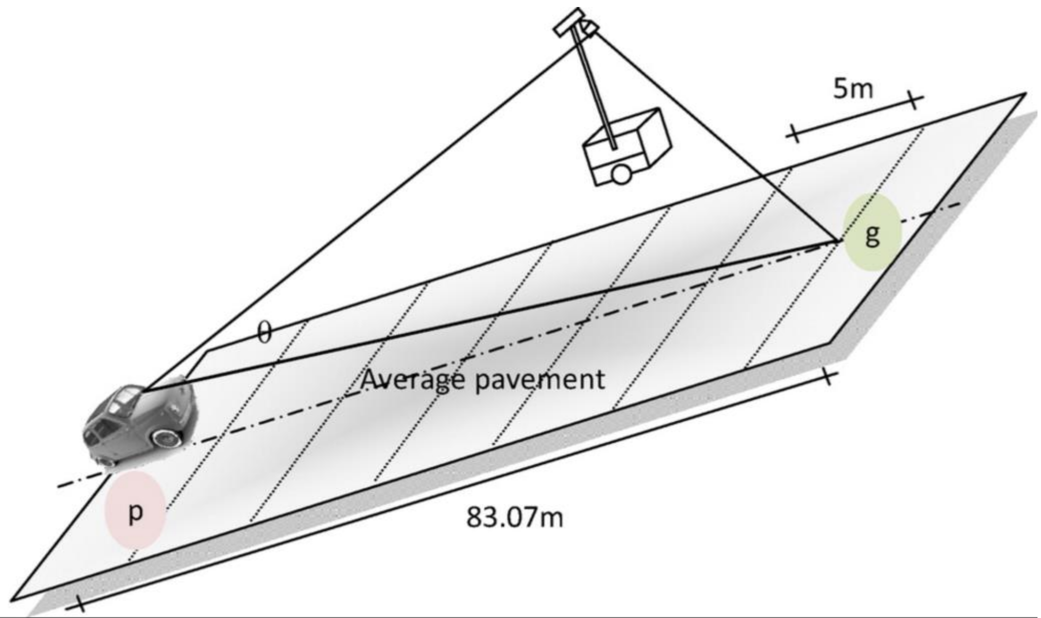
Level 1: General Construction **Minimum: 4 fc (40 lux)** **Target: 5–10 fc (55–110 lux)** **Max: 25 fc (270 lux) ***	**Level 2: Specialized Construction** **Minimum: 8 fc (80 lux)** **Target: 10–15 fc (110–160 lux)** **Max: 35 fc (380 lux) ***	**Level 3: Precision Operations** **Min: 15 fc (160 lux)** **Target: 20–30 fc (220–320 lux)** **Max: 45 fc (480 lux) ***
• Layout, measurement, and staking • Excavation • Embankment fill and compaction • Asphalt pavement rolling • Subgrade stabilization and construction	• Installation of barrier wall • Pavement milling and removal • Concrete demolition • Installation of pipes and other drainage structures • Construction of bridge decks	• Pavement patching and repair • Joint repair • Crack filling • Traffic signal installation • Highway lighting system installation

Source: FHWA 2023

Glare Assessment Calculation

From ANSI/IES RP-8-22, the key parameters in the calculation of veiling luminance include the definition of the glare angle Θ, corresponding number n, and parameter K, as explained in Figure

4. The research team used this diagram to complete the subsequent calculations to measure glare for the driver.



IES 2022

Figure 4. Geometry of observation angle

The following calculations were performed with reference to ANSI/IES RP-8-22:

Veiling luminance at each measurement point is calculated by equation (1):

$$L_{\mathrm{v}} = \frac{K}{\Theta^{n}} \quad (1)$$

where

- L_{v} = veiling luminance from one individual luminaire (unit: cd/m^2)
- K = 10 × (the vertical illuminance in lux at the plane of the observer's eye, which is perpendicular to the line of sight and adjusted for the effects of aging on vision). The observer in this formula is assumed to have the visual performance of a 25-year-old.
- n = 2.3 − 0.7$\log_{10}(\theta)$ for $\theta < 2; n = 2$ for $\theta \geq 2$
- θ = angle in degrees

θ is calculated by the measurement geometry, which is shown in Figure 4.

Pavement luminance was measured using a luminance meter to assess the level of glare affecting driver perception. For the driver's perspective, vertical illuminance readings were taken at eye level—approximately 1.2 m (3.9 ft)—using an illuminance meter positioned to face in the direction of travel.

Figure 5 illustrates the proper setup and usage of the LS-150 luminance meter, including its typical installation height (1.2 to 1.5 m or 3.9 to 4.9 ft) and aiming angle (1.5° to 2°), which simulate a driver's line of sight. To complete the pavement luminance measurements, the operator was positioned 273 ft from the initial measurement point (Point A), as shown in the figure. From this starting location, the operator used the LS-150 to record luminance values at a simulated driver's eye height.

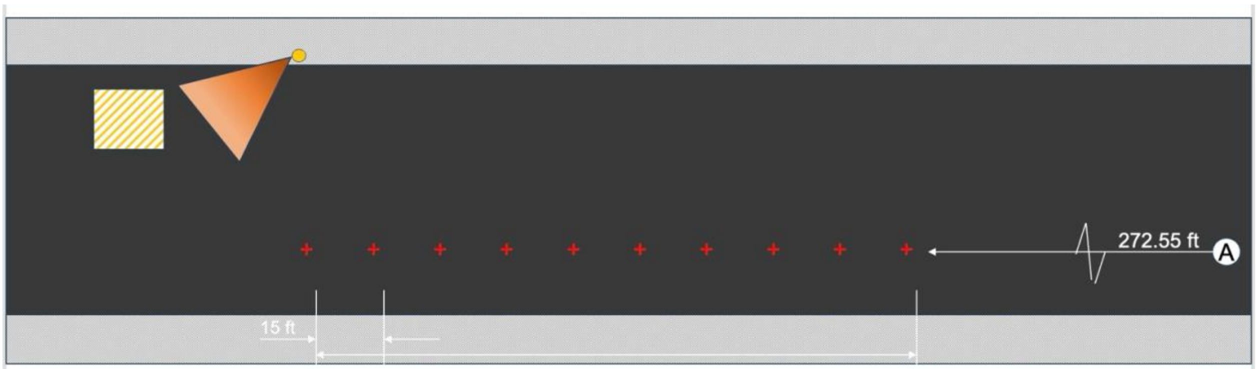


Figure 5. Pavement luminance measurement layout

Measurements were taken every 15 ft along a designated path (indicated by the red arrow in Figure 5), resulting in a total of seven data points. Throughout the process, the operator maintained a consistent viewing angle of approximately 1.5° to 2° relative to the pavement to accurately replicate the visual conditions experienced by drivers and workers in nighttime work zones.

Veiling ratio (VL_{ratio}) is calculated by equation (2). It is used to evaluate glare, which is used to assess the lighting configuration, and it should never be greater than 0.3 for the driver.

$$VL_{ratio} = \frac{L_v}{L_p} \quad (2)$$

where

- L_v = veiling luminance at the driver's eye produced by the selected luminaire at the measurement point calculated by equation (1)
- L_p = pavement luminance at the same measurement point, measured from the driver's perspective with the luminance meter at eye level (unit: cd/m^2)

Qualitative Task Performance Assessment

In addition to the quantitative photometric evaluation, the research team conducted a qualitative analysis to assess the practical use of the lighting configurations in actual construction activities. This assessment focused on the visual clarity and measurement precision needed for common tasks in nighttime construction, including construction layout reading and tape measure reading.

To evaluate visual task performance under different lighting conditions, a layout reading assessment was performed that used four hierarchical text levels based on a paving layout from the Nebraska Department of Transportation's official website. Figure 6 shows an example of the four levels used for the layout reading assessment. Each level represents different documentation requirements common in a construction work zone. This figure was created based on real construction documents and clearly shows the differences in font size and visual complexity, from the large-font project titles of Level 1 to the fine-print technical labels of Level 4. The classification system shown in the figure reflects the various types of documentation that workers need to read during actual nighttime construction and provided a standardized benchmark for the subsequent visual performance tests.

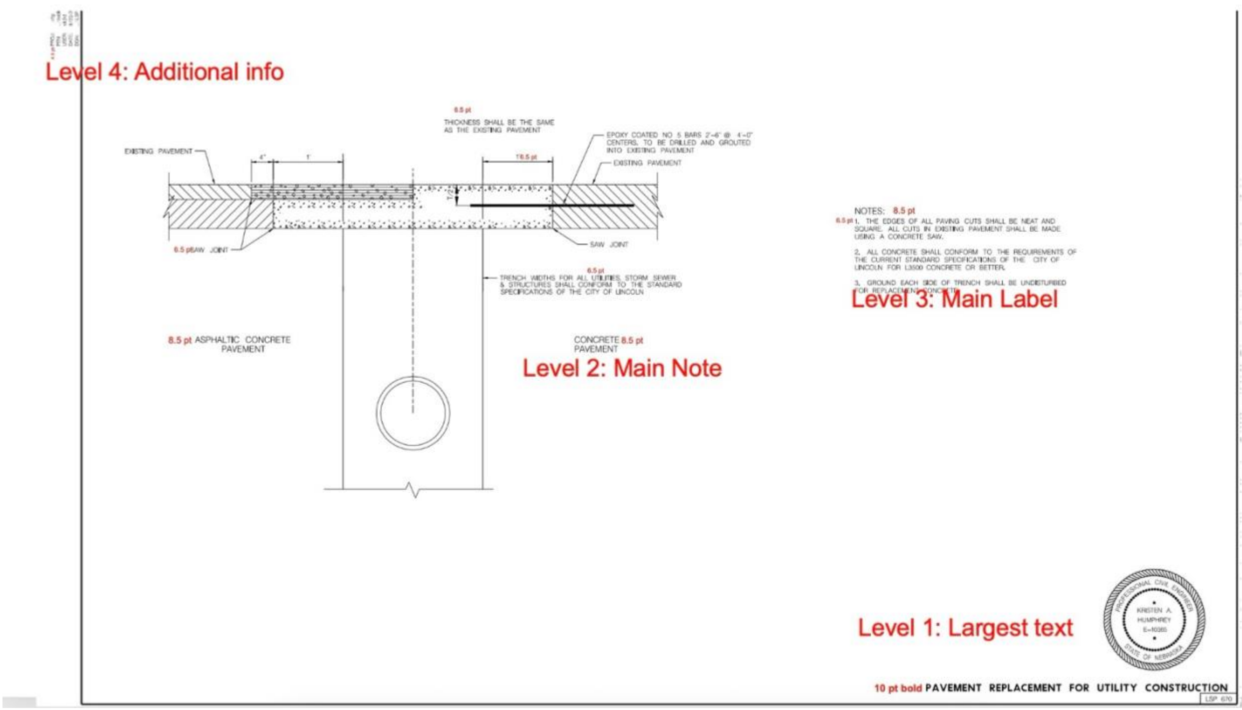


Figure 6. Layout reading example

The four text levels used in the layout reading assessment were defined as follows:

- Level 1 included major project titles and primary identifiers in large font.
- Level 2 included section headings and major component labels in medium font.
- Level 3 covered detailed specifications and technical notes in smaller font.

- Level 4 represented fine-print labels and key technical details in the smallest font.

In addition to measuring visual task performance using four text levels in the layout reading task, a tape measure reading task was performed and graded according to four precision levels. Figure 7 details the four precision levels used for the tape measure reading task, showing the differences in scale markings from coarse measurements at 1 in. intervals to precise measurements at 0.125 in. intervals. The figure uses a high-definition photograph of an actual construction tape measure to highlight the changes in the density and size of the scale markings at the different precision levels.

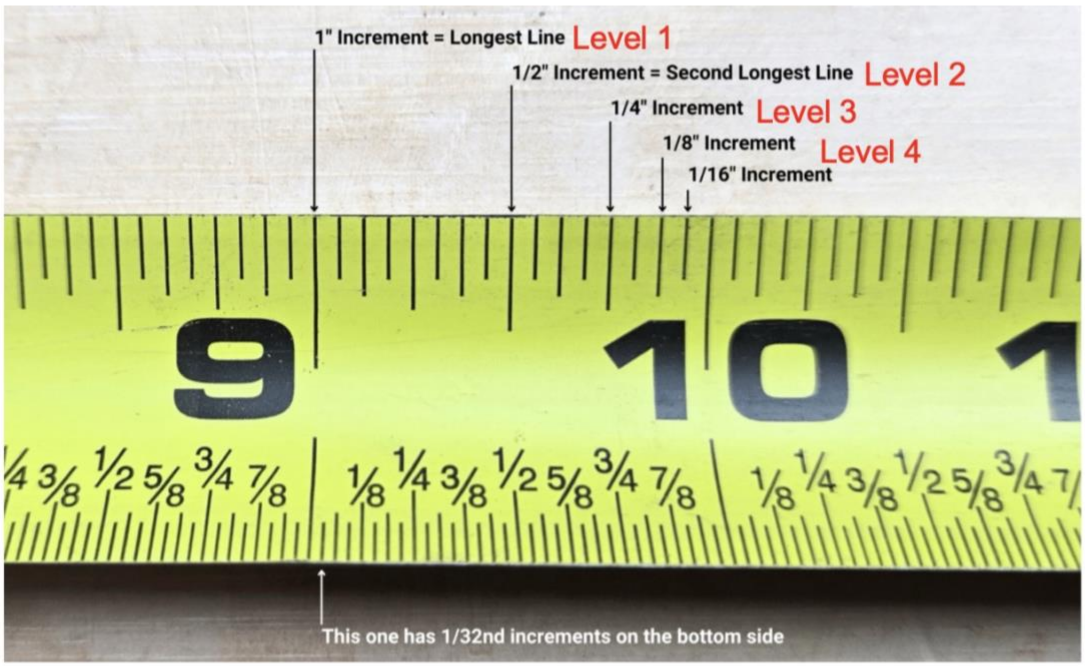


Figure 7. Tape measure reading

The four precision levels used in the tape measure reading assessment were defined as follows:

- Level 1 involved reading 1 in. interval markings.
- Level 2 included reading 0.5 in. interval markings.
- Level 3 required reading 0.25 in. interval markings.
- Level 4 required reading 0.125 in. interval markings.

The testing procedure used a controlled, single-source lighting method to isolate the specific effects of each lighting configuration. During each test sequence, only one light tower was operational. This eliminated the potential confounding effects of multiple light sources and allowed the performance results to be directly attributed to a specific combination of lighting parameters. This method ensured that the observed changes in task performance could be directly associated with the characteristics of the lighting configuration being tested.

During the test, a worker was equipped with a standardized printed layout and a calibrated tape measure. The worker performed a controlled walk along horizontal and vertical paths relative to the light tower's position. Figure 8 shows a layout of the qualitative task performance test setup, including the light tower position, the worker's movement paths, and the configuration of the light tower.

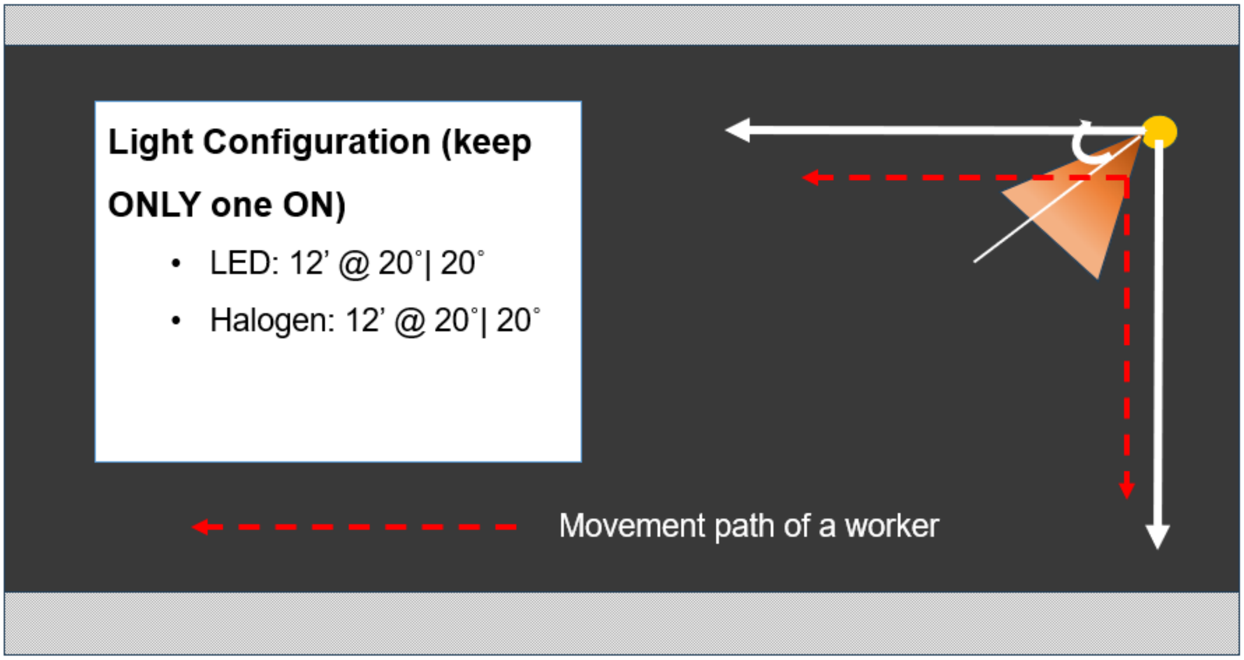


Figure 8. Layout of qualitative task performance assessment

The objective of each test was to determine the maximum distance at which the text or measurement markings for each classification level could be read. The test results established a clear effective range for each classification level under each lighting setup. This provided a scientific basis for optimizing lighting equipment positioning strategies to maximize effective work area coverage while maintaining adequate visual task performance levels for all operational requirements.

RESULTS

Survey Results

Survey Demographics

This project conducted a survey from November 9, 2023, to January 31, 2024. A questionnaire was distributed to all member states in the Smart Work Zone Deployment Initiative (SWZDI) program and industry partners. A total of 116 questionnaire responses were collected, and 79 of them were valid questionnaires (meaning the respondents answered all questions). As shown in Figure 9, among the valid questionnaires, 78% of the respondents were state DOT staff. Most of them were from the Michigan Department of Transportation (MDOT), and the rest were from Kansas, Wisconsin, Iowa, Illinois, and Missouri. Notably, this survey also received a response from the Alaska Department of Transportation and Public Facilities (Alaska DOT&PF), which added a unique perspective to the dataset. The remaining 22% of respondents were mainly from the construction industry, including consultants, contractors, and a few material suppliers.

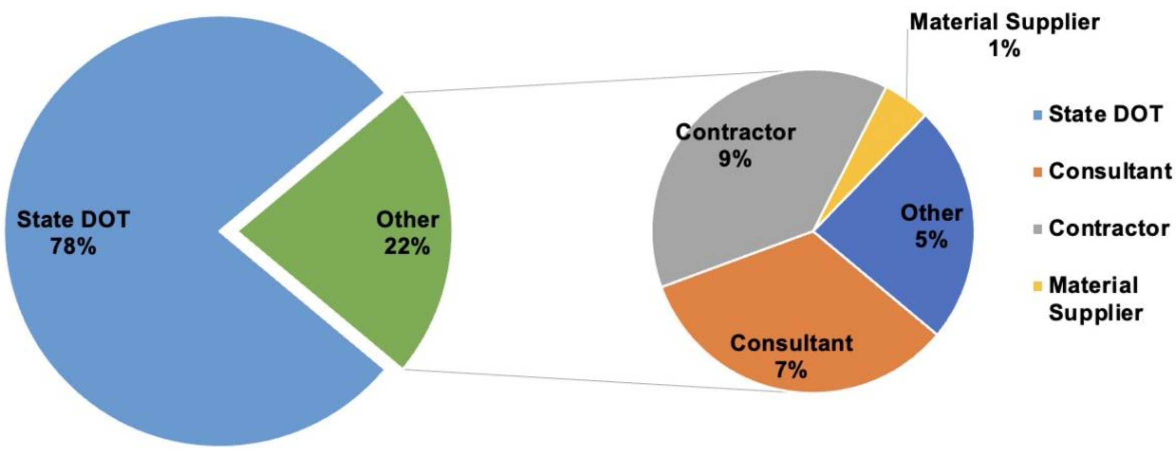


Figure 9. Response distribution

Lighting System Comfort Level Evaluation

To assess the overall satisfaction of respondents with existing nighttime work zone lighting systems, this study used a five-level rating scale: extremely comfortable, comfortable, somewhat comfortable, somewhat uncomfortable, and extremely uncomfortable. The survey results show (see Figure 10) that 68% of respondents selected the "comfortable" or "somewhat comfortable" options. This indicates that most participants were generally satisfied with nighttime work zone lighting systems.

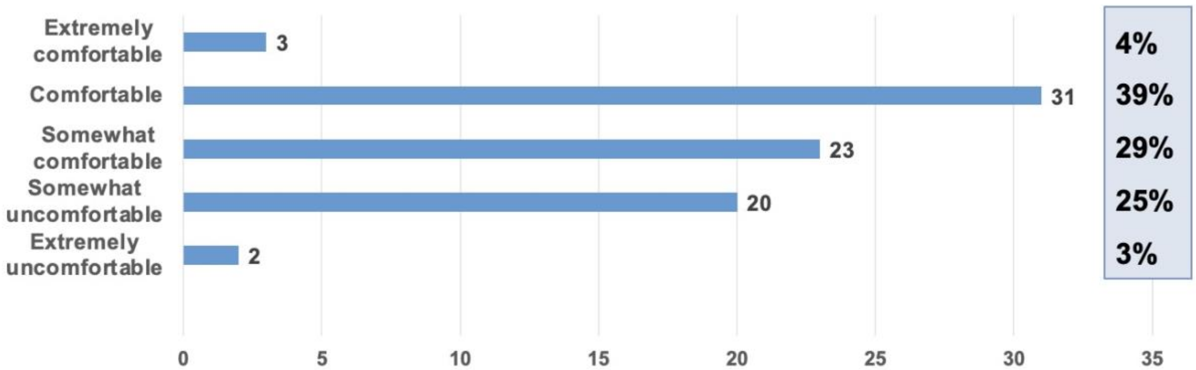


Figure 10. Comfort level with nighttime work zone lighting setup

To evaluate respondents' satisfaction with different light sources, this study used the same comfort scale and assigned numerical scores (5 for most comfortable, 1 for least comfortable). An average score higher than 3 was considered a comfortable level. As shown in Table 5, balloon lighting and LED lighting received the highest comfort scores, both exceeding 3. This indicates that respondents generally found these two light sources to be the most comfortable. Halogen lighting scored exactly 3, which represents a moderate comfort level. However, vehicle headlights received the lowest score, indicating that respondents found them to be relatively uncomfortable.

Table 5. Lighting source comfort value

Comfort Value	Average	Min	Max
Balloon lighting	3.53	1	5
LED Lighting	3.59	1	5
Halogen Lighting	3	1	5
Vehicle Headlight	2.05	1	5

Analysis of Discomfort Causes

To understand the reasons for workers' discomfort, this study collected 53 detailed responses through open-ended questions. The analysis of the results shows the following:

- Coverage issues (mentioned 28 times): Respondents reported "insufficient lighting..." and "limited number of light sources... difficult to see or be seen..."
- Glare and light/dark transitions (mentioned 19 times): "glare from the lighting setup..." and "sometimes glare on safety glasses..."
- Work quality/efficiency (mentioned 10 times): "work quality decreases at night..." and "it is difficult to see clearly during nighttime inspections..."
- Safety accidents and near misses (mentioned 9 times)
- Cost/standards/technology (mentioned 2 times)

Regarding the orientation of light sources, the survey shows (see Figure 11) that more than half of the light sources were set up facing away from the traffic flow, 26% were set up perpendicular to the traffic flow, 10% of the lighting systems faced toward oncoming traffic, and 6.3% belonged to other orientation categories.

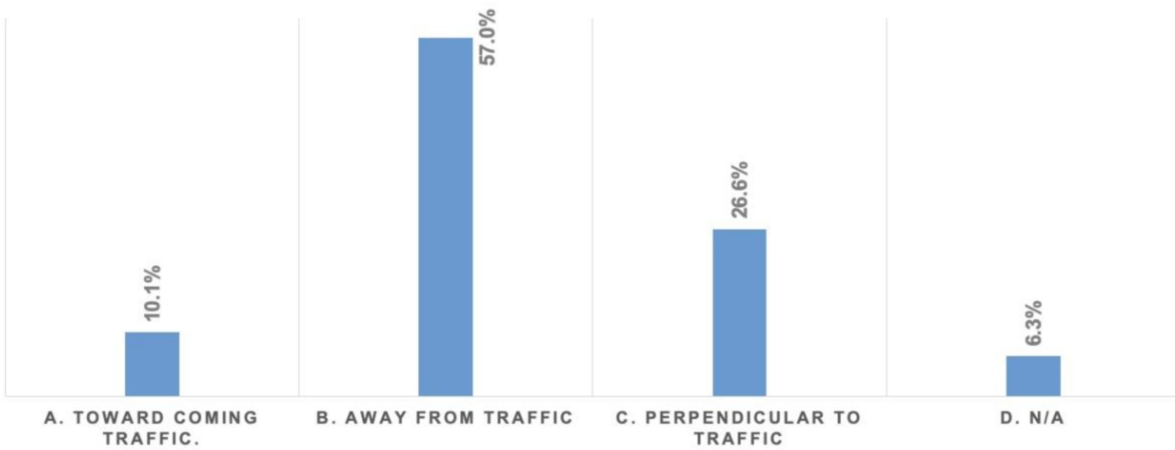


Figure 11. Lighting orientation

Glare Issues and Improvement Suggestions

Based on the findings on lighting orientation, a further analysis of glare causes shows (see Figure 12) that respondents primarily attributed glare to the aiming angle and rotation angle of the light source. The dark blue and green sections in Figure 12 represent these factors. The 50% threshold marked by the red line serves as a reference point, and factors exceeding this line are considered to be the main causes of glare. This visualization clearly shows that aiming angle and rotation angle are considered to be the main causes of hazardous glare in nighttime work zones.

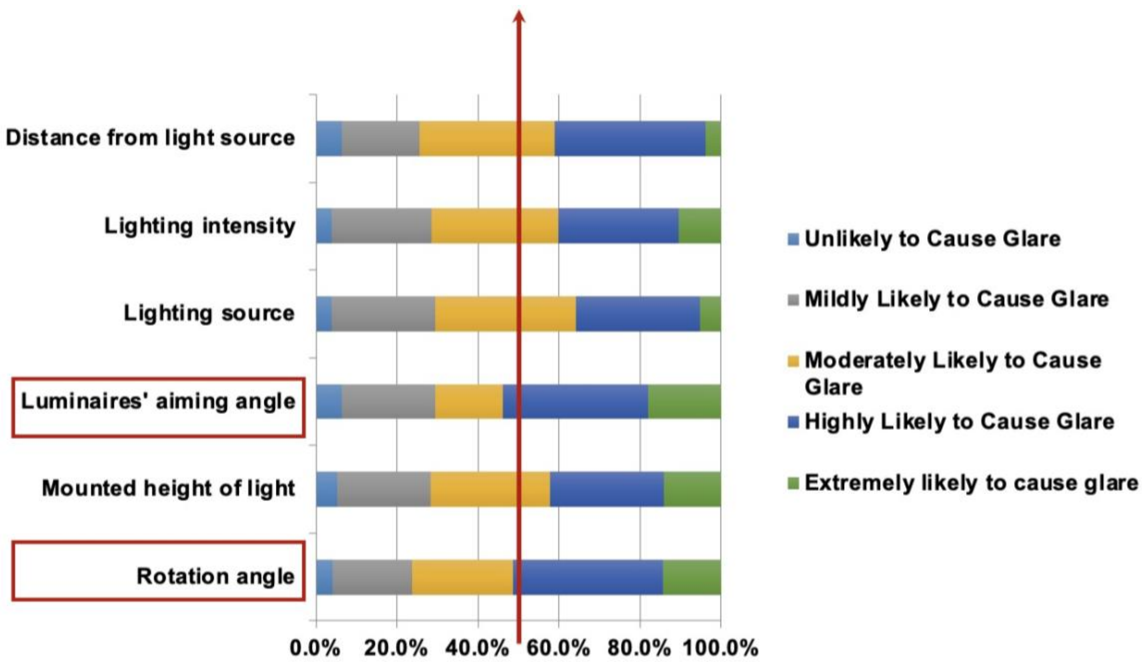


Figure 12. Glare sources

Regarding potential improvements to reduce hazardous glare (see Figure 13), the survey results show the following conclusions:

- Nearly 80% of respondents believed that adjusting the placement of lighting equipment would help reduce glare.
- Over 70% of respondents emphasized the importance of maintaining consistent lighting levels to reduce discomfort.
- Nearly half of the respondents considered glare shields or diffusers to be effective solutions.
- Light intensity received less attention, but more respondents preferred to increase rather than decrease brightness.
- Approximately 22% of respondents suggested setting up warning signs for bright lights.

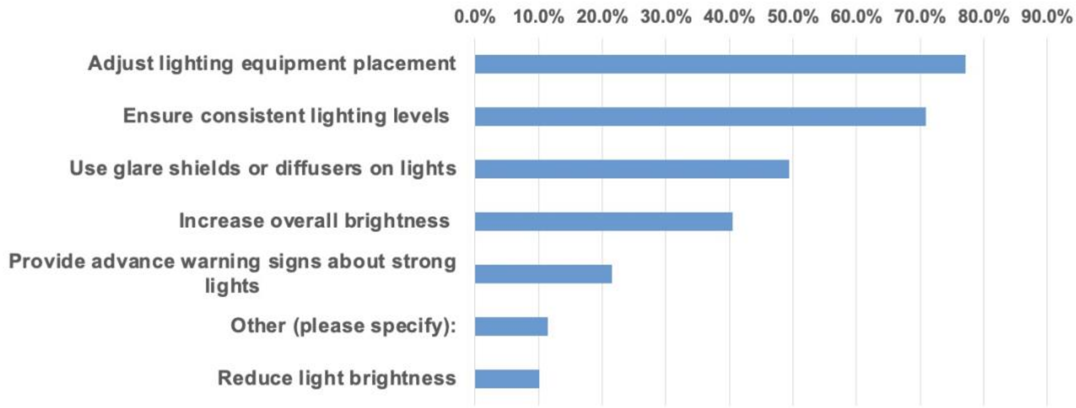


Figure 13. Improvements for reducing hazardous glare

Respondents also provided other suggestions for improvement, including the following:

- Using polarized lenses
- Adopting smaller, more diffused light sources
- Improving lighting patterns and arrangements
- Setting up light towers correctly
- Adjusting for vertical curves
- Replacing flashing lights on vehicles

Although these suggestions fall into the "other suggestions" category, they still mainly focus on the setup of the lighting system. This further emphasizes the key role of proper lighting configuration in reducing glare and improving overall visibility.

Use of Reference Documents

Finally, regarding the use of reference documents (e.g., lighting guidelines, standards) the survey results show (see Figure 14) that 58% of participants stated that they use reference documents, but only 18% (a total of 14 people) uploaded the files that they use. A detailed list of these documents is shown in Table 6. As mentioned in the table, MDOT cites three different documents, and KDOT uses two. In addition, there was one document from an unknown source. This highlights the inconsistency in reference guidelines among different states.

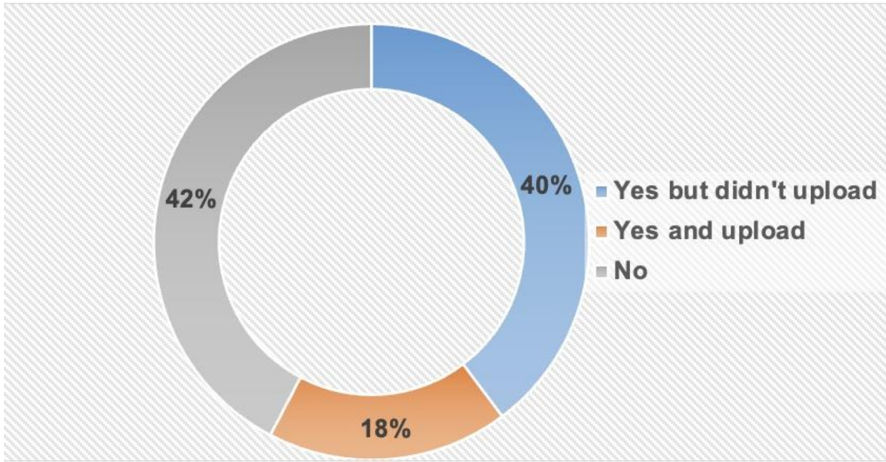


Figure 14. Reference documents

Table 6. Document sources

Referenced Document	Count
MDOT standard specifications for construction	7
Wisconsin Department of Transportation nighttime work lighting stationary	1
MDOT work zone safety and mobility Manual	1
MDOT special Provision lighting for night work specifications	1
IDOT Standard Specifications for Road and Bridge Construction	1
KDOT Mobilization	1
KDOT Specifications provision 104	1
Other	1

Field Test Analysis

Experimental Design and Method

This study conducted a series of field experiments to systematically evaluate the performance of lighting systems in nighttime work zones. As shown in Figure 2, the experiment considered four main parameters: mounting height (12, 13, 14 ft), aiming angle (10°, 20°, 40°), rotation angle (20° to 160° in 10° intervals), and two light sources (halogen and LED light towers). The combination of these parameters resulted in a total of 126 different lighting configurations.

Data collection used three spatial layout configurations:

- Away-from-traffic configuration (rotation angle less than 90°): Measurement points started in front of the light tower and extended to 90 ft at 15 ft intervals.
- Perpendicular-to-traffic configuration (rotation angle equal to 90°): Measurement points started 90 ft from the light tower and moved progressively closer to the light tower's position.

- Towards-traffic configuration (rotation angle greater than 90°): This used the same measurement strategy as the perpendicular configuration.

Each configuration had 7 measurement points, for a total of 882 sets of data. All measurements were conducted under standard nighttime conditions with an ambient illuminance below 0.1 lux.

Evaluation Metrics and Standards

This study used two main metrics to evaluate lighting performance:

Horizontal illuminance (Eh): Based on the FHWA-HRT-08-018 report, the following criteria were established against workers' visibility:

- Eh < 40 lux: Insufficient illuminance
- 40 ≤ Eh ≤ 480 lux: Appropriate illuminance
- Eh > 480 lux: Excessive illuminance

Veiling luminance ratio (VL_{ratio}): Based on the ANSI/IES RP-8-22 standard, the following thresholds were used against drivers' perception of hazardous glare:

- VL_{ratio}< 0.3: Acceptable glare
- 0.3 ≤ VL_{ratio} ≤ 0.4: Marginally acceptable glare
- VL_{ratio} > 0.4: Unacceptable glare

The veiling luminance ratio is calculated by equation (2).

Field Test Results

Overall Performance

A total of 126 different lighting configurations were evaluated against the two Eh and VLR standards. The overall results indicated a clear challenge in achieving compliance:

- Only 2 out of 126 configurations met both Eh and VLR requirements at all measurement points.
- 28 out of 126 configurations completely failed to meet the standard at all measurement points.
- 69 out of 126 configurations failed to meet the standards at more than 50% of their measurement points.
- The remaining 27 configurations met the standards at most measurement points, with only a few points falling short.

These findings suggest that most lighting arrangements require careful optimization to satisfy the distinct needs of worker visibility and driver glare control.

Parameter Influence Analysis

To determine key factors leading to poor visibility and/or discomfort glare, analysis of variance (ANOVA) was used to assess the degree of influence of each parameter—rotation angle, mounting height, aiming angle, and light source—on lighting performance. Table 7 shows the F-values and significance levels for each parameter and their interactions.

Table 7. ANOVA results for parameter influence (move to the back)

Parameter	F-value for Illuminance	F-value for VL_{ratio}	p-value
Rotation Angle	156.32	198.45	<0.001
Mounting Height	89.67	76.23	<0.001
Aiming Angle	23.45	12.34	<0.001
Light Source Type	45.78	8.92	<0.001
Rotation × Height	34.21	42.16	<0.001

The ANOVA results quantified the influence of key geometric parameters on lighting performance in nighttime work zones. Among the tested variables, rotation angle emerged as the most significant factor, with exceptionally high F-values for both illuminance and glare metrics (illuminance: $F = 156.32$; VLR: $F = 198.45$). These values indicate that adjustments to rotation angle have the greatest impact on both visibility and glare conditions.

Mounting height also demonstrated a strong influence, with F-values of 89.67 for illuminance and 76.23 for VLR, confirming its critical role in shaping lighting outcomes. Furthermore, the interaction between rotation angle and mounting height yielded notable effects (illuminance: $F = 34.21$; VLR: $F = 42.16$), suggesting that these parameters should be considered jointly when configuring lighting systems.

The findings presented in Table 7 underscore the importance of a multi-parameter approach to lighting design. Achieving optimal lighting performance in nighttime work zones requires careful coordination of rotation angle, mounting height, aiming angle, and light source type. Improper configurations can result in hazardous visibility conditions and excessive glare, posing risks to both workers and motorists.

Evaluation of Illuminance on Workers' Perception

Overall Performance

An analysis of all 882 measurement points was conducted to assess the adequacy of lighting for worker visibility. The results revealed a significant challenge in meeting recommended illuminance levels:

- Insufficient illuminance (Eh <40 lux): 416 measurement points (47.2%)
- Appropriate illuminance (40 ≤ Eh ≤ 480 lux): 440 points (49.9%)
- Excessive illuminance (Eh >480 lux): 26 points (2.9%)

These findings confirm that insufficient illuminance is the most prevalent issue, with nearly half of all measured points falling below the minimum threshold recommended by the FHWA lighting handbook (FHWA 2023). This shortfall poses a substantial safety risk for workers operating in nighttime work zones.

Extreme Illuminance Scenarios

While inadequate lighting was widespread, certain lighting configurations consistently failed to meet acceptable standards. As shown in Table 8, four specific configurations resulted in 100% of measurement points falling outside the FHWA-recommended illuminance range (40 to 480 lux). Notably, the following was found:

- All four configurations used LED light sources.
- Three of the four were set at a 90° rotation angle, corresponding to a perpendicular-to-traffic orientation.

Table 8. Configurations of lighting arrangements causing inadequate illuminance

Configuration	Mounting Height	Aiming Angle	Rotation Angle	Light Type
1	13 ft	40°	40°	LED
2	14 ft	10°	90°	LED
3	12 ft	20°	90°	LED
4	14 ft	40°	90°	LED

These results reinforce the conclusion that perpendicular lighting arrangements, particularly when paired with LED sources, are highly problematic for worker visibility. Such configurations should be avoided or carefully adjusted to prevent hazardous lighting conditions in the field.

Optimization of a Critical Scenario

To quantify the impact of the different parameters on workers' visibility, Configuration 2 (in Table 8) was selected for a focused optimization case study. This configuration—featuring an LED fixture mounted at 14 ft, with a 90° rotation angle and a 10° aiming angle—produced a critically low average illuminance of just 5.41 lux, well below the FHWA's minimum recommended threshold of 40 lux. The objective of this case study was to evaluate how adjustments to key parameters could improve lighting performance and bring the configuration into compliance with safety standards. The following summarizes the effects of modifying each parameter:

- **Rotation angle adjustment**: As the most influential parameter, adjusting the rotation angle yielded the most substantial improvement. Rotating the light tower from 90° to 40° increased the average illuminance from 5.41 lux to 78.36 lux, representing a +1348.4% improvement. This dramatic increase confirms that orientations away from traffic and perpendicular to traffic significantly enhance ground-level visibility, as shown in Figure 15.
- **Mounting height adjustment**: Lowering the mounting height from 14 ft to 12 ft raised the average illuminance to 38.50 lux—a +611.5% increase—bringing the configuration close to the FHWA's minimum threshold. The peak illuminance of 41.29 lux was observed at a 13 ft height, suggesting that moderate reductions in height can optimize lighting performance without compromising coverage (Figure 16).
- **Aiming angle adjustment:** Adjusting the aiming angle had a more modest effect. Increasing the angle from 10° to 20° improved the average illuminance to 10.55 lux, a +94.8% gain. However, further increases beyond 20° yielded no additional benefit, indicating that only minor aiming adjustments are effective for this configuration (Figure 17).

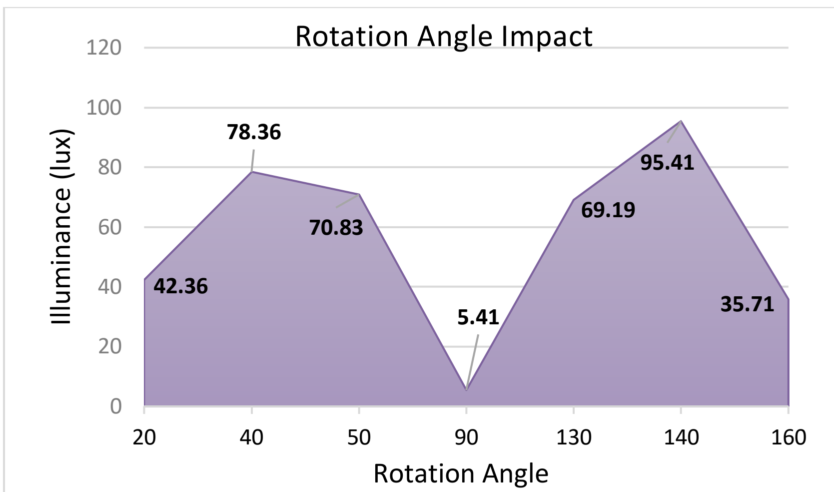


Figure 15. Rotation angle impact on illuminance

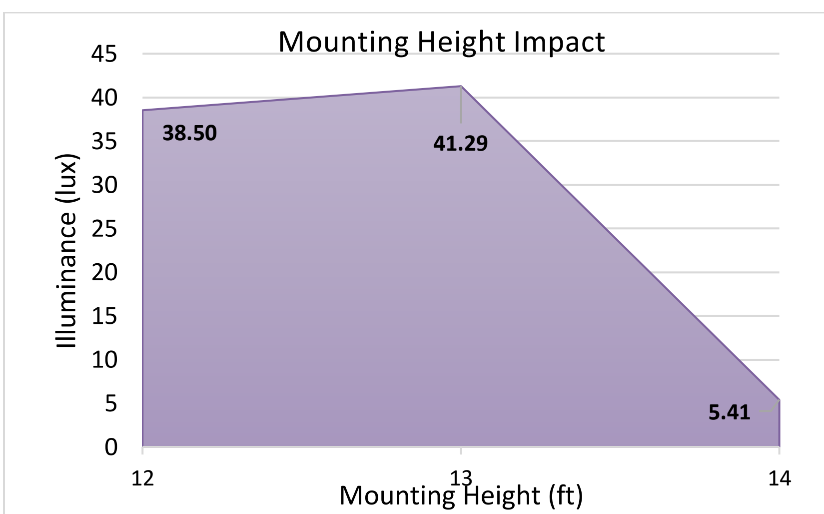


Figure 16. Mounting height impact on illuminance

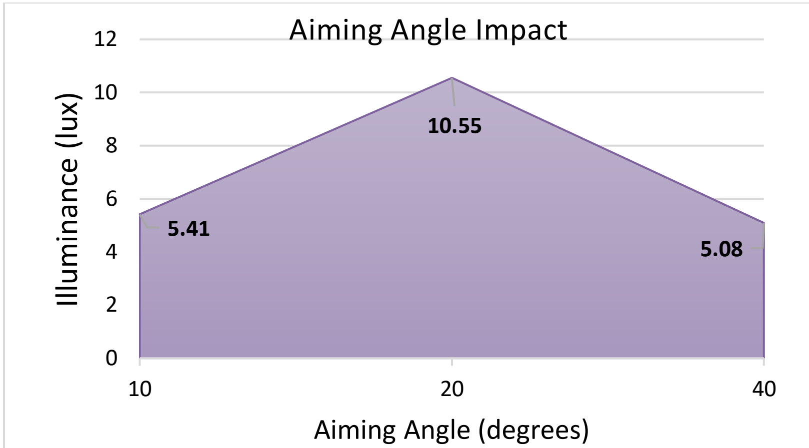


Figure 17. Aiming angle impact on illuminance

A regression analysis yielded the following relationship:

$$Eh = 0.234 \times e^{(-0.045 \times R)} \times H^{(-1.82)} \times (1 + 0.023 \times A) \quad (3)$$

where R is the rotation angle (degrees), H is the mounting height (feet), and A is the aiming angle (degrees).

This model serves as a practical tool for estimating illuminance levels for configurations within the tested parameter ranges, allowing for proactive planning and optimization of lighting setups before deployment.

Evaluation of Glare Effect on Drivers' Perception

Overall Performance

An analysis of 882 measurement points was conducted to evaluate the impact of glare on driver perception, using VLR as the primary metric. The results are categorized as follows:

- Acceptable glare (VLR <0.3): 453 points (51.4%)
- Marginally acceptable (0.3 ≤ VLR ≤ 0.4): 126 points (14.3%)
- Unacceptable glare (VLR >0.4): 303 points (34.3%)

These results indicate that unacceptable glare was a significant issue, present in over a third of the measurement points. Among the 303 unacceptable points, five key lighting configurations were identified that could produce either a comfortable level of glare or hazardous glare, as explained below and summarized in Table 9:

- The most hazardous glare was produced by a configuration featuring an LED light tower mounted at 14 ft, with a 40° aiming angle and a 130° rotation angle.

- In contrast, two configurations using halogen light towers demonstrated significantly lower glare levels:
  - A 13 ft height, 20° aiming angle, and 50° rotation angle
  - A 12 ft height, 40° aiming angle, and 40° rotation angle

Table 9. VLR values based on major configurations

Configuration*	Avg. VL_{ratio}	Max. VL_{ratio}	Min. VL_{ratio}	Points > 0.4 / Total
12ft_10°_130°_Halogen	1.136	3.056	0.087	5/7
12ft_10°_130°_LED	0.236	0.588	0.021	2/7
13ft_20°_50°_Halogen	0.029	0.132	0.003	0/7
12ft_40°_40°_Halogen	0.048	0.156	0.011	0/7
14ft_40°_130°_LED	3.996	8.124	1.235	7/7

* Configuration: Height_aiming angle_rotation angle_lighting source

These results reinforce the importance of selecting appropriate lighting parameters, particularly rotation angle, mounting height, and light source type, to minimize glare and enhance driver safety in nighttime work zones.

Analysis of Hazardous Configurations

Certain configurations consistently produced hazardous glare (VLR > 0.4) at all measurement points. Table 10 identifies five key arrangements. A clear pattern was identified from this finding: high rotation angles (90° and 130°), which direct the light perpendicular to or toward traffic, are a primary cause of excessive glare.

Table 10. Configurations of lighting arrangements causing glare

Configuration	Mounting Height	Aiming Angle	Rotation Angle	Light Type
1	12 ft	10°	130°	Halogen
2	13 ft	40°	90°	Halogen
3	13 ft	40°	50°	LED
4	13 ft	40°	90°	LED
5	14 ft	40°	130°	LED

Optimization Case Study: Glare Control

To evaluate the individual impact of lighting parameters on glare control, Configuration 1 from Table 10 was selected for a detailed case study. This setup featured a halogen light tower mounted at 12 ft, with a 10° aiming angle and a 130° rotation angle—a configuration that produced a critically high VLR of 7.95, indicating severe glare. The objective of this case study was to identify effective adjustments that could reduce glare and improve driver visibility. The results of parameter modifications are summarized below and illustrated in Figures 18 to 20.

- **Rotation Angle** (Figure 18). Rotation angle was confirmed as the dominant factor in glare control. When the light tower was oriented away from traffic (rotation angle < 90°), VLR values ranged from 0.08 to 0.31, indicating acceptable glare levels. However, when the tower was positioned perpendicular to traffic (rotation angle = 90°), VLR values spiked to 1.99. Further rotation toward traffic (130°, 140°, 150°) resulted in severely hazardous glare, with a peak VLR of 7.95 at 130°. This analysis demonstrates that reorienting the light tower from 130° to 20° can reduce VLR by approximately 99% (from 7.95 to 0.08). The optimal rotation angle range for minimizing glare is identified as 20° to 50°, corresponding to an away-from-traffic orientation.
- **Mounting Height** (Figure 19). While mounting height can moderate glare, it cannot fully compensate for poor rotation angles. For the hazardous 130° rotation angle setup, increasing the mounting height from 12 ft to 13 ft could only slightly reduce the VLR from 7.95 to 3.11 (an approximately 61% reduction). However, a further increase to 14 ft offered no additional benefit. This suggests that while mounting height can help mitigate glare, it is not an effective standalone solution when the light tower is oriented toward traffic.
- **Aiming Angle** (Figure 20). The effect of aiming angle on the level of glare control was found to be significant. A moderate increase from 10° to 20° substantially reduced the VLR values from 7.95 to 3.37 (an approximately 58% reduction). However, further increasing the aiming angle from 20° to 40° could cause the VLR value to spike to an extreme glare level of ≈22.01. These results suggest that a moderate aiming angle of 20° is optimal for glare control, as it reduces glare without triggering adverse effects on driver perception.

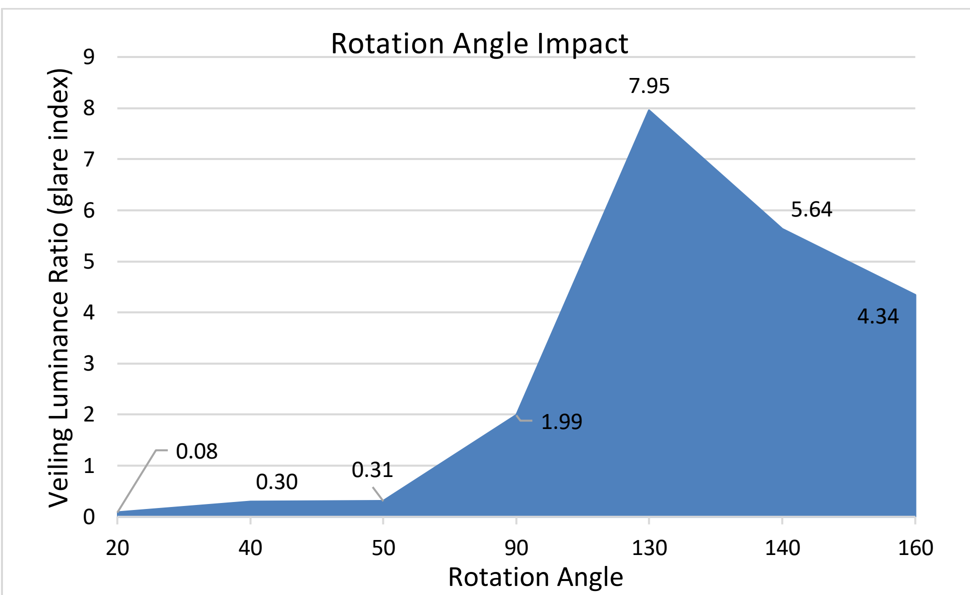


Figure 18. Rotation angle impact on level of glare

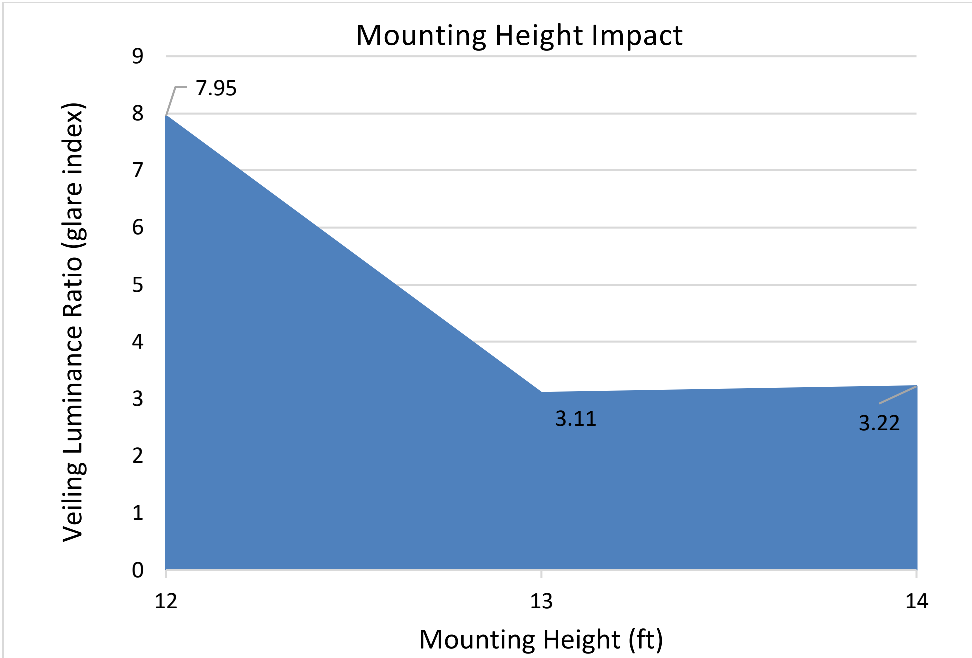


Figure 19. Mounting height impact on level of glare

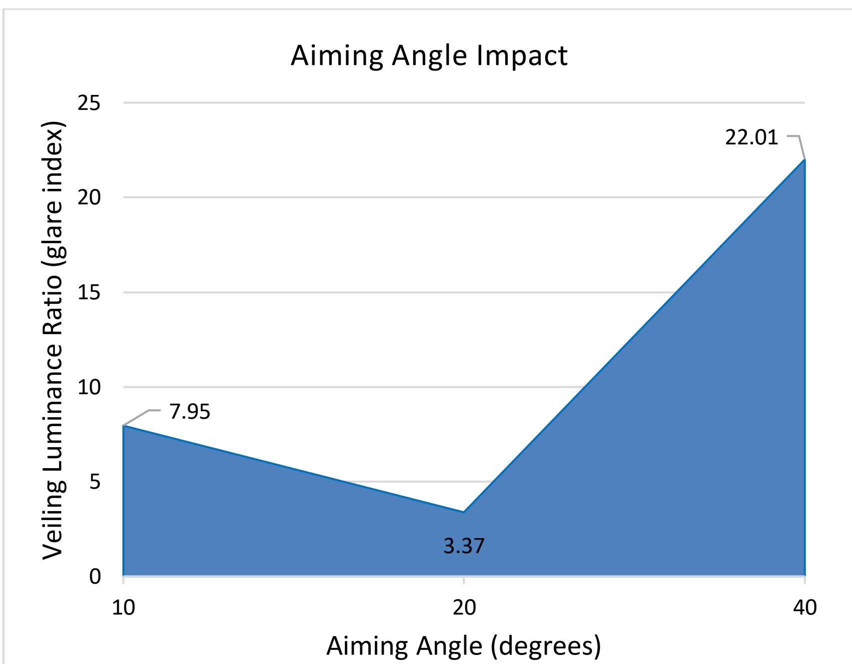


Figure 20. Aiming angle impact on level of glare

To further understand the interactions of these parameters and their effects on glare control, a series of glare index comparisons were performed to identify what lighting arrangements (i.e., rotation angles, aiming angles, and mounting heights) could lead to discomfort glare levels. Figure 21 shows the results of several lighting arrangements against the VLR changes using both halogen and LED light sources. Note that the analysis is based on Configuration 1 (Table 10) with the following adjustments: rotation angles varied from 20° to 130°, aiming angles changed between 10° to 40°, and mounting heights moved between 12 and 14 ft.

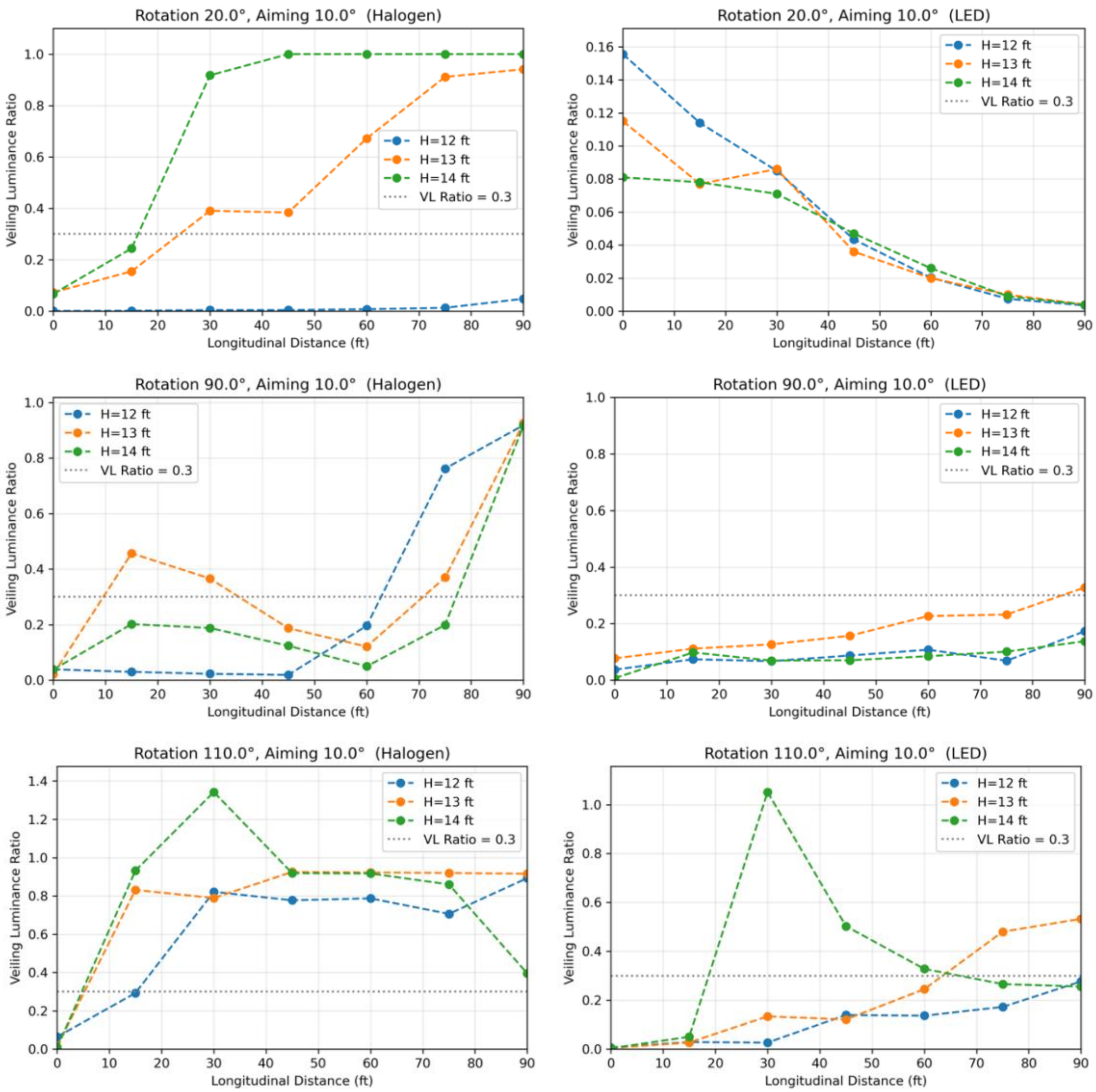


Figure 21. Glare index comparison: halogen (left), LED (right)

The graphs in Figure 21 show several important patterns:

- **LED lighting performance**: When the aiming angle of an LED light tower is fixed at 10° and the rotation angle is adjusted to 90° or less (i.e., the away-from-traffic and perpendicular-to-traffic orientations), all measured VLR values at 12, 13, and 14 ft mounting heights remain well below the 0.3 acceptable threshold. This consistent performance across all measurement points indicates that such configurations are highly effective in reducing hazardous glare for motorists. In contrast, applying the same configuration to halogen lighting does not yield comparable results. The VLR values for halogen fixtures exceed

0.3 even at lower rotation angles (20° and 40°), suggesting that halogen systems are more prone to discomfort glare under similar conditions. This comparison highlights that LED lighting is more reliable for glare control in away-from-traffic and perpendicular-to-traffic scenarios.

- **Halogen lighting performance**: Halogen lighting exhibits greater variability in glare levels as rotation angles increase. For example, when a halogen light tower is configured with a 20° rotation angle, 10° aiming angle, and 14 ft mounting height, the VLR values rise rapidly, exceeding the 0.4 unacceptable threshold beyond the 20 ft measurement zone. However, when the mounting height is reduced to 12 ft under the same rotation and aiming conditions, the glare effect drops significantly, with the VLR values dropping to below 0.1. This pattern suggests that mounting height plays a critical role in glare mitigation, particularly when rotation angles are not optimal.

These findings reinforce the importance of light source selection and parameter coordination in nighttime work zone lighting design. While LED fixtures offer more stable and predictable glare control across a range of configurations, halogen systems require more precise adjustments, especially in terms of rotation angle and mounting height, to maintain safe glare levels for drivers.

Comparative Analysis of Configurations

A comparative analysis of halogen and LED light sources was performed to identify the strengths and limitations of each lighting configuration. As summarized in Table 11, halogen fixtures demonstrated superior performance in terms of illuminance, while LED fixtures excelled in glare control.

Table 11. Lighting performance comparison of LED and halogen lighting

Performance Metric	Halogen	LED
Average Illuminance (lux)	150.1	66.9
Percentage of Insufficient Illuminance Measurements	30.2%	64.20%
Average VLR	0.559	0.349
Percentage of Measurements with Hazardous Glares	41.7%	21.1%
Percentage of Dual-Criteria	34.9%	23.4%

The results of the comparative analysis can be summarized as follows:

- **Illuminance performance assessment**: Halogen light towers delivered higher average illuminance and were less prone to insufficient lighting. Only 30.2% of halogen measurements fell below the 40 lux minimum threshold, compared to 64.2% for LED towers. This indicates that halogen systems are more effective in meeting visibility requirements for workers.

- **Glare control assessment**: In contrast, LED light towers provided better glare mitigation. The average VLR for LED lighting was 0.349, significantly lower than the 0.559 average for halogen lighting. Furthermore, only 21.1% of LED measurements exceeded the unacceptable glare threshold (VLR > 0.4), compared to 41.7% for halogen systems.

- **Overall compliance assessment**: When both lighting criteria (i.e., adequate illuminance and acceptable glare levels) were considered, halogen configurations showed a higher overall compliance rate. Approximately 34.9% of halogen measurements met both standards, while only 23.4% of LED configurations did. The limitations of both types of lighting were identified as follows:

    - **LED limitations**: The primary constraint for LED systems was insufficient illuminance. Despite their superior glare control, over 64% of LED setups failed to meet the minimum 40 lux requirement, reducing their overall effectiveness.
    - **Halogen limitations**: Halogen systems were primarily limited by excessive glare. Although they generally provided sufficient illuminance, more than 41% of measurements exceeded acceptable glare levels, impacting driver safety.

This analysis highlights the trade-offs between halogen and LED lighting systems. Halogen fixtures are more reliable for achieving adequate visibility, while LED fixtures offer better glare control. Optimal lighting design in nighttime work zones should consider a balanced approach, potentially integrating both technologies or refining configurations to meet both safety criteria.

Recommended Optimal Lighting Configurations and Sensitivity Analysis

Based on the comprehensive assessment of lighting performance, two configurations with halogen lighting were identified that meet both FHWA and IES standards for nighttime work zones. Even though none of the LED configurations meet both FHWA (40 < Eh < 480 lux) and IES (VLR <0.3) standards (shown below), we also provide the most promising LED configuration for use in nighttime construction zones. Based on the analysis results, these recommended configurations provide safer illuminance levels and acceptable glare control, ensuring improved visibility for workers and reduced discomfort for drivers.

Recommended Configuration 1 — Halogen (H = 12 ft, A = 40°, R = 40°)

Installed precisely at these setpoints, this configuration meets the target zone at all test distances: brightness (illuminance level) remains within 40 to 480 lux (FHWA), and glare (VLR) remains <0.30 (ANSI/IES RP-8-22). It passes 7/7 and serves as the baseline. Lights are spaced about 90 ft apart.

Installation and adjustment guidance (impact order: rotation, height, aiming) is as follows:

1. **Rotation (highest impact)**. Set 40°. Tolerance: -5° / +1° (35°–41°). Out-of-band: Glare (VLR) rises quickly above ~41°.

2. **Height**. Set 12.0 ft. Tolerance: ±0.5 ft (11.5 to 12.5 ft). Out-of-band: Far-distance brightness trends below 40 lux.
3. **Aiming**. Set 40°. Tolerance: -10° / +0° (30°–40°). Out-of-band: Exceeding 40° reduces brightness coverage/glare margin.

Recommended Configuration 2 — Halogen (H = 13 ft, A = 20°, R = 50°)

Installed precisely at these setpoints, this configuration meets the target zone at all test distances: Brightness stays within 40 to 480 lux, and VLR stays <0.30. It passes 7/7 and is the secondary halogen baseline. Lights are spaced about 90 ft apart.

Installation and adjustment guidance (impact order: rotation, height, aiming) is as follows:

1. **Rotation (highest impact)**. Set 50°. Tolerance: -5° / +15° (45°–65°). Out-of-band: Near 70° the minimum brightness is ~40 lux (margin thins).
2. **Height**. Set 13.0 ft. Tolerance: ±0.3 ft (12.7–13.3 ft). Out-of-band: Brightness stability across distances degrades.
3. **Aiming**. Set 20°. Tolerance: ±5° (15°–25°). Out-of-band: Coverage/glare trade-offs increase.

Recommended Configuration 3 — LED (H = 14 ft, A = 10°, R = 40°)

At the original spacing, this configuration was too dim at the last two points (60 ft = 36.3 lux, 75 ft = 31.5 lux). We therefore set the spacing so the far point is 60 ft. With five points (0, 15, 30, 45, 60 ft), it passes 5/5 (brightness 40 to 480 lux; VLR <0.30). Lights are spaced about 60 ft apart.

Installation and adjustment guidance (impact order: rotation, height, aiming) is as follows:

1. **Rotation (highest impact)**. Set 40°. Tolerance: -8° / +6° (32°–46°). Out-of-band: At least one of the five points (often 45/60 ft) falls <40 lux; VLR stays <0.30.
2. **Height**. Set 14.0 ft. Tolerance: -0.35 / +1.00 ft (13.65–15.00 ft). Out-of-band: One or more of the five points falls <40 lux; VLR stays <0.30.
3. **Aiming**. Set 10°. Tolerance: -0° / +8° (10°–18°). Out-of-band: At least one of the five points falls <40 lux; VLR stays <0.30.

These three configurations represent practical, field-ready solutions for agencies and contractors seeking to enhance safety in nighttime work zones through evidence-based lighting design. Table 12 summaries the installation and adjustment recommendations.

Table 12. Summary of three recommended configurations

Parameter	Recommended Setpoint	Field Spec / Tolerance	Impact Priority	Primary Risk If Out-of-Band
Recommended Configuration 1 — Halogen (H = 12 ft, A = 40°, R = 40°)				
Rotation	40°	35°–41°	1 (highest)	Glare (VLR) increases rapidly for positive drift
Height	12.0 ft	11.0–12.5 ft	2	Far-distance brightness trends below 40 lux when too high
Aiming	40° (do not exceed)	30°-40°	3	Exceeding 40° may reduce brightness coverage/glare margin
Recommended Configuration 2 — Halogen (H = 13 ft, A = 20°, R = 50°)				
Rotation	50°	50° with -5° / +15°	1 (highest)	Far-distance brightness margin thins toward 70°; avoid sustained operation >65°
Height	13.0 ft	13.0 ft +/- 0.3 ft	2	Brightness stability degrades outside band
Aiming	20°	20° +/- 5°	3	Coverage/glare trade-offs increase outside band
Recommended Configuration 3 — LED (H = 14 ft, A = 10°, R = 40°)				
Rotation	40°	32°–46°	1 (highest)	If rotation is outside band, at least one of the 5 points falls below 40 lux; VLR remains <0.30
Height	14.0 ft	13.65–15.00 ft	2	If height is outside band, brightness drops below 40 lux at one or more of the 5 points; VLR remains <0.30
Aiming	10°	10°–18°	3	If aiming is outside band, at least one of the 5 points falls below 40 lux; VLR remains <0.30

Qualitative Analysis: Task Performance Assessment Results

In addition to the quantitative analyses of the effects of lighting sources on visibility and glare control, a qualitative task assessment was conducted to understand the ability of workers to read construction notes and a tape measure under halogen and LED lighting conditions (Figure 6 and Figure 7). A configuration featuring a 12 ft height, 20° rotation angle, and 10° aiming angle for both LED and halogen lighting sources was used for this qualitative analysis. A worker holding a construction layout with different sizes of construction notes walked along the horizontal and vertical directions away from the light tower (Figure 8). While walking along the site, the worker rated his ability to read the notes and measure differences at four different levels of text size or precision. Table 13 summarizes the task performance results under the two lighting sources.

Table 13. Visual reading task performance results (feet)

Task Type	Precision Level	Halogen-Horizontal	Halogen-Vertical	LED-Horizontal	LED-Vertical
Layout Reading	Level 4	145	75	115	90
	Level 3	230	120	130	110
	Level 2	280	180	200	150
	Level 1	300	230	280	200
Tape Measure Reading	Level 4 (1/8")	200	130	300	300
	Level 3 (1/4")	250	180	300	300
	Level 2 (1/2")	280	220	300	300
	Level 1 (1")	300	260	300	300

For the construction note reading task, the worker was capable of reading the Level 4 text (the smallest notes, 6.5 font size) up to 175 ft horizontally and 75 ft vertically, while LED lighting reduced horizontal readability to 115 ft but extended vertical readability to 90 ft. The tape measure reading task showed that LED lighting has a clear advantage, enabling readability at a Level 4 precision (1/8 in. marks) across the entire 300 ft test range in both directions, while halogen lighting could only provide enough illumination to enable readability at a Level 4 precision up to 200 ft horizontally and 130 ft vertically.

Under this lighting configuration, the minimum illuminance measured within the 0° to 90° range was 20.5 lux for LEDs and 20.0 lux for halogen. Further qualitative task performance assessment revealed key differences between the two light sources.

In the layout reading task, halogen lights performed better for horizontal visibility. Workers could read Level 4 text up to 145 ft (approximately 44 m) with halogen lights, compared to only 115 ft (approx. 35 m) with LED lights, giving halogen a 26% advantage. This result is notable because, as shown in Table 9, LEDs produced 113% higher average illuminance. The reason for this difference relates to the light's characteristics: halogen's warmer color temperature creates better contrast on printed plans, and its wider beam spread produces more uniform illumination across a horizontal surface. In contrast, LED lights were better for vertical reading (90 ft versus 75 ft), an advantage consistent with the higher light output and focused beam of LEDs.

The results of the tape measure reading task clearly showed the advantages of LED technology. With LED lights, workers could read Level 4 precision marks (1/8 in.) along the entire 300 ft range in both directions. Readability with halogen lights, however, decreased significantly at longer distances, dropping to 200 ft horizontally and 130 ft vertically. This 50% improvement in horizontal readability for fine details is directly related to two key LED features: a higher luminous intensity and a superior color rendering index (CRI). The LED's CRI was over 80, while the halogen's CRI was approximately 70.

CONCLUSIONS

This study conducted a comprehensive performance assessment of nighttime work zone lighting systems using three methods: an industry survey, controlled field experiments, and a qualitative task performance evaluation. The following conclusions were drawn from the results:

1. **Survey Findings**: Addressing visibility and safety concerns from both drivers' and workers' perspectives, the survey revealed that while 68% of respondents were generally satisfied with current lighting systems, significant issues remain. These include insufficient coverage affecting worker visibility (53%) and glare affecting drivers (36%). Respondents primarily attributed these problems to improper geometric configurations—specifically aiming and rotation angles—rather than inadequate lamp output.

2. **Field Experiment Results**: A total of 126 lighting configurations were systematically evaluated. Driver glare was assessed using VLR, while worker visibility was evaluated based on ground-level horizontal illuminance (Eh), identified according to FHWA's three-level system (insufficient, appropriate, excessive) within the 40 to 480 lux range. Optimal configurations that met both driver and worker visibility criteria typically featured the following:

    - Rotation angles of 40° to 50°
    - Mounting heights of 12 to 13 ft
    - Aiming angles of 20° to 40°

    Under these conditions, workers could read Level 4 text at 145 ft (halogen) and perform precise tape measurements at 300 ft (LED), all while maintaining acceptable glare levels.

3. **Hazardous Configurations Identified**: Certain configurations were found to be unsafe. For example, a perpendicular orientation (90° rotation angle) often resulted in excessive illuminance, exceeding FHWA's maximum thresholds.

4. **Glare from Improper Geometry**: High rotation angles (130° to 160°) combined with low aiming angles (10°) produced unacceptable glare (VLR >0.4) across the entire work zone. Two representative configurations illustrate this risk:

    - Halogen lighting setup (12 ft, 10°, 130°): VLR = 1.136
    - LED lighting setup (14 ft, 40°, 130°): VLR = 3.996

    These results demonstrate that an improper lighting arrangement poses serious safety risks, regardless of lighting sources.

5. **Improvements with Optimized LED Configurations**: When LED light towers were configured with appropriate rotation angles (40° to 50°), lighting performance improved significantly:

   - Measurement points with insufficient illuminance readings dropped from 48.2% to 25.6% (≈47% reduction)
   - Average VLR decreased from 0.385 to 0.308 (≈20% reduction)

6. **Task Performance and Illuminance Thresholds**: Qualitative tests showed that both halogen and LED lighting sources provided Eh ≥40 lux within a 105 ft range. Under these areas with proper lighting coverage, workers achieved the highest precision (Level 4) on all tasks, including layout reading and tape measure reading.

7. **Overall Findings**: The finding from the quantitative field experiments that 34.3% of all measurements produced unacceptable glare underscores that three configuration parameters—rotation angle, aiming angle, and mounting height—are more influential than the choice of lighting source. Prioritizing optimal lighting configurations would enable agencies to provide safer construction environments for workers in the vicinity of nighttime work zones.

RECOMMENDATIONS FOR OPTIMIZING NIGHTTIME WORK-ZONE LIGHTING SYSTEMS

Based on the findings of this research, the following recommendations are proposed to enhance the performance and safety of nighttime lighting systems in work zones:

1. Recommended Lighting Configuration 1 — Halogen (H = 12 ft, A = 40°, R = 40°)

   Installed precisely at these setpoints, this configuration meets both FHWA and IES standards for nighttime work zones. When changes to this setup are needed, the following adjustment instructions are encouraged:

   a. Rotation (highest impact). Set 40°. Tolerance: -8° / +6° (32°–46°). Out-of-Band: At least one of the five points (often 45/60 ft) falls <40 lux; VLR stays <0.30.
   b. Height. Set 14.0 ft. Tolerance: -0.35 / +1.00 ft (13.65–15.00 ft). Out-of-Band: One or more of the five points falls <40 lux; VLR stays <0.30.
   c. Aiming. Set 10°. Tolerance: -0° / +8° (10°–18°). Out-of-Band: At least one of the five points falls <40 lux; VLR stays <0.30.

2. Recommended Lighting Configuration 1 — Halogen (H = 13 ft, A = 20°, R = 50°)

   Installed precisely at these setpoints, this configuration meets both FHWA and IES standards for nighttime work zones. When changes to this setup are needed, the following adjustment instructions are encouraged:

   a. Rotation (highest impact). Set 50°. Tolerance: -5° / +15° (45°–65°). Out-of-Band: Near 70° the minimum brightness is ~40 lux (margin thins).
   b. Height. Set 13.0 ft. Tolerance: ±0.3 ft (12.7–13.3 ft). Out-of-Band: Brightness stability across distances degrades.
   c. Aiming. Set 20°. Tolerance: ±5° (15°–25°). Out-of-Band: Coverage/glare trade-offs increase.

3. Recommended Lighting Configuration 3 — LED (H = 14 ft, A = 10°, R = 40°)

   Installed precisely at these setpoints, this configuration comes closest to meeting both FHWA and IES standards for nighttime work zones among the LED lighting configurations. When changes to this setup are needed, the following adjustment instructions are encouraged:

   a. Rotation (highest impact). Set 40°. Tolerance: -8° / +6° (32°–46°). Out-of-Band: At least one of the five points (often 45/60 ft) falls <40 lux; VLR stays <0.30.
   b. Height. Set 14.0 ft. Tolerance: -0.35 / +1.00 ft (13.65–15.00 ft). Out-of-Band: One or more of the five points falls <40 lux; VLR stays <0.30.

c. Aiming. Set 10°. Tolerance: -0° / +8° (10°–18°). Out-of-Band: At least one of the five points falls <40 lux; VLR stays <0.30.

4. Lighting Selection Considerations

- LED lighting systems tend to reduce the risk of discomfort glare, making them preferable for minimizing driver distraction.
- Halogen lighting systems generally provide better illuminance on the perception of construction workers.

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APPENDIX A. STATE AGENCY STANDARDS

State	Status	Activity	Equipment	Specifications
Alabama	Numeric specification provided	Temporary traffic control during nighttime hours	Floodlighting	Average horizontal illuminance 50 lux; tasks requiring high precision may require 216 lux. Floodlighting must not produce disabling glare for approaching road users, flaggers, or workers.
Alaska	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Arizona	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Arkansas	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
California	Numeric specification provided	All nighttime operations	—	10 fc (foot-candles).
Colorado	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Connecticut	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Delaware	Numeric specification provided	Nighttime work zone lighting (three NCHRP levels)	—	Target illuminance: 59 lux, 108 lux, and 215 lux; maximum uniformity ratio 10:1.
Florida	Numeric specification provided	Proper workmanship and inspections	—	5 fc.
Georgia	Numeric specification provided	All nighttime operations; average maintained horizontal illuminance	Tower lights; machine lights	Tower lights: 20 fc over the work area; ≥50,000 lm per tower; 460,000 lm combined per tower. Machine lights: 22,000–50,000 lm.

State	Status	Activity	Equipment	Specifications
Hawaii	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Idaho	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Illinois	Numeric specification provided	All nighttime operations	Tower lighting and/or balloon lighting	Provide ≥5 fc throughout the work area; provide ≥10 fc for flaggers.
Indiana	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Iowa	Numeric specification provided	Trailer-mounted LED luminaire for nighttime work zones	Trailer-mounted LED luminaire	Mast arm orientation 88°–92° (if not otherwise specified); mounted LED at least 17 ft.
Kansas	Numeric specification provided	Nighttime work zone lighting	LED (full cutoff; some cutoff)	1,600–34,000 lumens; minimum mounting height 8 ft.
Kentucky	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Louisiana	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Maine	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.

State	Status	Activity	Equipment	Specifications
Maryland	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Massachusetts	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Michigan	Practice/Guideline (several items mentioned; details not in materials)	Nighttime work zone operations (general)	—	Several practice items mentioned; numeric levels not provided in your materials.
Minnesota	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Mississippi	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Missouri	Numeric specification provided	Construction equipment and labor are active; flaggers and plan-specified locations	—	Active work areas: 5 fc. Flaggers/plan-specified locations: 0.6 fc.
Montana	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Nebraska	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Nevada	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.

State	Status	Activity	Equipment	Specifications
New Hampshire	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
New Jersey	Numeric specification provided	Tasks on/around equipment; specific tasks (crack filling, saw-cutting, joint sealing)	—	100 lux (uniformity ≤5:1) for equipment tasks; 200 lux (uniformity ≤5:1) for specific tasks.
New Mexico	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
New York	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
North Carolina	Numeric specification provided	Nighttime operations with tower/machine lighting	Tower lights; machine lights	Tower lights: 50,000–460,000 lm and 20 fc. Machine lights: 22,000–50,000 lm to provide 10 fc; 13 ft mounting height.
North Dakota	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Ohio	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Oklahoma	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Oregon	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.

State	Status	Activity	Equipment	Specifications
Pennsylvania	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Rhode Island	Numeric specification provided	Rollers, pavers, and pick-up trucks	250 W Metal Halide type lights	Use 250 W Metal Halide type lights.
South Carolina	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
South Dakota	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Tennessee	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Texas	Numeric specification provided	Nighttime work zone lighting (three NCHRP levels)	—	Target illuminance: 59 lux, 108 lux, and 215 lux; maximum uniformity ratio 10:1.
Utah	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Vermont	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Virginia	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.

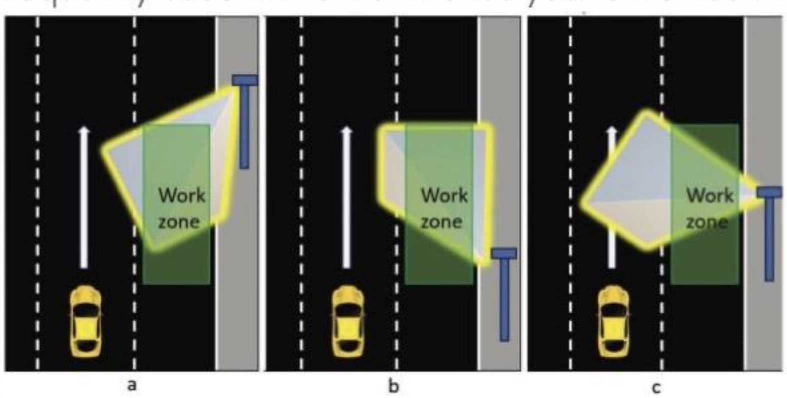
State	Status	Activity	Equipment	Specifications
Washington	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
West Virginia	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
Wisconsin	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.
Wyoming	Practice/Guideline (nighttime lighting addressed in state manuals/specs)	Nighttime work zone operations (general)	—	State documents address nighttime lighting; numeric levels not provided in your materials.
District of Columbia	General requirements (per state work zone design manual/MUTCD)	Nighttime work zone operations (general)	—	No state-specific numeric lighting levels provided in your materials.

APPENDIX B. SURVEY QUESTIONS

Ql. How satisfied are you with the different types of lighting systems used in nighttime work zone projects you have experienced? Please indicate your level of comfort with each type.

	Extremely uncomfortable	Somewhat uncomfortable	Somewhat comfortable	Comfortable	Extreme comforta
Balloon:Right	○	○	○	○	○
Light Tower:Right	○	○	○	○	○
Halo Light:Right	○	○	○	○	○
Vehicle Headlight:Right	○	○	○	○	○
Other (please specify):	○	○	○	○	○

Q2. In your experience, which light source orientation is most frequently used in the work zones you've worked in or observed?



- ○ a. Toward coming traffic.
- ○ b. Away from traffic
- ○ c. Perpendicular to traffic
- ○ d. N/A

Q3. Have you ever experienced any safety incidents or near misses that you believe were due to inadequate lighting in nighttime work zones?

- ○ Never
- ○ Rarely
- ○ Sometimes
- ○ Often
- ○ Always

Q4. When you worked at a nighttime work zone, how comfortable did you feel about the lighting setup?

- ○ Extremely uncomfortable: Significant discomfort impacting my ability to work
- ○ Somewhat uncomfortable: Frequent eye strain or discomfort affecting my work.
- ○ Somewhat comfortable: Occasional eye strain or need to adjust to the lighting.
- ○ Comfortable: Minor discomfort that does not affect my work
- ○ Extremely comfortable: No discomfort or eye strain.

Q5. Based on your response to last question, please provide detailed reason which makes you discomfortable.

Q6. Does the glare from construction zone lighting affect your ability to see the nearby construction equipment, construction vehicles, or construction workers?

- ◯ Not at all
- ◯ Significantly affects
- ◯ Severely affects

Q7. Based on your experience, how would you rate the likelihood of glare caused by the following aspects of lighting systems used in nighttime work zone projects?

	Unlikely to Cause Glare	Mildly Likely to Cause Glare	Moderately Likely to Cause Glare	Highly Likely to Cause Glare	Extremely likely to cause glare
Luminaires' aiming angle	◯	◯	◯	◯	◯
Lighting intensity	◯	◯	◯	◯	◯
Mounted height of light	◯	◯	◯	◯	◯
Rotation angle	◯	◯	◯	◯	◯
Lighting source	◯	◯	◯	◯	◯
Distance from light source	◯	◯	◯	◯	◯
Other (please specify):	◯	◯	◯	◯	◯

Q8. What is your perception of the flashing lights installed on vehicles at nighttime work zones for alerting drivers and others?

- ○ Very effective for safety, enhancing visibility and awareness
- ○ Somewhat effective but occasionally distracting
- ○ Neutral, no significant impact noticed.
- ○ Somewhat ineffective, causing glare or visibility issues.
- ○ Very ineffective, potentially leading to confusion or safety concerns.

Q9. What measures do you think could improve visibility and reduce glare in nighttime construction zones? (Please select all that apply)

- ☐ Adjust lighting equipment placement to avoid direct glare
- ☐ Use glare shields or diffusers on lights
- ☐ Reduce light brightness
- ☐ Provide advance warning signs about strong lights
- ☐ Increase overall brightness (without causing glare)
- ☐ Ensure consistent lighting levels throughout the work zone
- ☐ Other (please specify):

Q10. Do you have any standards, guidelines, specifications related to nighttime lighting system at work zone for reference?

- ○ Yes
- ○ No

APPENDIX C. SELECTED VEILING LUMINANCE RATIO CALCULATION

Halogen rotation angle 20°

Mounted Height	Distance (ft)	Aiming angle 10˚				Aiming angle 20˚				Aiming angle 40˚			
		VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio
12 ft	0	3.47	4.975	0.009	0.001	7.26	1.212	0.019	0.006	3.9	1.764	0.010	0.004
	15	2.57	8.62	0.019	0.002	9.95	0.968	0.073	0.024	3.76	2.148	0.028	0.011
	30	2.2	4.445	0.048	0.005	6.355	1.541	0.138	0.046	2.46	2.094	0.053	0.021
	45	1.03	5.085	0.047	0.005	4.435	1.635	0.202	0.067	2.265	2.597	0.103	0.041
	60	1.04	6.53	0.082	0.008	3.965	2.988	0.312	0.104	2.18	2.679	0.172	0.069
	75	1.14	20.595	0.139	0.013	8	4.205	0.973	0.324	4.485	3.049	0.545	0.220
	90	2.88	22.37	0.501	0.048	10.035	8.494	1.746	0.581	5.255	3.056	0.914	0.368
	Average	-	10.374	-	-	-	3.006	-	-	-	2.484	-	-
13 ft	90	3.47	0.082	0.009	0.073	4.86	1.943	0.012	0.003	3.24	0.229	0.008	0.003
	75	2.57	0.128	0.019	0.155	4.52	3.344	0.033	0.008	3.71	0.252	0.027	0.011
	60	2.2	0.105	0.048	0.391	2.67	2.015	0.058	0.014	2.5	0.326	0.054	0.022
	45	1.03	0.114	0.047	0.384	1.65	3.11	0.075	0.018	1.12	0.277	0.051	0.020
	30	1.04	0.12	0.082	0.672	1.12	5.528	0.088	0.021	1.13	0.434	0.089	0.036
	15	1.14	0.143	0.139	1.138	1.84	5.643	0.224	0.054	1.31	0.986	0.159	0.064
	0	2.88	0.161	0.501	4.111	5.24	7.188	0.912	0.222	1.1	1.024	0.191	0.077
	Average	-	0.122	-	-	-	4.110	-	-	-	0.504	-	-
14 ft	90	4.9	0.124	0.013	0.067	8.37	2.705	0.022	0.007	42.4	0.458	0.109	0.044
	75	6.23	0.152	0.046	0.244	30.5	1.111	0.224	0.071	55.3	0.478	0.407	0.164
	60	15.27	0.204	0.330	1.761	66.8	2.064	1.446	0.460	87.9	0.61	1.902	0.766
	45	46.3	0.189	2.104	11.213	113.2	3.075	5.144	1.639	95.6	0.71	4.344	1.749
	30	87.7	0.201	6.907	36.814	171.5	2.988	13.507	4.303	161.9	0.844	12.751	5.134
	15	133.9	0.211	16.282	86.780	226.7	4.34	27.566	8.781	169.6	0.917	20.623	8.303
	0	273.7	0.232	47.611	253.762	259	5.692	45.053	14.351	153.7	1.181	26.736	10.764
	Average	-	0.188	-	-	-	3.139	-	-	-	0.743	-	-

Halogen rotation angle 90°

Mounted Height	Distance (ft)	Aiming angle 10˚				Aiming angle 20˚				Aiming angle 40˚			
		VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio
12 ft	90	16.22	1.624	2.821	1.183	13.97	4.16	2.430	0.405	22.4	0.923	3.897	2.677
	75	14.95	2.139	1.818	0.762	2.59	5.58	0.315	0.053	35.4	1.344	4.304	2.957
	60	5.93	2.752	0.467	0.196	2.18	4.489	0.172	0.029	52.9	1.061	4.166	2.862
	45	0.99	2.764	0.045	0.019	5.65	5.342	0.257	0.043	44.3	1.142	2.013	1.383
	30	2.49	2.579	0.054	0.023	35.9	5.925	0.777	0.130	110.35	1.205	2.388	1.640
	15	9.81	1.773	0.072	0.030	176.4	8.012	1.297	0.216	225.7	2.115	1.659	1.140
	0	36.6	3.058	0.094	0.039	54.7	8.475	0.141	0.023	29.9	2.4	0.077	0.053
	Average	-	2.384	-	-	-	5.998	-	-	-	1.456	-	-
13 ft	90	13.51	0.342	2.350	2.592	9.96	2.395	1.733	0.271	10.8	0.919	1.879	0.852
	75	2.76	0.485	0.336	0.370	1.85	4.018	0.225	0.035	35.2	1.007	4.280	1.004
	60	1.39	0.645	0.109	0.121	1.98	5.163	0.156	0.024	25.95	1.117	2.044	1.043
	45	3.74	0.624	0.170	0.187	7.21	5.567	0.328	0.051	49.2	1.515	2.236	1.112
	30	15.33	0.78	0.332	0.366	43.2	7.754	0.935	0.146	106.5	1.733	2.305	1.188
	15	56.3	0.96	0.414	0.457	192.5	9.458	1.415	0.221	170	1.648	1.250	1.384
	0	7.49	2.51	0.019	0.021	22.64	10.39	0.058	0.009	17.5	2.201	0.045	1.307
	Average	-	0.907	-	-	-	6.392	-	-	-	1.449	-	-
14 ft	90	12.09	0.693	2.103	1.701	8.4	1.683	1.461	0.235	28.1	0.334	4.888	3.358
	75	2.02	0.375	0.246	0.199	3.4	4.263	0.413	0.066	32.3	1.087	3.928	2.698
	60	0.79	1.372	0.062	0.050	3.21	5.068	0.253	0.041	58.1	0.697	4.576	3.143
	45	3.38	0.442	0.154	0.124	108.4	5.627	4.926	0.792	59.9	0.99	2.722	1.870
	30	10.77	0.822	0.233	0.188	41	7.641	0.887	0.143	33	1.018	0.714	0.491
	15	34	2.342	0.250	0.202	138.6	8.984	1.019	0.164	63.8	1.02	0.469	0.322
	0	18.4	2.611	0.047	0.038	19.66	10.27	0.051	0.008	16.72	1.189	0.043	0.030
	Average	-	1.237	-	-	-	6.219	-	-	-	0.905	-	-

Halogen rotation angle 130°

Mounted Height	Distance (ft)	Aiming angle 10˚				Aiming angle 20˚				Aiming angle 40˚			
		VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio
12 ft	90	78.25	4.534	13.612	3.056	45.7	10.71	7.950	0.783	33.3	2.711	5.793	2.048
	75	69.6	5.831	8.463	1.900	21.745	11	2.644	0.260	60	2.873	7.296	2.580
	60	91.2	4.008	7.183	1.613	114.7	10.68	9.034	0.890	70.5	2.785	5.552	1.963
	45	123.95	4.415	5.632	1.264	173.95	10.83	7.904	0.779	91.1	2.866	4.140	1.464
	30	200.15	3.585	4.331	0.972	213.6	11.55	4.622	0.455	155.3	2.847	3.361	1.188
	15	384.5	4.255	2.827	0.635	268.35	9.495	1.973	0.194	270.55	2.849	1.989	0.703
	0	840.5	4.552	2.161	0.485	38.2	6.8	0.098	0.010	71.1	2.864	0.183	0.065
	Average	-	4.454	-	-	-	10.152	-	-	-	2.828	-	-
13 ft	90	22.9	5.401	3.983	0.629	26.1	9.034	4.540	0.477	134.5	3.169	23.396	8.274
	75	27.6	5.114	3.356	0.530	61.9	9.366	7.527	0.790	137	3.138	16.659	5.891
	60	49.3	5.847	3.883	0.613	99.7	10.33	7.852	0.825	160.6	3.209	12.649	4.473
	45	90.4	6.186	4.108	0.649	153.5	11.13	6.975	0.732	50.4	3.105	2.290	0.810
	30	100.9	7.017	2.183	0.345	175.4	10.35	3.796	0.399	77.7	3.266	1.681	0.595
	15	261.8	7.241	1.925	0.304	282	8.548	2.073	0.218	204.1	3.26	1.501	0.531
	0	90.4	7.501	0.232	0.037	28.9	7.902	0.074	0.008	31.4	3.421	0.081	0.029
	Average	-	6.330	-	-	-	9.523	-	-	-	3.224	-	-
14 ft	90	55.5	6.418	9.654	1.683	38.8	17.48	6.749	0.461	127.2	4.847	22.127	7.825
	75	50.7	5.471	6.165	1.075	61.8	19.35	7.515	0.513	137.4	5.027	16.707	5.908
	60	9.45	4.889	0.744	0.130	69.1	17.28	5.442	0.372	190.3	3.666	14.988	5.300
	45	21.71	5.543	0.986	0.172	152.3	13.81	6.920	0.473	86.1	4.172	3.912	1.384
	30	142.3	5.844	3.079	0.537	119.6	13.74	2.588	0.177	72.5	3.38	1.569	0.555
	15	279.4	6.346	2.054	0.358	182.6	10.64	1.343	0.092	126.8	3.467	0.932	0.330
	0	434	5.636	1.116	0.195	17.5	10.18	0.045	0.003	33.7	3.379	0.087	0.031
	Average	-	5.735	-	-	-	14.640	-	-	-	3.991	-	-

LED rotation angle 20°

Mounted Height	Distance (ft)	Aiming angle 10˚				Aiming angle 20˚				Aiming angle 40˚			
		VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio
12 ft	90	1.46	0.437	0.254	0.156	3.61	0.254	0.628	0.254	1.85	0.769	0.322	0.245
	75	1.53	1.097	0.186	0.114	4.24	6.29	0.516	0.208	1.65	0.487	0.201	0.153
	60	1.76	1.032	0.139	0.085	7.23	0.944	0.569	0.230	1.81	0.499	0.143	0.109
	45	1.56	1.179	0.071	0.043	2.91	0.91	0.132	0.053	1.49	0.329	0.068	0.052
	30	1.53	1.93	0.033	0.020	2.24	2.838	0.048	0.020	1.62	6.317	0.035	0.027
	15	1.66	2.293	0.012	0.007	2.47	1.785	0.018	0.007	1.63	0.403	0.012	0.009
	0	2.23	3.462	0.006	0.004	5.26	4.296	0.014	0.005	2.31	0.381	0.006	0.005
	Average	-	1.633	-	-	-	2.474	-	-	-	1.312	-	-
13 ft	90	0.39	0.390	0.068	0.115	2.2	0.372	0.383	0.351	1.17	0.494	0.204	0.155
	75	0.372	0.372	0.045	0.077	2.81	0.926	0.342	0.313	1.22	0.627	0.148	0.113
	60	0.639	0.639	0.050	0.086	4.36	1.215	0.343	0.315	1.36	0.598	0.107	0.082
	45	0.467	0.467	0.021	0.036	2.02	0.61	0.092	0.084	1.16	0.593	0.053	0.040
	30	0.53	0.530	0.011	0.020	1.73	1.138	0.037	0.034	1.26	0.686	0.027	0.021
	15	0.797	0.797	0.006	0.010	1.84	1.213	0.014	0.012	1.17	0.413	0.009	0.007
	0	0.917	0.917	0.002	0.004	3.05	2.163	0.008	0.007	1.37	0.2896	0.004	0.003
	Average	-	0.587	-	-	-	1.091	-	-	-	0.529	-	-
14 ft	90	0.382	0.382	0.066	0.081	0.600	0.29	0.104	0.085	0.680	0.296	0.118	0.090
	75	0.525	0.525	0.064	0.078	2.880	0.39	0.350	0.285	0.760	0.357	0.092	0.070
	60	0.732	0.732	0.058	0.071	1.250	1.469	0.098	0.080	0.830	0.435	0.065	0.050
	45	0.841	0.841	0.038	0.047	1.330	0.417	0.060	0.049	0.335	0.36	0.015	0.012
	30	0.963	0.963	0.021	0.026	1.705	0.347	0.037	0.030	0.360	0.4	0.008	0.006
	15	1.042	1.042	0.008	0.009	0.895	1.47	0.007	0.005	0.600	0.465	0.004	0.003
	0	1.227	1.227	0.003	0.004	1.035	4.227	0.003	0.002	1.120	0.593	0.003	0.002
	Average	-	0.816	-	-	-	1.230	-	-	-	0.415	-	-

LED rotation angle 90°

Mounted Height	Distance (ft)	Aiming angle 10˚				Aiming angle 20˚				Aiming angle 40˚			
		VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio	VI (lux)	Pav. Luminance	VL	VL Ratio
12 ft	90	1.425	0.661	0.248	0.173	0.755	1.485	0.131	0.035	0.65	0.436	0.113	0.233
	75	0.81	0.656	0.098	0.069	0.55	2.522	0.067	0.018	0.745	0.438	0.091	0.186
	60	1.96	1.265	0.154	0.108	2.84	3.417	0.224	0.060	1.21	0.449	0.095	0.196
	45	2.75	0.691	0.125	0.087	5.705	3.491	0.259	0.069	1.785	0.45	0.081	0.167
	30	4.44	1.358	0.096	0.067	13.525	4.91	0.293	0.078	2.73	0.477	0.059	0.122
	15	14.385	2.305	0.106	0.074	14.23	5.069	0.105	0.028	2.895	0.525	0.021	0.044
	0	20.72	3.088	0.053	0.037	101.2	5.3	0.260	0.070	6.11	0.626	0.016	0.032
	Average	-	1.432	-	-	-	3.742	-	-	-	0.486	-	-
13 ft	90	1.63	0.637	0.284	0.328	0.13	0.396	0.023	0.010	0.83	0.368	0.144	0.852
	75	1.65	0.492	0.201	0.232	0.16	0.699	0.019	0.008	1.18	0.413	0.143	1.004
	60	2.49	1.066	0.196	0.227	3.09	1.435	0.243	0.103	1.18	0.44	0.093	1.043
	45	2.99	0.683	0.136	0.157	5.45	1.603	0.248	0.105	1.49	0.458	0.068	1.112
	30	5.06	0.51	0.109	0.127	13.23	1.814	0.286	0.121	2.1	0.497	0.045	1.188
	15	13.12	1.12	0.096	0.112	14.26	5.129	0.105	0.044	3.58	0.534	0.026	1.384
	0	25.97	1.545	0.067	0.077	95	5.468	0.244	0.103	8.27	0.558	0.021	1.307
	Average	-	0.865	-	-	-	2.363	-	-	-	0.467	-	-
14 ft	90	1.23	0.526	0.214	0.138	1.475	0.713	0.257	0.081	1.18	0.489	0.205	0.422
	75	1.29	0.672	0.157	0.101	1.845	1.479	0.224	0.071	1.85	0.478	0.225	0.463
	60	1.675	0.628	0.132	0.085	3.12	1.661	0.246	0.078	2.605	0.458	0.205	0.422
	45	2.405	1.897	0.109	0.070	5.51	1.27	0.250	0.079	1.3	0.489	0.059	0.122
	30	4.975	1.885	0.108	0.069	5.795	3.771	0.125	0.040	2.26	0.515	0.049	0.101
	15	20.715	2.172	0.152	0.098	18.36	7.115	0.135	0.043	4.045	0.675	0.030	0.061
	0	4.31	3.101	0.011	0.007	39.6	6.17	0.102	0.032	10.28	0.634	0.026	0.054
	Average	-	1.554	-	-	-	3.168	-	-	-	0.534	-	-

LED rotation angle 130°

Mounted Height	Distance (ft)	Aiming angle 10˚ VI (lux)	Aiming angle 10˚ Pav. Luminance	Aiming angle 10˚ VL	Aiming angle 10˚ VL Ratio	Aiming angle 20˚ VI (lux)	Aiming angle 20˚ Pav. Luminance	Aiming angle 20˚ VL	Aiming angle 20˚ VL Ratio	Aiming angle 40˚ VI (lux)	Aiming angle 40˚ Pav. Luminance	Aiming angle 40˚ VL	Aiming angle 40˚ VL Ratio
12 ft	90	4.83	3.636	0.840	0.146	22.7	1.964	3.949	1.088	20.64	0.585	3.590	5.445
	75	27.9	4.621	3.393	0.588	32.6	1.38	3.964	1.092	21.12	0.667	2.568	3.894
	60	22.9	4.765	1.804	0.313	34.9	3.361	2.749	0.757	21.54	0.634	1.696	2.573
	45	38.3	5.334	1.740	0.302	55.3	3.317	2.513	0.692	31.8	0.616	1.445	2.191
	30	46.9	7.13	1.015	0.176	55.3	4.376	1.197	0.330	51.4	0.75	1.112	1.687
	15	65.9	7.441	0.485	0.084	53.5	4.197	0.393	0.108	47.6	0.614	0.350	0.531
	0	94.4	7.454	0.243	0.042	70.4	6.82	0.181	0.050	70.7	0.75	0.182	0.276
	Average	-	5.769	-	-	-	3.631	-	-	-	0.659	-	-
13 ft	90	4.5	2.358	0.783	0.172	9.8	1.643	1.705	0.518	4.99	1.113	0.868	1.316
	75	6.19	3.421	0.753	0.165	12.36	2.563	1.503	0.456	6.41	1.177	0.779	1.182
	60	6.23	3.533	0.491	0.108	13.7	2.83	1.079	0.328	7.87	1.187	0.620	0.940
	45	18.98	4.337	0.862	0.190	22.37	3.653	1.016	0.309	14.72	1.29	0.669	1.014
	30	24.03	5.073	0.520	0.114	27.1	3.84	0.586	0.178	27.1	1.387	0.586	0.889
	15	30.5	6.248	0.224	0.049	30.2	4.222	0.222	0.067	30.2	1.217	0.222	0.337
	0	41.2	6.882	0.106	0.023	39.7	4.308	0.102	0.031	39.7	1.213	0.102	0.155
	Average	-	4.550	-	-	-	3.294	-	-	-	1.226	-	-
14 ft	90	0.78	2.908	0.136	0.035	17.44	8.849	3.034	0.196	32.81	1.289	5.707	8.655
	75	26.47	2.914	3.219	0.830	37.95	11.65	4.615	0.298	36.55	1.341	4.444	6.740
	60	48.1	2.967	3.788	0.977	36.3	13.17	2.859	0.185	42.15	1.333	3.320	5.034
	45	44.75	3.439	2.033	0.524	85.75	15.15	3.896	0.252	45.95	1.484	2.088	3.166
	30	69.75	4.711	1.509	0.389	190.65	15.3	4.126	0.267	70.35	1.521	1.522	2.309
	15	152.6	4.717	1.122	0.289	243.45	20.46	1.790	0.116	128.25	1.506	0.943	1.430
	0	269	5.492	0.692	0.178	270.5	23.7	0.696	0.045	162.8	1.749	0.419	0.635
	Average	-	3.878	-	-	-	15.468	-	-	-	1.460	-	-