2026

Final Report SPR-FY25(041)

The Effect of Nighttime Lighting on Construction Workers' Safety

Chun-Hsing Ho, Ph.D., P.E.
Associate Professor
Durham School of Architectural Engineering & Construction
University of Nebraska-Lincoln

Kyungki Kim, Ph.D.
Assistant Professor
Durham School of Architectural Engineering & Construction
University of Nebraska-Lincoln

Nyawa Allieu
Graduate Research Assistant
Durham School of Architectural Engineering & Construction
University of Nebraska-Lincoln

Kewei Ren
Graduate Research Assistant
Durham School of Architectural Engineering & Construction
University of Nebraska-Lincoln

Nebraska Department of Transportation Research
Headquarters Address
1400 Nebraska Parkway
Lincoln, NE 68509
ndot.research@nebraska.gov
(402) 479-4697
https://dot.nebraska.gov/business-center/research/

Nebraska Transportation Center
262 Prem S. Paul Research Center at Whittier School
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-1932
http://ntc.unl.edu

This report was funded in part through grant from the U.S. Department of Transportation Federal Highway Administration. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. Department of Transportation.

The Effect of Nighttime Lighting on Construction Workers' Safety

Chun-Hsing Ho, Ph.D., P.E.
Associate Professor
Durham School of Architectural Engineering & Construction
University of Nebraska – Lincoln

Kyungki Kim, Ph.D.
Assistant Professor
Durham School of Architectural Engineering & Construction
University of Nebraska – Lincoln

Nyawa Allieu
Graduate Research Assistant
Durham School of Architectural Engineering & Construction
University of Nebraska – Lincoln

Kewei Ren
Graduate Research Assistant
Durham School of Architectural Engineering & Construction
University of Nebraska – Lincoln

A Report on Research Sponsored by

Nebraska Department of Transportation

and

Nebraska Transportation Center

University of Nebraska–Lincoln

June 2026

Technical Report Documentation Page

1. Report No. SPR-FY25(041)	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Effect of Nighttime Lighting on Construction Workers' Safety		5. Report Date June 2026
		6. Performing Organization Code
7. Author(s) Chun-Hsing Ho, Kyungki Kim, Nyawa P. Allieu, Kewei Ren		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Nebraska-Lincoln, Nebraska Transportation Center 113 Nebraska Hall, PO Box 880500 900 N 16th Street, Lincoln, NE.68588		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Organization Name and Address Nebraska Department of Transportation 1400 Nebraska Parkway Lincoln, NE 68502		13. Type of Report and Period Covered Final Report July 2024-June 2026.
		14. Sponsoring Agency Code MATC TRB RiP No. 34760
15. Supplementary Notes		

16. Abstract

This research evaluated the effectiveness of nighttime construction lighting systems in improving worker visibility and safety while minimizing glare impacts on motorists in Nebraska work zones. The study combined an industry survey with controlled field testing to assess current lighting practices and quantify lighting performance. Survey responses from construction professionals documented commonly used lighting systems, perceived adequacy, safety impacts, and public concerns related to glare. Field experiments were conducted at the Midwest Roadside Safety Facility using LED, halogen, and balloon light towers. Lighting configurations were systematically varied by mounting height, aiming angle, and rotation angle. Worker visibility was evaluated using horizontal illuminance based on Federal Highway Administration recommendations, and driver glare was assessed using veiling luminance ratios in accordance with Illuminating Engineering Society RP-8-22 standards. Results indicate that lighting performance depends primarily on configuration rather than lighting type alone, and only a limited number of configurations satisfied both illuminance and glare criteria. The findings can be used to guide safer nighttime work zone lighting setup and support the development of NDOT-specific lighting recommendations.

17. Key Words Nighttime lighting, discomfort glare, illuminance, work zone safety		18. Distribution Statement No restrictions.	
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages 84	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

Table of Contents

List of Figures

List of Tables

Acknowledgments

The authors thank the Nebraska Department of Transportation (NDOT) for the financial support needed to complete this study. In particular, the authors thank the NDOT Technical Advisory Committee (TAC) for their technical support and invaluable discussions and comments. Thank you to the team at Midwest Roadside Safety Facility (MwRSF) for their help in mitigating deliveries and setting up and allowing use of their facility.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. The contents do not necessarily reflect the official views or policies neither of the Nebraska Department of Transportation (NDOT) nor the University of Nebraska-Lincoln (UNL). This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report.

The United States (U.S.) government and the State of Nebraska do not endorse products or manufacturers. This material is based upon work supported by the Federal Highway Administration under SPR-FY25(041). Any opinions, findings and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration.

This report has been reviewed by the Nebraska Transportation Center for grammar and context, formatting, and compliance with Section 508 of the Rehabilitation Act of 1973.

Abstract

This research evaluated the effectiveness of nighttime construction lighting systems in improving worker visibility and safety while minimizing glare impacts on motorists in Nebraska work zones. The study combined an industry survey with controlled field testing to assess current lighting practices and quantify lighting performance. Survey responses from construction professionals documented commonly used lighting systems, perceived adequacy, safety impacts, and public concerns related to glare. Field experiments were conducted at the Midwest Roadside Safety Facility using LED, halogen, and balloon light towers. Lighting configurations were systematically varied by mounting height, aiming angle, and rotation angle. Worker visibility was evaluated using horizontal illuminance based on Federal Highway Administration recommendations, and driver glare was assessed using veiling luminance ratios in accordance with Illuminating Engineering Society RP-8-22 standards. Results indicate that lighting performance depends primarily on configuration rather than lighting type alone, and only a limited number of configurations satisfied both illuminance and glare criteria. The findings can be used to guide safer nighttime work zone lighting setup and support the development of NDOT-specific lighting recommendations.

Executive summary

Nighttime highway construction is increasingly used to reduce traffic congestion and improve project efficiency; however, it introduces heightened safety risks due to reduced visibility and glare. In nighttime work zones, construction workers must perform visually demanding tasks while exposed to moving traffic, heavy equipment, and uneven surfaces. At the same time, motorists must safely navigate through temporary traffic control layouts under unfamiliar and often visually complex conditions. Effective lighting is therefore essential for maintaining safe nighttime operations. While national guidelines for work zone lighting exist, there is limited state-specific research evaluating how current lighting practices perform under Nebraska conditions. This study was conducted to address this gap by systematically evaluating nighttime work zone lighting systems from both worker and driver perspectives.

The primary objective of this research was to assess the adequacy, effectiveness, and safety implications of commonly used nighttime lighting systems and configurations in Nebraska construction work zones. Specifically, the study sought to (1) document current nighttime lighting practices and perceptions of safety among industry professionals, (2) quantify worker visibility and driver glare under controlled lighting configurations, and (3) identify lighting arrangements that best balance adequate illuminance with acceptable glare levels. The findings are intended to inform NDOT and industry stakeholders and support the development of improved, evidence-based nighttime lighting guidance.

A mixed-methods research approach was used, combining surveys, site observations, and controlled field experiments. An industry survey was administered to contractors, inspectors, DOT personnel, and maintenance staff with experience in nighttime work zones. The survey collected information on lighting types used, perceived adequacy of lighting, effects on visibility

and injury prevention, worker training practices, public complaints related to glare, and overall satisfaction with worker safety. This information provided insight into real-world practices and identified areas of concern that warranted further investigation.

To complement the survey findings, field experiments were conducted at the Midwest Roadside Safety Facility at the University of Nebraska-Lincoln. This controlled environment allowed systematic evaluation of lighting performance under realistic nighttime conditions with minimal ambient light. Three commonly used lighting systems, LED light towers, halogen (metal halide) light towers, and balloon lighting, were tested. Lighting configurations were varied by mounting height (12, 14, and 16 feet), aiming angle (15°, 30°, and 45°), and rotation angle relative to traffic direction (ranging from away from traffic to toward traffic). In total, 189 lighting configurations were evaluated, generating over 3,000 data points.

Lighting performance was evaluated using established Federal Highway Administration (FHWA) and (Illuminating Engineering Society) IES metrics. Worker visibility was assessed using horizontal illuminance measurements and compared against FHWA-recommended illuminance ranges for nighttime construction tasks. Driver glare was evaluated by calculating the veiling luminance ratio using pavement luminance and vertical illuminance measurements in accordance with IES RP-8-22. A veiling luminance ratio of less than 0.3 was considered acceptable for driver safety.

Survey results revealed that most respondents viewed current nighttime lighting as only moderately adequate. Nearly half rated lighting as "adequate," while a substantial portion expressed neutral or dissatisfied opinions, indicating room for improvement. Portable light towers and vehicle-mounted lights were the most commonly used lighting systems. Uneven lighting distribution and glare were the most frequently cited concerns, affecting both worker comfort and motorist safety. Training in proper lighting setup was inconsistent, with many respondents reporting only basic or no formal training. Overall satisfaction with worker safety under current lighting conditions was mixed, reinforcing the need for improved lighting practices.

Field testing results demonstrated that lighting type alone does not determine safety performance; instead, mounting height, orientation, and aiming angle play a critical role. Halogen lighting most consistently met minimum horizontal illuminance requirements across tested configurations, making it reliable for achieving baseline visibility. However, halogen lights exhibited moderate glare and limited adaptability to changes in configuration. LED lighting produced high brightness and superior coverage uniformity, particularly at lower mounting heights, and generated lower glare levels than other lighting types when properly oriented. Improper LED configurations, however, often resulted in excessive localized brightness that exceeded recommended illuminance levels. Balloon lighting provided uniform, low-glare illumination but had a limited effective coverage area, reducing its suitability for larger or complex work zones.

Across all lighting systems, glare and illuminance hazards were strongly influenced by rotation and aiming angles. Lighting directed toward traffic significantly increased driver glare, while higher mounting heights generally reduced glare but also decreased illuminance levels. Only one configuration satisfied both illuminance and glare criteria across all measured distances; however, several additional configurations demonstrated consistent compliance within operational tolerances and are suitable for field deployment, suggesting that practical safety improvements are achievable through informed setup rather than equipment replacement alone.

Overall, the findings emphasize that safe nighttime work zone lighting requires an integrated, human-centered approach. Lighting systems must be selected and configured to provide sufficient visibility for workers while minimizing glare for motorists. LEDs offer the greatest flexibility and potential safety benefits when properly calibrated, while halogen and balloon lighting remain useful in specific applications. The results of this study provide a data-driven foundation for refining NDOT nighttime lighting practices and underscore the need for clearer configuration guidance, improved training, and greater emphasis on glare management to enhance safety for both workers and the traveling public.

Chapter 1 Introduction

Nighttime work zones present unique challenges for both construction workers and the traveling public, especially in terms of safety and visibility. As construction projects increasingly extend into the night to minimize traffic disruptions, it is critical to ensure that adequate lighting is in place to protect workers, reduce the likelihood of accidents, and maintain safe road conditions for motorists. Proper lighting is essential not only for task visibility but also for preventing injuries and fatalities in these environments. Despite the importance of this issue, there remains a significant gap in research specifically focused on nighttime lighting standards for construction zones in Nebraska. While national lighting standards exist, these guidelines may not be fully applicable or tailored to the specific conditions and needs of the state of Nebraska.

Current research on nighttime lighting primarily focuses on generalized national standards, which, while valuable, do not always account for regional differences in climate, geography, traffic patterns, or construction methods. This lack of localized research presents a critical gap in the development of effective, state-specific lighting strategies. Although some states have begun to address these gaps, Nebraska has yet to develop comprehensive, evidence-based lighting standards for nighttime construction zones. As a result, there is a pressing need to explore and establish more precise lighting protocols that account for the specific environmental and operational challenges faced by workers and motorists in Nebraska's diverse construction settings.

The goal of this research is to fill this gap by investigating the adequacy and effectiveness of nighttime lighting in Nebraska’s construction zones. Our study involved a combination of experiments, surveys, and expert consultations to assess current lighting practices, worker safety, and public safety concerns. Through a comprehensive survey of construction professionals, we gathered insights into their experiences with nighttime lighting, including the types of lighting used, their perceived effectiveness, and any areas for improvement. This data helped identify patterns, limitations, and potential risks associated with existing lighting solutions. Additionally, we designed and conducted experiments to evaluate the visibility and safety outcomes under varying lighting conditions specific to Nebraska's construction zones. These experiments provide empirical data on how different lighting types and setups impact visibility, injury prevention, and overall safety for workers and motorists.

The culmination of this research is the development of a Nebraska Department of Transportation (NDOT) lighting standard for nighttime construction zones. This state-specific standard is grounded in both the latest research and the practical insights gained from our surveys and experiments. By addressing the unique needs of Nebraska's construction zones, this standard provides a robust framework for improving worker safety, enhancing visibility, and minimizing risks associated with nighttime work. Ultimately, this research contributes to the growing body of knowledge on construction safety and lighting while supporting the creation of a more localized and effective lighting standard for Nebraska's nighttime construction environments.

Chapter 2 Literature review

2.1 Nighttime Work Zones and Lighting Challenges

Nighttime work zones are inherently hazardous due to reduced visibility and inadequate glare management. Glare, a significant concern, manifests as disability glare, discomfort glare, and glare recovery. Disability glare scatters light, reducing visibility by creating a contrast-reducing "veil," while discomfort glare causes an unpleasant sensation without necessarily impairing vision. Recovery from glare refers to the time needed for visibility to return after exposure to bright light. These effects are influenced by factors such as light type, orientation, and intensity.

Studies highlight the dual impact of lighting systems on both motorists and workers. For motorists, complaints often center around the high intensity of headlights, especially HID headlamps with "bluer" tones, and the glare from taller vehicles like trucks and SUVs. Excessive glare has been shown to impair steering control, lane-keeping, and speed management. Studies by Bhagavathula and Gibbons (2017) confirmed that light towers aimed directly at motorists significantly reduce visual performance, whereas proper orientation and increased tower height mitigate these effects. For workers, Huckaba (2009) found balloon lighting to be an effective solution, providing consistent illumination with minimal glare.

Field testing has revealed that most workers can perform tasks requiring low contrast with 10–20 lx of horizontal illuminance, even in the presence of glare. However, older workers often need higher illuminance levels. The Illuminating Engineering Society (IES) recommends task-specific illuminance levels: 54 lx for general activity areas, 108 lx for paving and milling zones, and 215 lx for detailed mechanical work. These findings align with studies emphasizing the balance between sufficient illumination and reduced glare.

2.2 Current Practices in Nighttime Lighting and Glare Management

Many U.S. states have adopted glare management in their work zone lighting standards, yet only Louisiana and New York provide quantifiable criteria, such as light positions, angles, and maximum vertical illuminance. In most cases, contractors are merely required to minimize glare without clear evaluation guidelines. States like Illinois have developed practical field guides, including the *"Field Guide on Installation and Removal of Temporary Traffic Control"* (FHWA, 2008), which provides actionable steps for setting up and maintaining work zone lighting plans. Temporary traffic control measures, such as flashing arrow panels, rumble strips, crash cushions, and changeable message signs, play a crucial role in ensuring worker and driver safety.

Additional resources, such as the NIOSH Construction Equipment Visibility webpage (NIOSH, 2024) and *"Know the Blind Spots"* posters (Work zone Safety, 2026), help mitigate risks around construction vehicles. Federal standards like MUTCD Part 6 Section 6D.03 (USDOT, 2024) also mandate high-visibility apparel for workers, enhancing their safety and visibility in low-light conditions.

2.3 Safety Data and Nighttime Work Zone Accidents

Fatality trends in work zones underscore the risks of nighttime operations. According to Work zone Barriers (2023), annual work zone fatalities averaged 794 between 2015 and 2020, a sharp increase from 635 deaths per year between 2008 and 2014. The economic toll is staggering, with work zone crashes costing over $32.9 billion annually. Notably, 954 fatalities were recorded in 2021 alone, with pickup trucks, SUVs, and other large vehicles contributing significantly to collision rates.

Arditi and Lee (2007) found that nighttime highway construction projects are five times more hazardous than daytime projects. Additionally, Shehab and Phu (2015) reported that while nighttime traffic volumes are lower, nighttime crashes constitute 22% of all work zone collisions—far higher than the expected 7%. Unsafe speeds for nighttime conditions contributed to 98% of these incidents, with human error being a significant factor.

2.4 Glare and Lighting Systems in Work Zones

The relationship between glare and lighting systems has been explored extensively. Odeh et al. (2009) emphasized that the height, aiming, and rotational angles of light towers significantly affect glare levels. Increasing the height of towers reduces glare for motorists, but rotational angles must complement aiming angles to avoid directing light toward motorists. Bhagavathula and Gibbons (2017) echoed these findings, noting that orientation, rather than light type, plays a crucial role in minimizing glare.

Huckaba (2009) recommended balloon lighting as a practical solution for consistent illumination with minimal glare. Complementing these efforts, Fotios and Kent (2020) developed metrics for discomfort glare and proposed four testing procedures—rating, discrimination, adjustment, and matching—along with standardized scales to quantify glare's impact on human vision. These methodologies provide a framework for improving glare mitigation practices in nighttime work zones.

2.5 Wearable and Flashing Light Systems

Wearable lighting systems (WLSs) have proven effective in enhancing worker visibility. Nnaji and Gambatese (2020) identified five WLS categories, recommending halo lights for situations with limited additional lighting. Ahmed et al. (2021) found that flashing blue lights on construction equipment reduced vehicle speeds by 2.6–16 mph when positioned at sufficient distances, emphasizing their effectiveness in improving safety. The Oregon Department of Transportation has adopted this approach, highlighting its practical application in mitigating nighttime work zone risks.

2.6 Human Factors and Safety Recommendations

Human factors play a critical role in nighttime work zone safety. Reduced visual function under mesopic lighting conditions, as reported by Wood (2020), significantly impacts driving performance. Age, pre-existing visual impairments, and driving habits further exacerbate these challenges. Recommendations include reflective clothing, improved lighting technologies, and enhanced reporting systems to address accident patterns.

The Federal Highway Administration (FHWA, 2013) provides detailed guidelines for developing effective lighting plans, including steps to determine appropriate lighting levels, select suitable systems, and conduct field checks. These recommendations, combined with technological innovations and regulatory standards, form an integrated approach to improving safety in nighttime work zones.

2.7 Summary of Nighttime Work Zone Lighting Research

Research consistently shows that nighttime work zones present elevated safety risks due to reduced visibility and ineffective glare management. Glare—particularly disability glare, discomfort glare, and delayed glare recovery—negatively affects visual performance for both motorists and workers, with impacts strongly influenced by lighting intensity, orientation, and placement. Improperly aimed or overly intense lighting degrades driver performance by impairing lane-keeping, speed control, and steering, while workers benefit from uniform, low-glare illumination systems. Field studies indicate that most construction tasks can be completed at relatively low illuminance levels when glare is controlled, though older workers require higher lighting levels, supporting task-specific recommendations from the Illuminating Engineering Society.

Despite extensive research on lighting performance, implementation standards remain inconsistent. While many U.S. states acknowledge glare as a safety concern, few provide quantifiable criteria for lighting configuration, leaving glare mitigation largely dependent on contractor judgment. Practical guidance documents and federal requirements—such as high-visibility apparel standards and temporary traffic control measures—partially address visibility challenges but do not fully resolve lighting-related risks. Crash data further reinforces the need for improved practices, showing that nighttime work zones experience disproportionately high crash and fatality rates despite lower traffic volumes, largely due to unsafe speeds, human error, and visual limitations under low-light conditions.

Collectively, the literature emphasizes that effective nighttime work zone safety depends more on lighting design and human-centered considerations than on lighting type alone. Proper light tower height and orientation significantly reduce glare, while solutions such as balloon lighting, wearable lighting systems, and flashing equipment lights improve worker visibility and driver awareness. Advances in glare measurement methodologies and federal lighting-planning guidelines provide a foundation for improving consistency and effectiveness in practice. Overall, existing research highlights the critical need for integrated lighting strategies that balance adequate illumination, glare control, and human factors to reduce nighttime work zone risks.

Chapter 3 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 motorists 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 driver's and worker's perspectives in controlled test environments, followed by analysis of the collected data.

3.1 Preliminary Site Visit

Before beginning the project, the team conducted site visits to current NDOT projects in the area that were at night and utilized nighttime lighting. This served as a way of seeing what practices contractors in the state were employing and what setups consisted of. The team made notes of types of lighting used, gaps in lighting, comfort and concentration of workers while working and heights that were set up. This served as a ground base of what contractors are expecting when it comes to nighttime work set up, areas of improvement to recognize, and establishing what the main factors that contribute to good nighttime lighting would be. Figure 3.1 below shows what lighting set ups on site were at that time.

Figure 3.1 Preliminary Site Visit Photos

3.2 Survey Design

The survey questions (Q1–Q12) were intentionally designed to align around four interrelated themes: current lighting conditions, perceived safety and visual performance, organizational practices, and risk identification and improvement strategies. These themes allow relationships between lighting design, human perception, and safety outcomes to be examined holistically rather than in isolation.

3.2.1 Current Lighting Conditions and Practices

Questions addressing lighting adequacy, fixture types, and visibility impacts establish a baseline understanding of existing nighttime work zone conditions. Ratings of overall lighting adequacy (Q2) are directly linked to reported lighting technologies in use (Q3) and perceived effects on visibility (Q4). Together, these questions allow comparison between what lighting systems are deployed and how well they perform in practice, identifying whether certain fixture types are associated with improved or degraded visibility.

3.2.2 Visual Performance, Glare, and Safety Outcomes

Several questions collectively examine how lighting influences visual performance and safety for both workers and motorists. The perceived effect of lighting on visibility (Q4) connects to the effectiveness of lighting in preventing worker injuries (Q5), while reports of adverse impacts on the traveling public, such as glare (Q8), capture driver-related safety concerns. Overall satisfaction with worker safety (Q10) serves as an integrative outcome measure, reflecting the combined effects of visibility, glare, and lighting design on perceived safety performance.

3.2.3 Training, Oversight, and Institutional Controls

Questions related to training and governance assess the role of organizational practices in ensuring safe lighting conditions. Worker training on lighting installation and maintenance (Q6) is thematically linked to oversight measures such as inspections, adherence to safety standards, and contract requirements (Q11). The follow-up question requesting specific standards or guidelines (Q12) provides contextual depth, enabling analysis of whether formal policies and references correlate with higher perceived lighting adequacy and safety outcomes.

3.2.4 Risk Identification and Improvement Opportunities

The survey also emphasizes proactive risk identification and solution development. Suggested lighting improvements (Q7) are informed by reported negative impacts on motorists (Q8) and overall safety satisfaction (Q9). This linkage allows respondents’ experiences with glare, uneven lighting, or inadequate intensity to be directly translated into actionable recommendations, bridging the gap between problem identification and practical mitigation strategies.

3.2.5 Experience as a Contextual Anchor

The final question regarding prior experience with nighttime work zones (Q12) serves as a contextual anchor for all responses. This allows stratification of results by experience level and supports interpretation of findings by distinguishing perceptions formed through direct exposure from those based on indirect knowledge.

3.3 Survey Implementation

This study aims to evaluate the effects of nighttime work zone lighting on safety by incorporating the perspectives of both construction workers and motorists. Specifically, the survey examines how lighting characteristics—such as glare, luminance, and visibility—affect worker visual performance; how the orientation and placement of light towers influence perception for workers and the traveling public; and how unsafe conditions may arise from inadequate nighttime lighting arrangements.

The survey was designed to collect perceptions, experiences, and practices related to nighttime work zone lighting from industry professionals. The target population included contractors, state Departments of Transportation (DOTs) personnel, inspectors, and maintenance staff, ensuring representation across planning, implementation, and field-level operations. The survey instrument consisted of twelve questions structured to follow logical progression from experience and current practices to performance evaluation, safety impacts, and improvement strategies. A complete list of survey questions is provided in Appendix A.

The survey began by establishing respondent eligibility and experience with night-time work zones. An initial screening question asked participants whether they had experience working in nighttime work zones, ensuring that subsequent responses reflected firsthand knowledge. Following this, respondents were asked to rate the overall adequacy of lighting in their current nighttime work zones using a five-point scale ranging from “Superior” to “Unacceptable,” with an additional “No Opinion” option to avoid forced responses.

Subsequent questions documented existing lighting practices and their perceived effects on visibility and safety. Respondents identified the types of lighting fixtures most commonly used in their work zones, including portable light towers, fixed overhead lights, vehicle-mounted lights, handheld lights, and other systems. Participants then evaluated how lighting affected visibility using an ordinal scale ranging from significant improvement to significant reduction, capturing both beneficial and adverse lighting conditions. The survey further assessed how effectively current lighting systems contribute to preventing worker personal injuries, using a five-point effectiveness scale.

The instrument also examined training and operational practices related to nighttime lighting. Respondents indicated whether workers receive comprehensive, basic, or no training on the proper installation, operation, and maintenance of lighting systems. To identify areas for improvement, participants selected recommended enhancements such as increased lighting intensity, improved uniformity, advanced lighting technologies, better maintenance practices, and other agency-specific solutions.

To address impacts on the traveling public, the survey included a question assessing the frequency of reported adverse effects—such as glare—on motorists, ranging from “Many” to “None.” Overall satisfaction with worker safety under current night-time lighting conditions was then measured using a five-point satisfaction scale. The final set of questions focused on governance and oversight, asking respondents to identify measures in place to ensure proper lighting, including inspections, equipment quality, worker feedback, adherence to safety standards, and contract requirements. Respondents who indicated adherence to standards were invited to specify the guidelines or references used by their agency.

Together, the survey structure enabled a comprehensive assessment of nighttime work zone lighting by linking current practices to perceived safety outcomes, training, public impact, and improvement opportunities. This systematic approach supports the identification of gaps between existing lighting arrangements and best practices, providing a foundation for data-driven recommendations to improve nighttime work zone safety.

3.4 Field Testing Protocol

This study employed field experiments to assess key photometric characteristics and evaluate the effectiveness of nighttime work zone lighting from both driver and worker perspectives. Table 3.1 below shows the IES RP-8-22 guidelines (Illuminating Engineering Society, 2022) which were followed and three primary parameters were recorded: horizontal illuminance to evaluate worker task performance, and pavement luminance along with vertical illuminance at driver eye height to analyze glare. To examine the driver's experience, the research team computed a glare index using measured pavement luminance and vertical illuminance. From the worker's perspective, horizontal illuminance at ground level—recommended by the FHWA Lighting Handbook (U.S. Department of Transportation, Federal Highway Administration, 2023)—was measured to assess perceived brightness in the work zone. Figure 3.2 shows the conceptual layout for measuring vertical and horizontal illuminance along with worker glare while Figure 3.3 shows the set up for individual Lightower measurements.

Table 3.1 Current FHWA Lighting Setup Guidelines (FHWA, 2023)

Category	Specifics	Values (Lux/Foot-Candles)
Work Area Lighting	Minimum illumination on the work surface	10 lux (1 foot-candle)
	Desirable illumination for most construction activities	30-50 lux (3-5 foot-candles)
	High-intensity work (high-precision tasks)	>50 lux (5 foot-candles)
Traffic Area Lighting	Minimum lighting along lanes of traffic	5 lux (0.5 foot-candles)
	Increased lighting for roadways with heavy traffic	10 lux (1 foot-candle)
Fixture Height	Height of light poles in highway work zones	12-20 feet
Pole Spacing	Distance between light poles for optimal coverage in work zones	30 to 100 feet

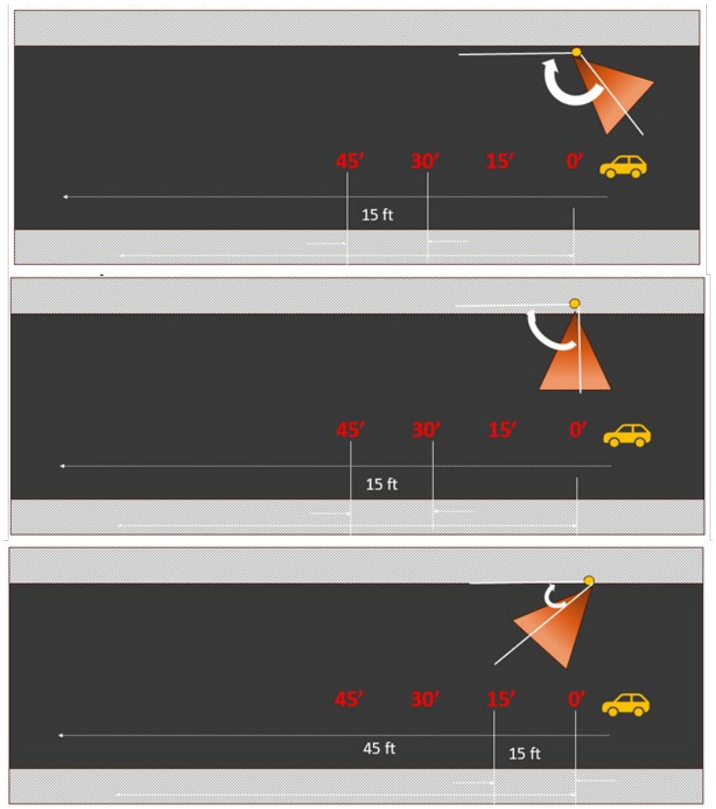


Figure 3.2 Experiment Layouts (Direction of Vehicle pertinent to light Tower)

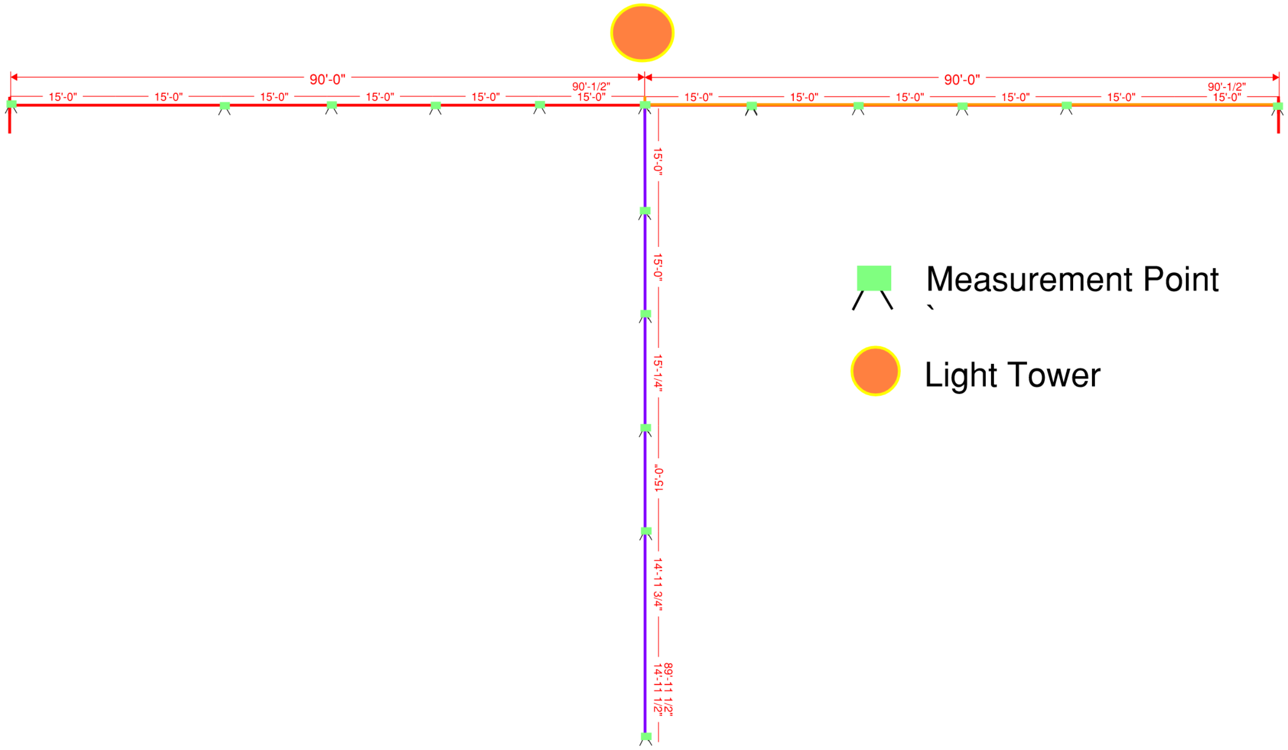


Figure 3.3 Individual Lightower Measurement Setup

3.4.1 Worker Glare Perspective Set Up

After the experimental plan was established, we prototyped the proposed lighting arrangements. The experimental plan and corresponding prototypes were designed to facilitate glare and illuminance data collection from both motorists' and workers' perspectives. From the workers' perspective, horizontal and vertical illuminance (units: lux in SI or foot-candles in the US system) were measured according to the lighting arrangements. Note: Illuminance quantifies the amount of light incident on and distributed over a given surface area. Horizontal illuminance represents the light incident on a horizontal surface, such as a pavement, whereas vertical illuminance represents the light incident on a vertical surface, such as the eyes of an observer, as illustrated in Figure 3.4. Both horizontal and vertical illuminance data were collected using an illuminance meter, which was procured through the project budget. Note: The definitions of the two axes representing vertical and horizontal illuminance in Figure 3.4 follow the IES standard.

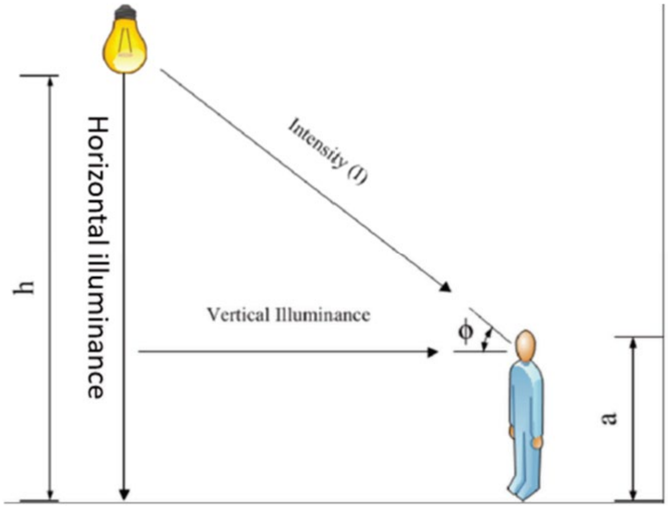


Figure 3.4 IES Set Up Standard

3.5 Testing Site and Setup

Field measurements were carried out at the Midwest Roadside Safety Facility (MwRSF) at the University of Nebraska-Lincoln (UNL), providing a controlled nighttime environment for systematic testing. The study utilized two types of portable light towers rented from Sunbelt Rentals, featuring LED modules and metal halide lamps to represent commonly used lighting technologies in current construction practice. Table 3.2 presents the technical specifications of each tower, including light source type, power settings, adjustable mounting height ranges, and supplier details. This comparison highlights operational differences between LED and metal halide systems in terms of power density, flexibility, and suitability for nighttime work zone applications. Figure 3.5 shows the site set up.

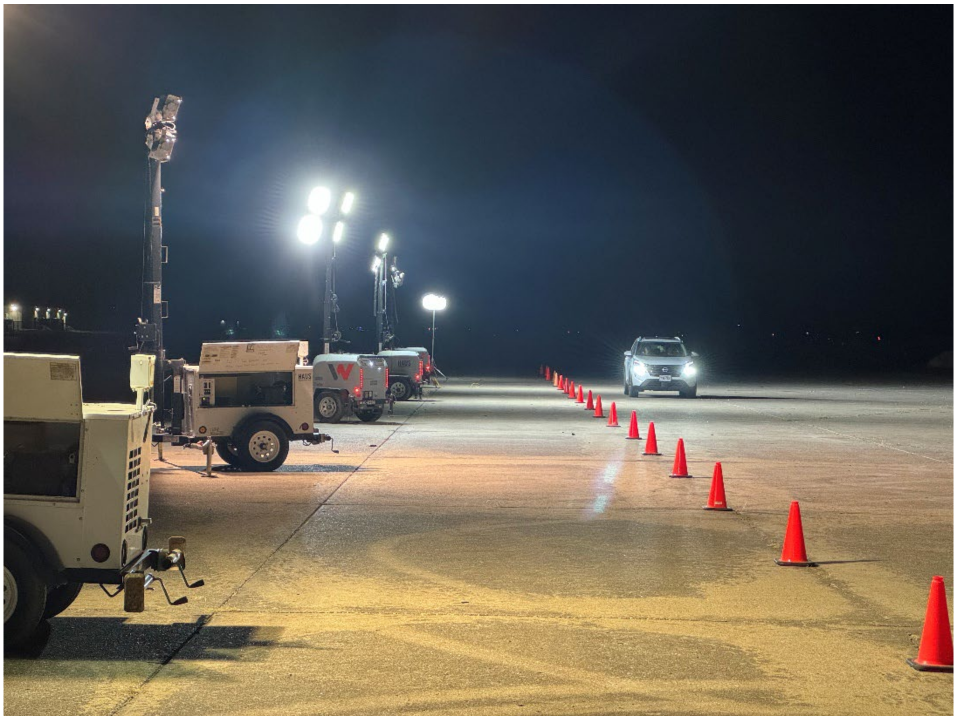


Figure 3.5 Test Site Set Up

Table 3.2 Portable Light Tower Specifications

Equipment Type	Light Source Type	Power Configuration	Mounting Height Range
LED Light Tower	LED Modules	4×1000W	12 - 16ft
Halogen Light Tower	Metal Halide	4×1000W	12 – 16ft
Balloon Light Tower	LED Module	800W	13 ft

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 drivers' and workers' 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

(Illuminating Engineering Society 2022). Figure 3.6 shows an example of the aiming and rotation angles for a light tower; the red arrow indicates the direction of traffic flow. Table 3.3 lists the complete combination of factors used in the experimental design, totaling 126 configurations with the balloon lighting staying stationary as shown in Table 3.4.

Table 3.3 Test Configuration Factor Matrix

Factor	Levels
Light Source Type	LED; Halogen
Mounting Height	12 ft; 14 ft; 16 ft
Aiming Angle	15°; 30°; 45°
Rotation Angle	30°; 45°; 60°; 90°; 120°; 135°; 150°

Table 3.4 Test Configuration Matrix (Balloon Lighting)

Factor	Levels
Light Source Type	Balloon Tower
Mounting Height	13 ft
Aiming Angle	N/A
Rotation Angle	N/A

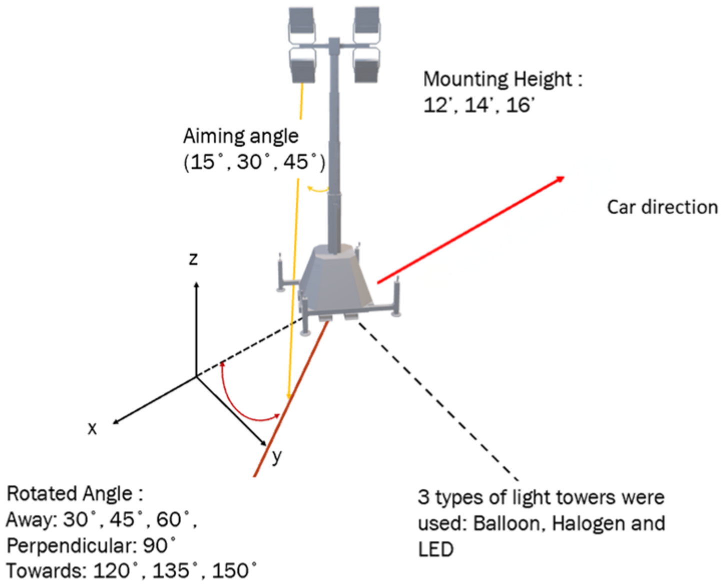


Figure 3.6 Light Tower Configuration

3.6 Nighttime Work Zone Illuminance Levels Assessment

The research team set up a single lane at MwRSF. For all light tower configurations, measurements were taken at 24 points marked by safety cones, with each cone placed at a 15-foot (4.6-meter) interval and each light tower placed 45 feet apart as seen in Figure 3.7 and on site set up as shown in Figure 3.8. Figure 3.9 shows the conceptual three site layouts for a light tower positioned 'away from traffic' (rotation angle less than 90°), 'perpendicular to traffic' (rotation angle equals 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 feet, for a total of 24 measurement points over a 345-foot stretch. The same measurement rule applied to the other two lighting arrangements. Table 3.5 shows the specifications of the equipment used to measure the light tower data.

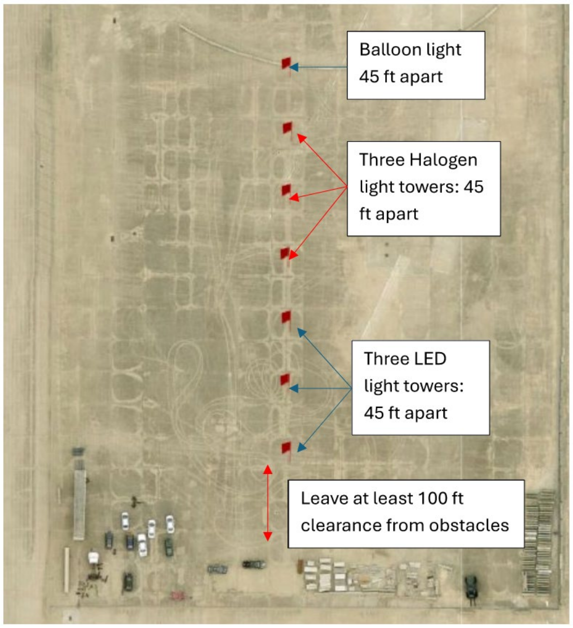


Figure 3.7 Light Tower Full Layout

Figure 3.8 Light Tower on Site Set Up

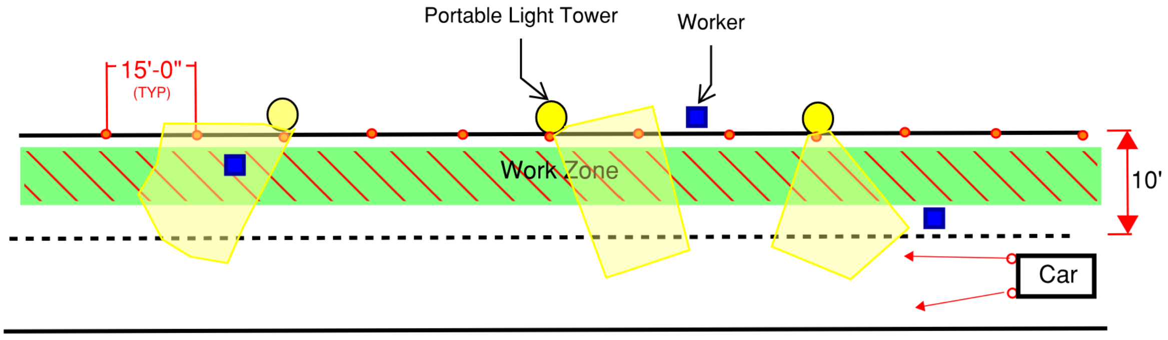


Figure 3.9 Light Tower Set Up Plan

Table 3.5 Measurement Equipment Specifications

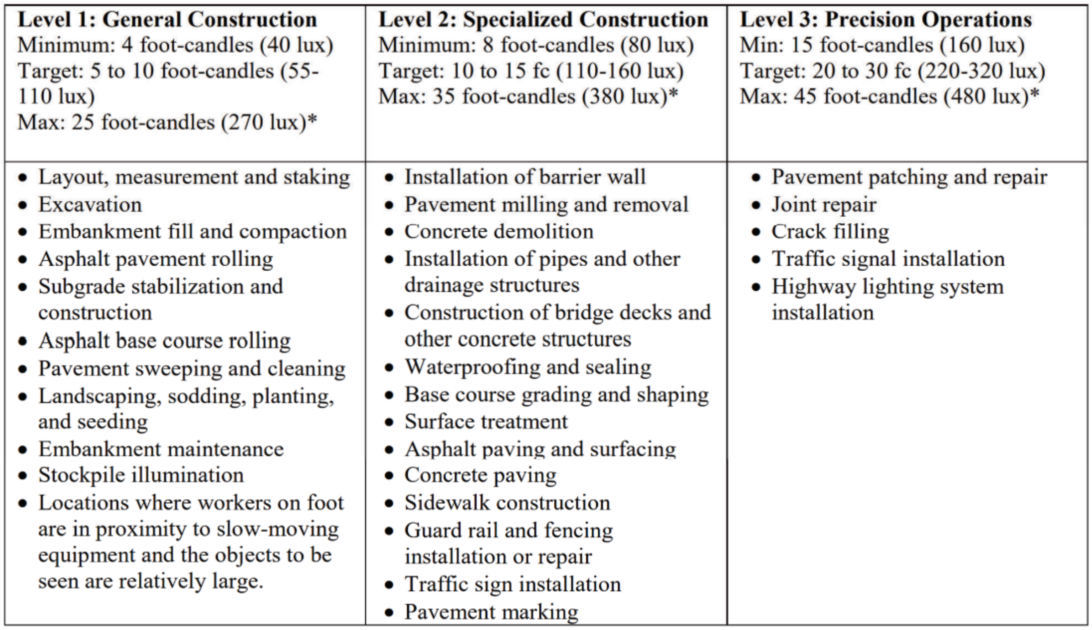
Measurement Type	**Equipment Model**	**Manufacturer**	**Application Perspective**
Pavement Luminance	LS-150 Luminance Meter	Konica Minolta	Driver's Perspective
Vertical Illuminance	Illuminance Meter T-10A	Konica Minolta	Driver's Perspective
Horizontal Illuminance	Illuminance Meter T-10A	Konica Minolta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

Following the guidance in ANSI IES RP 8-22 Chapter 19, Temporary and Work Area Lighting, the Horizontal Illuminance Measurement (Illuminating Engineering Society 2022) was taken from the worker's perspective. The 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 are important for preventing accidents such as collisions, traps and slips.

The measured horizontal illuminance data was evaluated against the classification standard for nighttime construction lighting established by FHWA (2023). Table 3.6 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 3.6 Recommended Illuminance Levels for Highway Worker Task Areas (FHWA 2025)



Level 1: General Construction Minimum: 4 foot-candles (40 lux) Target: 5 to 10 foot-candles (55-110 lux) Max: 25 foot-candles (270 lux)*	**Level 2: Specialized Construction** Minimum: 8 foot-candles (80 lux) Target: 10 to 15 fc (110-160 lux) Max: 35 foot-candles (380 lux)*	**Level 3: Precision Operations** Min: 15 foot-candles (160 lux) Target: 20 to 30 fc (220-320 lux) Max: 45 foot-candles (480 lux)*
• Layout, measurement and staking • Excavation • Embankment fill and compaction • Asphalt pavement rolling • Subgrade stabilization and construction • Asphalt base course rolling • Pavement sweeping and cleaning • Landscaping, sodding, planting, and seeding • Embankment maintenance • Stockpile illumination • Locations where workers on foot are in proximity to slow-moving equipment and the objects to be seen are relatively large.	• Installation of barrier wall • Pavement milling and removal • Concrete demolition • Installation of pipes and other drainage structures • Construction of bridge decks and other concrete structures • Waterproofing and sealing • Base course grading and shaping • Surface treatment • Asphalt paving and surfacing • Concrete paving • Sidewalk construction • Guard rail and fencing installation or repair • Traffic sign installation • Pavement marking	• Pavement patching and repair • Joint repair • Crack filling • Traffic signal installation • Highway lighting system installation

3.7 Glare Assessment Calculation

From 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

3.10. The research team used this diagram to complete the subsequent calculations to measure glare for the driver. The following calculations were performed with reference to IES RP 8-22:

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

$$L_{\mathrm{v}} = \frac{K}{\Theta^{n}} \tag{1}$$

$where$: L_{v}=veiling luminance from one individual luminaire

$n = 2.3 - 0.7\log_{10}(\theta)$ 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 3.10.

$K = 10 \times$ (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.

$$n\theta < 2; n = 2\theta \geq 2\theta$$

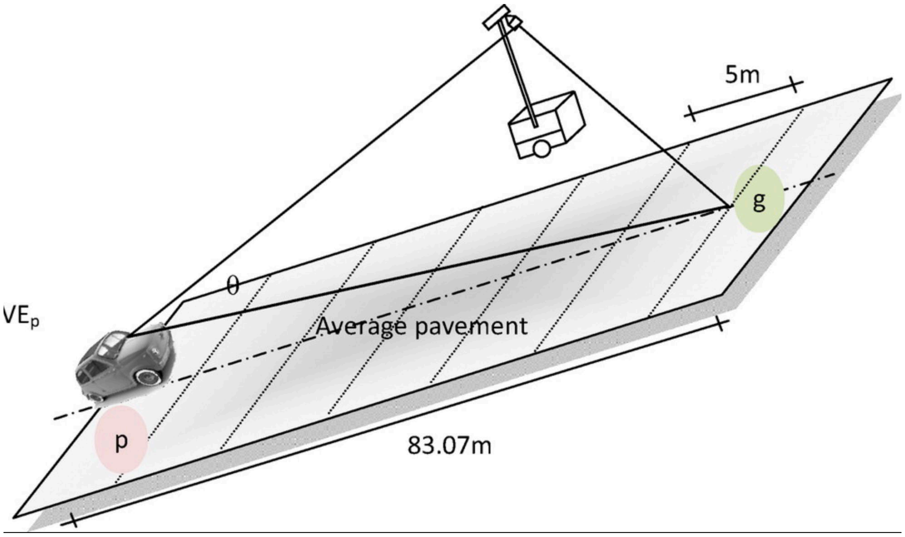


Figure 3.10 Geometry of Observation Angle (IES 2022)

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 meters (3.9 feet)—using an illuminance meter positioned to face the direction of travel.

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

$$\mathrm{VL}_{\mathrm{ratio}} = \frac{\mathrm{L}_v}{L_p} \tag{2}$$

where:

L_v = veiling luminance at the driver's eye produced by the selected luminaire at measurement point calculated by Eq. (1).

L_p = pavement luminance at same measurement point, measured from the driver's perspective with the luminance meters at eye level.

Figure 3.10 also illustrates the proper setup and usage of the LS-150 luminance meter, including its typical installation height (1.2–1.5 meters or 3.9–4.9 feet) and aiming angle (1.5°–2°), which simulate a driver's line of sight. To complete the pavement luminance measurements, the operator was positioned 273 feet 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 simulated driver eye height.

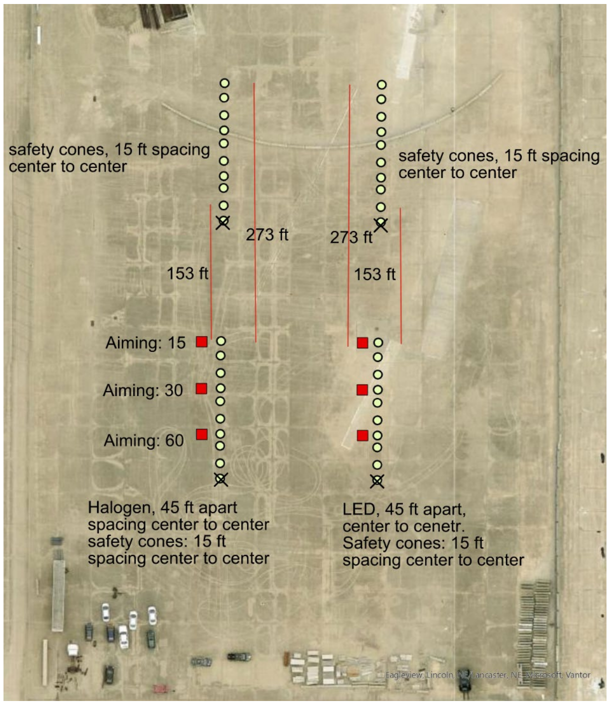


Figure 3.11 Pavement Luminance Measurement Layout

Measurements were taken every 15 feet along a designated path (indicated by the red arrow in Figure 3.11), resulting in a total of seven data points. Throughout the process, the operator maintained a consistent viewing angle of approximately 1.5°–2° relative to the pavement to accurately replicate the visual conditions experienced by motorists and workers in nighttime work zones. Test site photos and conditions are seen in Figure 3.12.

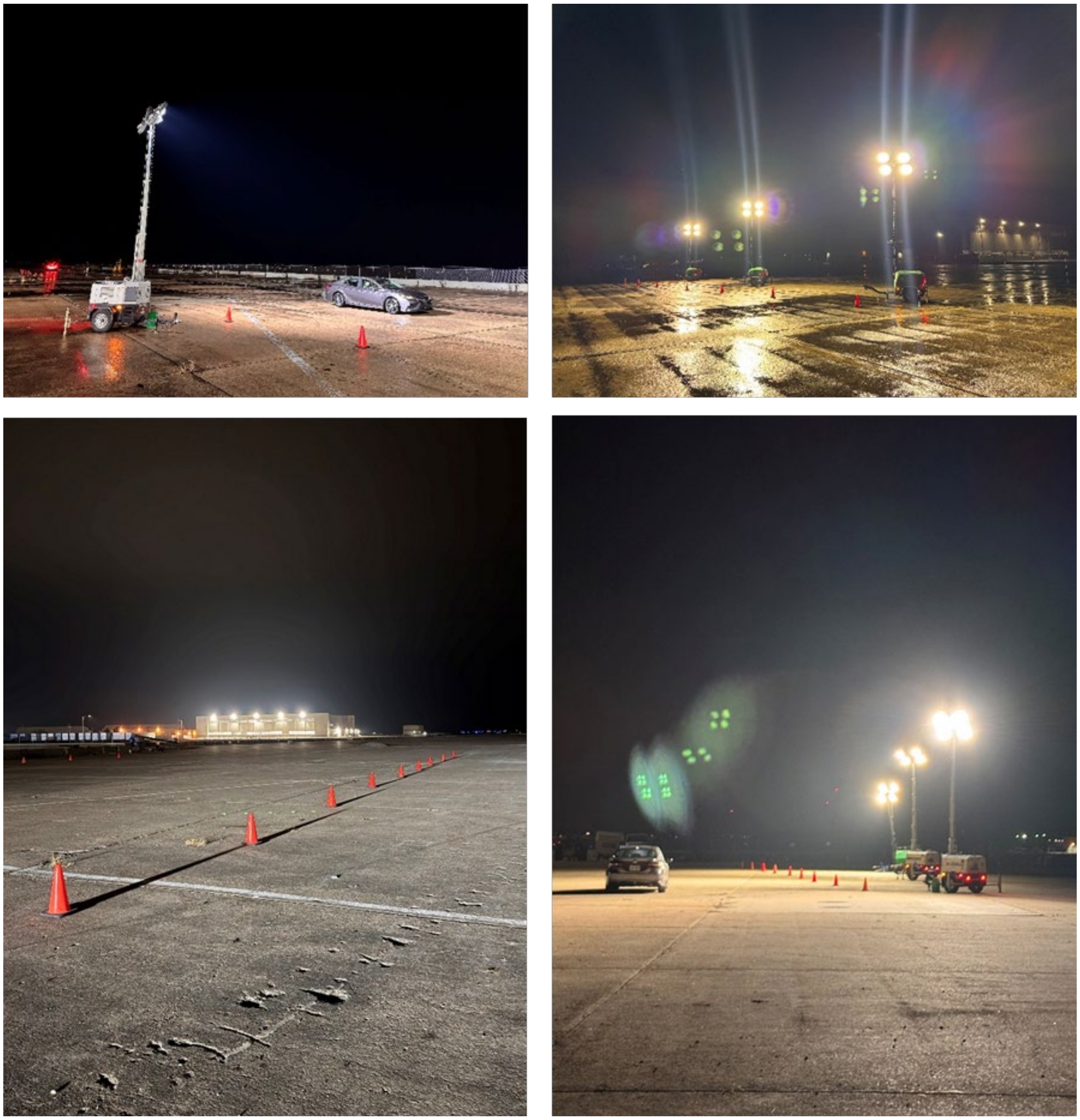


Figure 3.12 Pavement Luminance Test Site Photos

Chapter 4 Results

4.1 Survey results

4.1.1 *Experience with Nighttime Work Zones and Lighting Adequacy*

- **Experience**: Among the 60 respondents, 83% (39 individuals) had prior experience working in nighttime work zones, indicating that most participants were familiar with such environments. Only 17% (8 individuals) lacked experience, suggesting that the majority of responses came from informed individuals (see Figure 4.1).

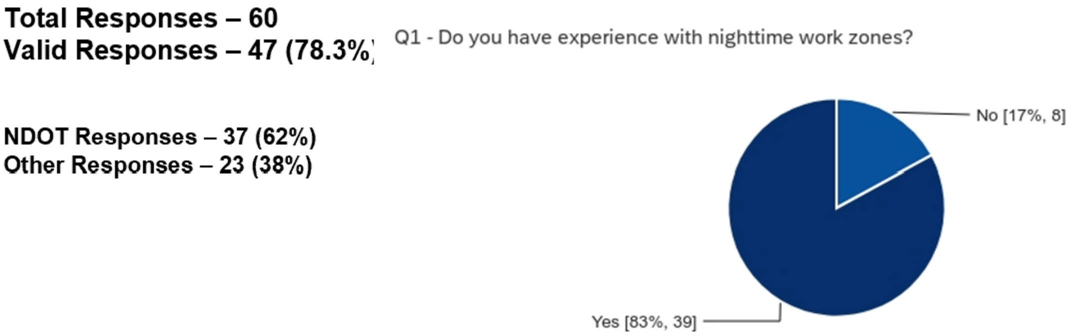


Figure 4.1 Survey Demographic

- **Lighting Adequacy**: Responses showed varied levels of satisfaction regarding lighting adequacy (see Figure 4.2):
    - 48% (22 individuals) rated the lighting as "adequate," implying that while functional, there is potential for improvement.
    - 37% (17 individuals) were less favorable, selecting "neutral" (15 individuals) or "inadequate" (2 individuals).
    - No respondents rated the lighting as "superior" or "unacceptable," indicating an absence of extreme satisfaction or dissatisfaction.

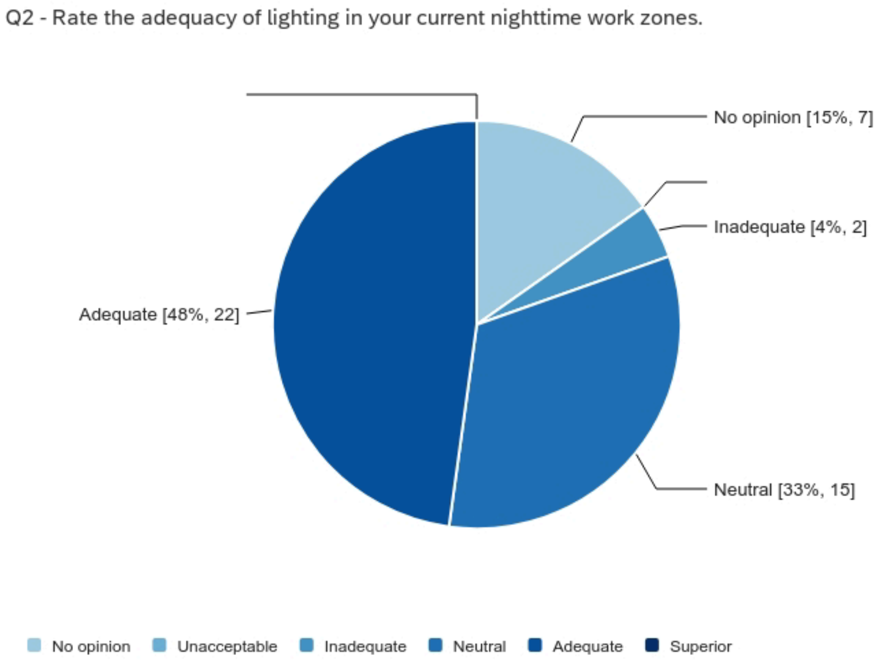
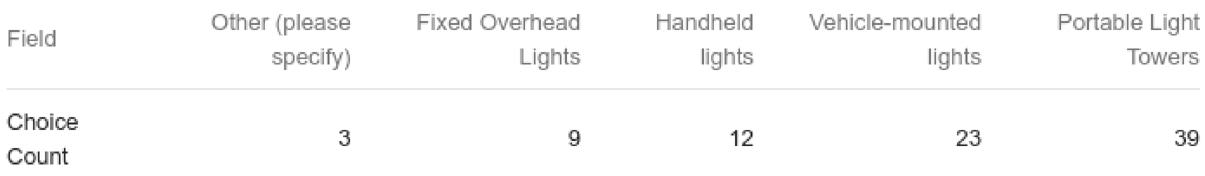


Figure 4.2 Lighting Adequacy Results

4.1.1 Lighting Fixtures and Visibility

- **Lighting Types** (see Figure 4.3):
    - Portable lights were the most used, with 39 respondents indicating their preference, reflecting their convenience and adaptability.
    - Vehicle-mounted lights followed closely, used by 23 respondents, highlighting their practicality for mobile operations.
    - Fixed overhead lights and handheld lights were less frequently used while other respondents noted the use of other lighting types, likely for niche or specialized purposes.

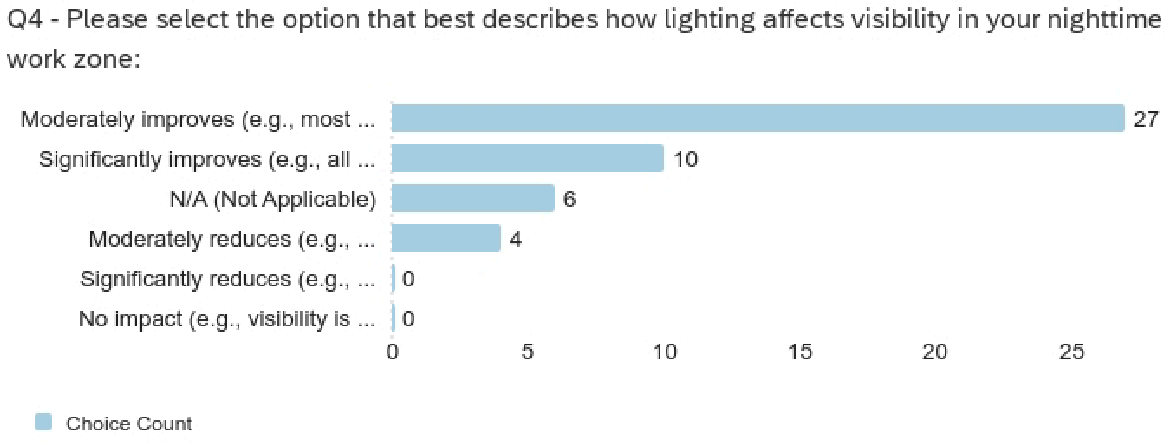


Field	Other (please specify)	Fixed Overhead Lights	Handheld lights	Vehicle-mounted lights	Portable Light Towers
Choice Count	3	9	12	23	39

Figure 4.3 Snapshot of Lighting Type Usage Survey Response

Other responses included Equipment Mounted Light such (i.e cars, excavation machines etc.) which was mentioned twice and one response indicating use of balloon Lighting.

- **Visibility Impact** (see Figure 4.4):
    - 27 respondents reported that lighting "moderately improved" visibility, suggesting its general effectiveness, though not optimal.
    - 10 respondents noted "significant improvement," indicating instances where lighting exceeded expectations.
    - 10 respondents observed "no impact" or negative effects, and one respondent found the question "not applicable."



Q4 - Please select the option that best describes how lighting affects visibility in your nighttime work zone:

Figure 4.4 Lighting Effect on Visibility in Work Zones Response

4.1.2 Lighting's Role in Injury Prevention

- **Lighting's Contribution to Injury Prevention** (see Figure 4.5):
    - 30% of respondents rated lighting as "moderately effective" in preventing injuries, indicating that while it helps reduce risks, additional safety measures may be necessary.
    - 38% regarded it as "very effective" or "extremely effective," highlighting the significant role lighting plays in worker safety.
    - Importantly, no respondents rated lighting as "not effective at all," underscoring its importance in safety protocols.

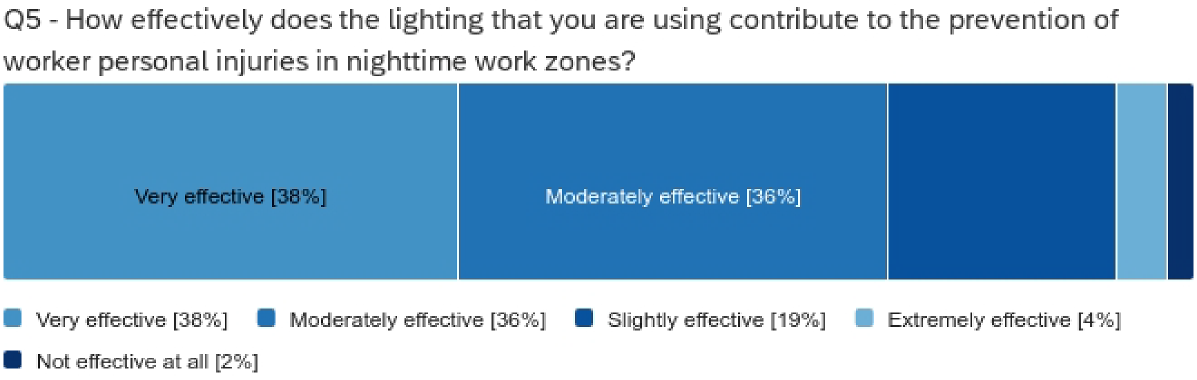
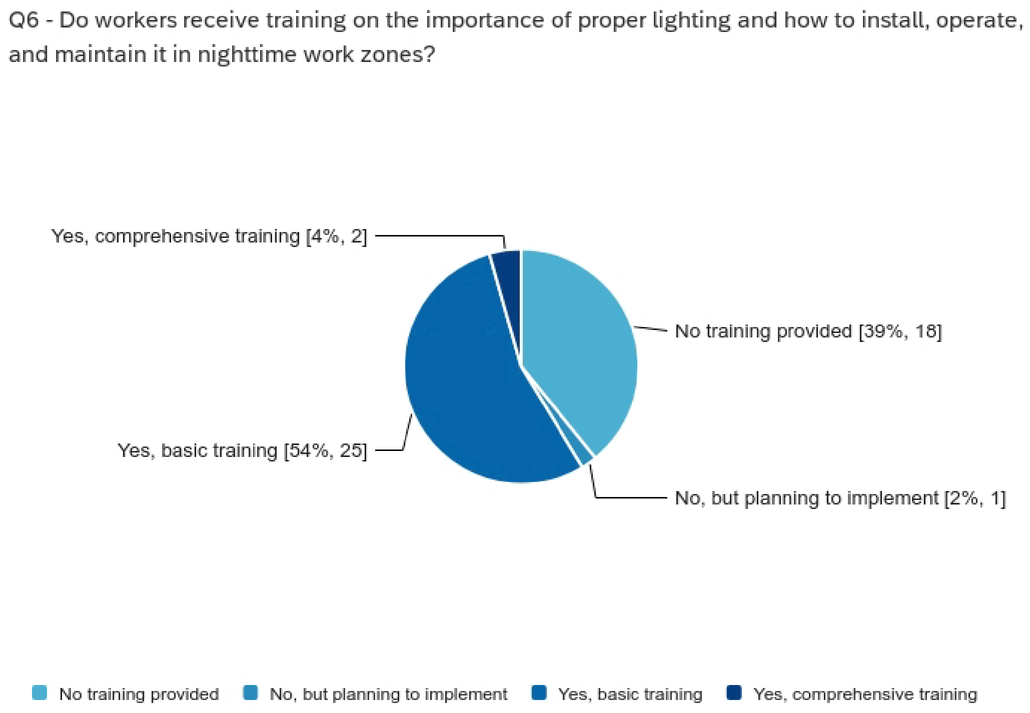


Figure 4.5 Effectiveness of Existing Lighting on Prevention of Injuries

4.1.3 Training and Suggested Improvements

- **Training** (see Figure 4.6):
    - 54% reported receiving basic training on lighting use and maintenance, while 4% received comprehensive training.

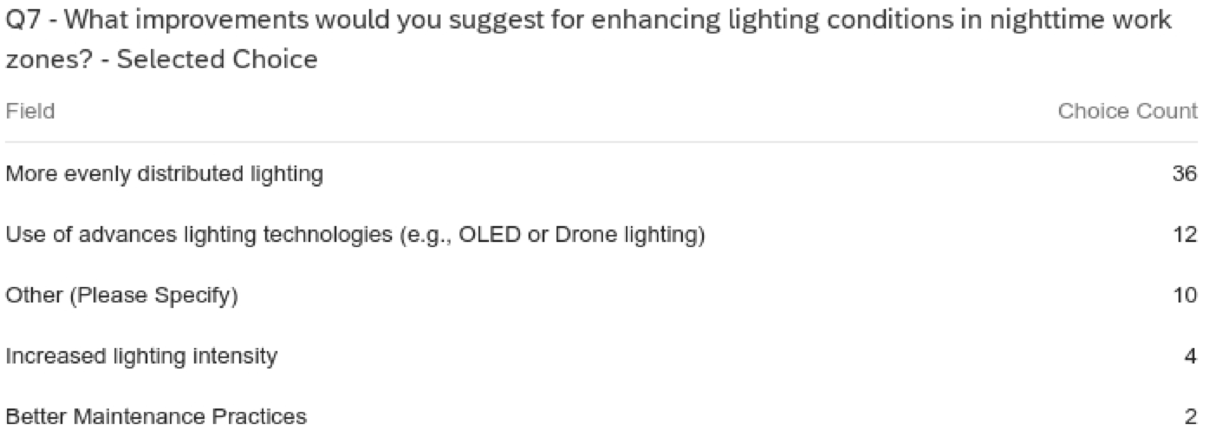
    - 39% indicated no training had been provided, and 2% mentioned plans to implement training, suggesting that some organizations may still have gaps in training provision.



Q6 - Do workers receive training on the importance of proper lighting and how to install, operate, and maintain it in nighttime work zones?

Figure 4.6 Working Training Results

- **Improvements** (see Figure 4.7):
    - The most common suggestion for improvement (36 respondents) was more evenly distributed lighting to address visibility hazards from uneven lighting patterns.
    - 12 respondents highlighted the potential for advanced technologies to modernize lighting systems.
    - Other recommendations included increased lighting levels (4 respondents), better maintenance (2 respondents) and additional suggestions (10 respondents).



Q7 - What improvements would you suggest for enhancing lighting conditions in nighttime work zones? - Selected Choice

Field	Choice Count
More evenly distributed lighting	36
Use of advances lighting technologies (e.g., OLED or Drone lighting)	12
Other (Please Specify)	10
Increased lighting intensity	4
Better Maintenance Practices	2

Figure 4.7 Improvements for Enhancing Conditions Response

Other Suggestions Included:

- Higher lights to avoid workers' eyes (2 responses)
- Individual worker lighting systems (2 responses)
- Better equipment lighting (1 response)
- Phased Temp Lighting (1 response

4.1.5 Impact on Public and Worker Safety

- **Reports of Public Impact** (see Figure 4.8):
  - 46% (13 respondents) reported no issues, such as glare, affecting the traveling public.
  - 24% (7 respondents) noted a few or some isolated reports of adverse effects, indicating that these problems may require further attention.
  - 26% Reported some reports.

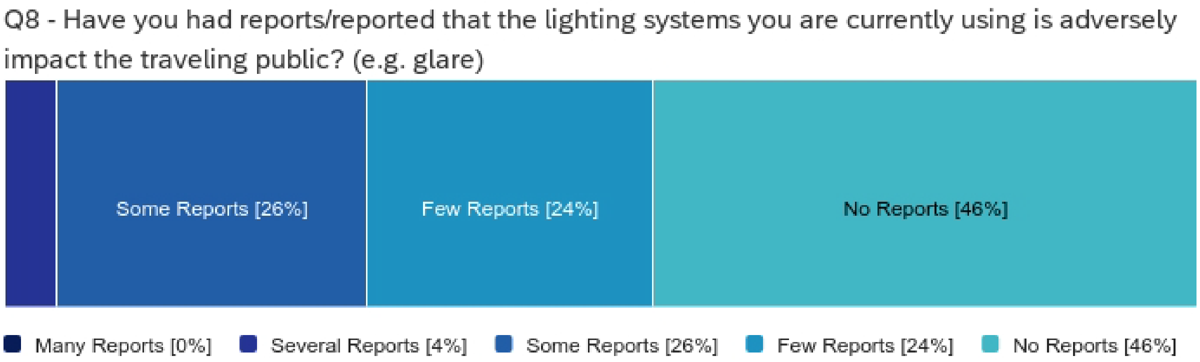


Figure 4.8 Reports of Glare from Lighting Systems

- **Worker Safety Satisfaction** (see Figure 4.9):
    - A majority of respondents expressed positive sentiments about worker safety under the current lighting conditions:
        - 43% were "somewhat satisfied."
        - 37% were neutral, suggesting potential areas for improvement.
        - 13% were "somewhat dissatisfied," while 2% (1 respondent) were "extremely satisfied."

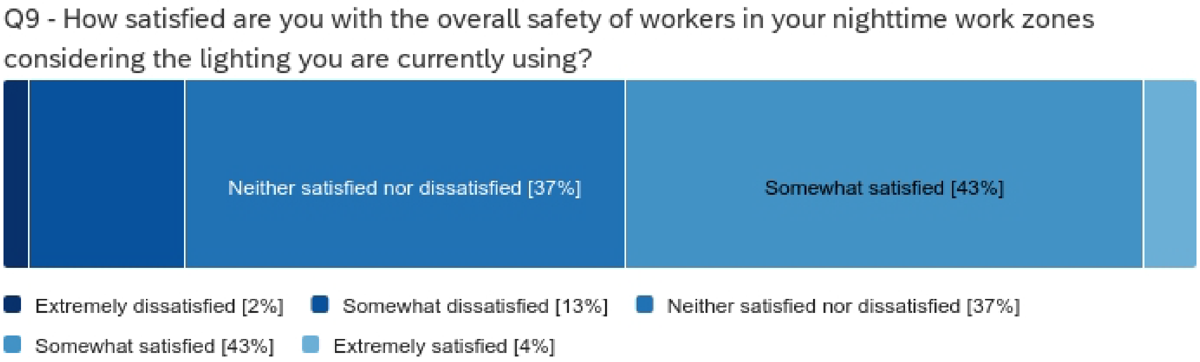


Figure 4.9 Worker Safety Satisfaction Survey Results

With 52% of all respondents neutral or dissatisfied, current practices have room for improvement.

4.1.6 Measure for Proper Lighting

- **Ensuring Proper Lighting** (see Figure 4.10):
    - Worker feedback (55%) and adherence to contract specifications (65%) were the most commonly used strategies, underscoring the importance of incorporating insights from frontline workers and meeting project requirements.
    - Compliance with lighting standards and conducting regular inspections were each employed by 40% (8 respondents), indicating the value of oversight and adherence to regulations.
    - Less frequently used measures included "other strategies" (35%) and the use of "checklists" (10%).

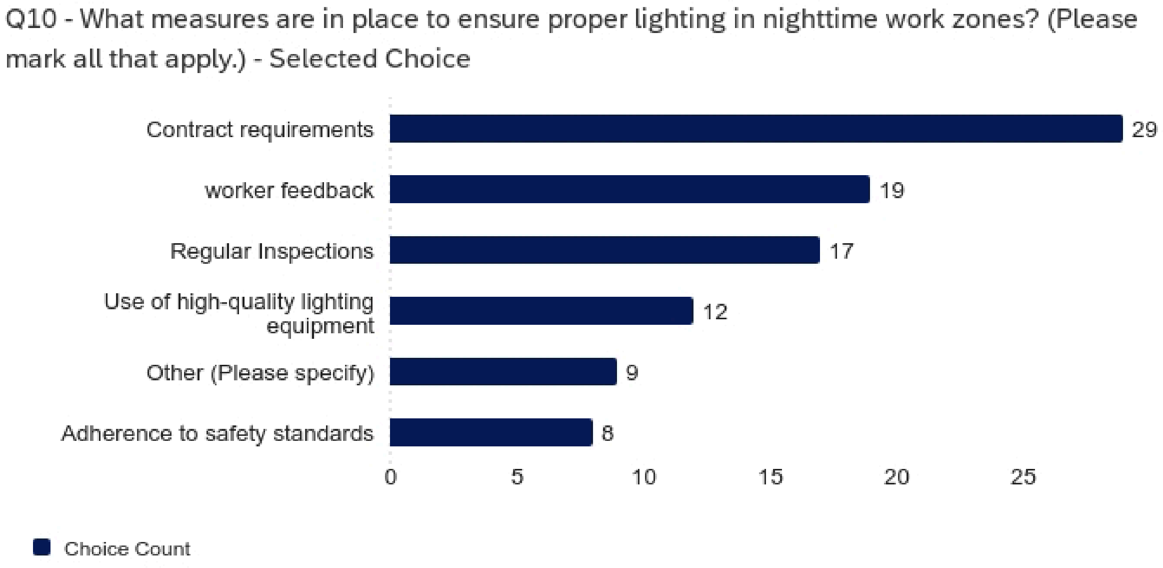


Figure 4.10 Measures for Proper Lighting Survey Results

No documents were submitted to showcase current rules and regulations being used in the State.

4.2 Field Test Analysis

This study conducted field experiments to evaluate the performance of lighting systems in nighttime work zones, considering both worker and driver perspectives. The experiments systematically varied rotational angle, mounting height, aiming angle, and light source type, producing a comprehensive set of configurations to simulate realistic nighttime work zone conditions.

Lighting Parameters and Configurations:

- Rotational Angles:
  - Away from traffic: 30°, 45°, 60°
  - Perpendicular to traffic: 90°
  - Towards traffic: 120°, 135°, 150°
- Light Sources:
  - LED light towers
  - Halogen light towers
  - Balloon tower (fixed height, rotational angle, and aiming angle; used as a baseline)
- Mounting Heights: 12’, 14’, 16’
- Aiming Angles: 15°, 30°, 45°
- Tower Arrangement and Measurement Layout:
  - Each test configuration included seven towers:
    1. LED – Away
    2. LED – Perpendicular

        3. LED – Towards
        4. Halogen – Away
        5. Halogen – Perpendicular
        6. Halogen – Towards
        7. Balloon – fixed setup
    - Measurements were taken at 15-foot intervals along the lane to capture horizontal and vertical illuminance for both driver and worker perspectives.
- Driver metrics: vertical and horizontal illuminance at eye level, used to assess glare according to IES RP-8-22.
- Worker metrics: horizontal and vertical illuminance at ground level, used to evaluate task visibility based on FHWA guidelines.

The balloon tower acted as a reference light source, remaining constant across all measurements to provide a baseline for comparison with LED and halogen towers.

- Total lighting configurations: 7 rotational angles × 3 aiming angles × 3 mounting heights × 3 light types = 189 configurations
- Total data points collected: 7 measurement points × 3 heights × 3 aiming angles × 7 rotational angles × 3 light sources = 3,087 points
- Each measurement was performed under controlled nighttime conditions, with ambient illuminance below 0.1 lux.

Summary Metrics:

- Driver glare: assessed via veiling luminance ratio (IES RP-8-22).
- Worker brightness: quantified as horizontal and vertical illuminance at ground level (FHWA technical report guidance).

This setup provides a systematic and comprehensive dataset to evaluate the impact of different lighting configurations on visibility and glare in nighttime work zones, supporting both safety assessments and optimization of lighting strategies.

4.3 Evaluation Metrics and Standards

As illustrated in Figure 4.11, this study used two main metrics to evaluate lighting performance: Horizontal Illuminance (Eh) and Veiling Luminance Ration ($\mathrm{VL}_{\mathrm{ratio}}$).

Horizontal Illuminance (Eh)

Based on the FHWA-HRT-08-018 report, the following evaluation criteria were established against workers' visibility:

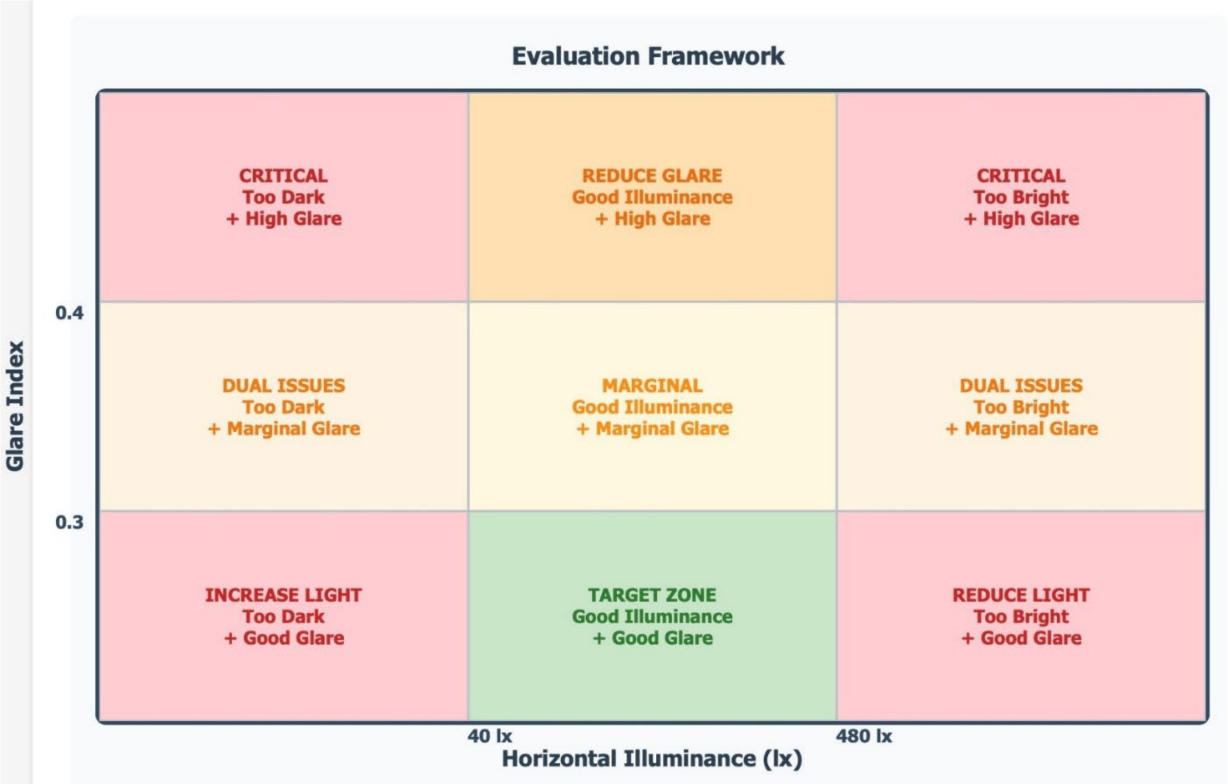
- Eh < 40 lux: Insufficient illuminance
- 40 ≤ Eh ≤ 480 lux: Appropriate illuminance
- Eh > 480 lux: Excessive illuminance

Veiling Luminance Ratio (VL_{ratio})

Based on the IES RP-8-22 standard, the following thresholds were used against motorists' perception of hazardous glare:

- $\mathrm{VL}_{\mathrm{ratio}} < 0.3$: Acceptable glare
- $0.3 \leq \mathrm{VL}_{\mathrm{ratio}} \leq 0.4$: Marginally acceptable glare
- $\mathrm{VL}_{\mathrm{ratio}} > 0.4$: Unacceptable glare

The Veiling Luminance Ratio is calculated by equation (2). Figure 4.11 shows a visual matrix of how target zone was analyzed.



Evaluation Framework

CRITICAL Too Dark + High Glare	REDUCE GLARE Good Illuminance + High Glare	CRITICAL Too Bright + High Glare
DUAL ISSUES Too Dark + Marginal Glare	MARGINAL Good Illuminance + Marginal Glare	DUAL ISSUES Too Bright + Marginal Glare
INCREASE LIGHT Too Dark + Good Glare	TARGET ZONE Good Illuminance + Good Glare	REDUCE LIGHT Too Bright + Good Glare

Figure 4.11 Glare and Illuminance Framework Matrix

4.4 Field Test Results

4.4.1 Overall Performance

A total of 189 configurations were evaluated against the two Eh and VLR standards. The overall results indicated a clear challenge in achieving compliance: There was a limit in safe configurations fully available due to the nature of the lights.

4.4.2 Worker Glare

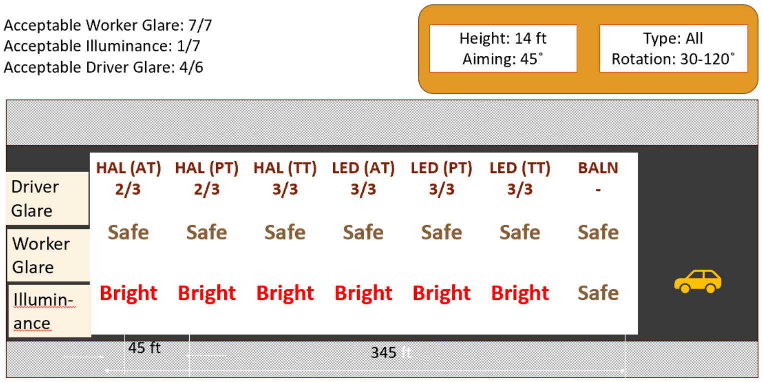
Worker glare was evaluated using the same photometric framework; however, measurements indicated no significant differentiation between worker glare from approaching vehicle headlights and surrounding lighting. As a result, driver glare (VL ratio) was treated as the controlling safety criterion.

4.4.3 Multiple Hazards Demonstration:

In the multiple hazards demonstration, as shown by Figure 4.12, despite worker glare being safe, all light sources produced horizontal illuminance measurments that were above the threshold of 480 and hence were too bright. Exact Lux measurements at each light tower are shown in Table 4.1 with the green highlighted cell showing the balloon light as the only acceptable light source in this configuration set up. This configuration is generally safe for glare (both workers and drivers) but fails illumination standards due to excessive brightness. It demonstrates how a setup can be glare-safe yet still create a brightness hazard.

Table 4.1 Unsafe Configuration Setting

Distance (ft)	**Source**	**Horizontal illuminance (Lux)**
45	Ballon light	87
90	LED light tower	1720
135	LED light tower	2610
180	LED light tower	1535
225	Halogen	498
270	Halogen	554
315	Halogen	952



Acceptable Worker Glare: 7/7
Acceptable Illuminance: 1/7
Acceptable Driver Glare: 4/6

Height: 14 ft
Aiming: 45˚

Type: All
Rotation: 30-120˚

	HAL (AT)	HAL (PT)	HAL (TT)	LED (AT)	LED (PT)	LED (TT)	BALN
Driver Glare	2/3	2/3	3/3	3/3	3/3	3/3	-
Worker Glare	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Illumin-ance	Bright	Bright	Bright	Bright	Bright	Bright	Safe

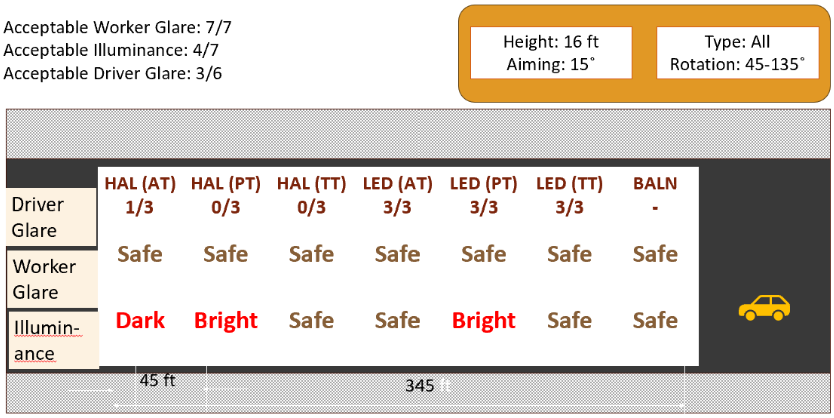
Figure 4.12 Unsafe Configuration Set Up

4.4.4 Tolerance Demonstration example

The Tolerance Demonstration in Figure 4.13 shows a scenario in which 2/7 sets ups were too bright while 1/7 was too dull. Table 4.2 below shows exact measurements, color coded to compliance to code with green being good, red being unacceptable and yellow being acceptable. This setup shows moderate tolerance. It performs well for worker glare but has inconsistent illuminance and driver glare outcomes, depending on light type and orientation. LED generally performs better than halogen under this configuration.

Table 4.2 Tolerant Configuration Setting

Distance (ft)	**Source**	**Horizontal illuminance (lux)**
45	Ballon light	264
90	LED light tower	460
135	LED light tower	592
180	LED light tower	156.2
225	Halogen	342
270	Halogen	513
315	Halogen	34.8



Acceptable Worker Glare: 7/7
Acceptable Illuminance: 4/7
Acceptable Driver Glare: 3/6

Height: 16 ft
Aiming: 15˚

Type: All
Rotation: 45-135˚

	HAL (AT)	HAL (PT)	HAL (TT)	LED (AT)	LED (PT)	LED (TT)	BALN
Driver Glare	1/3	0/3	0/3	3/3	3/3	3/3	-
Worker Glare	Safe	Safe	Safe	Safe	Safe	Safe	Safe
Illumin-ance	Dark	Bright	Safe	Safe	Bright	Safe	Safe

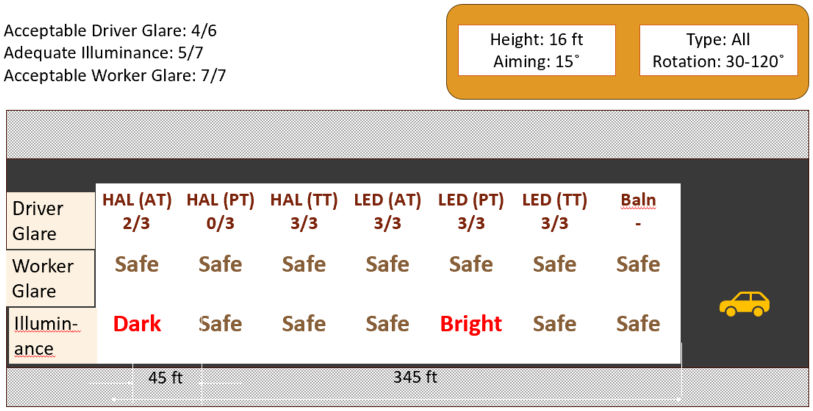
Figure 4.13 Tolerant Configuration Set Up

4.4.5 Safe Configuration

In the safest configuration demonstrated in Figure 4.14, 5/7 setups were good for illuminance, and all were good for worker glare control. Table 4.3 shows exact lux readings at each individual light tower emphasizing 5 lighting set ups were within standards as seen highlighted in green, 1 set up was within margin as highlighted in yellow, and 1 was unsafe as highlighted in red. This is a balanced and generally safe configuration, achieving acceptable performance across all three safety metrics (worker glare, driver glare, and illuminance). It represents some of the best overall trade-off among the tested scenarios.

Table 4.3 Safe Configuratiion Setting

Distance (ft)	**Source**	**Horizontal illuminance (lux)**
45	Ballon light	320
90	LED light tower	462
135	LED light tower	580
180	LED light tower	223
225	Halogen	365
270	Halogen	369
315	Halogen	25.7



Acceptable Driver Glare: 4/6
Adequate Illuminance: 5/7
Acceptable Worker Glare: 7/7

Height: 16 ft
Aiming: 15˚

Type: All
Rotation: 30-120˚

Driver Glare	**HAL (AT)** **2/3**	**HAL (PT)** **0/3**	**HAL (TT)** **3/3**	**LED (AT)** **3/3**	**LED (PT)** **3/3**	**LED (TT)** **3/3**	**Baln** **-**
Worker Glare	**Safe**	**Safe**	**Safe**	**Safe**	**Safe**	**Safe**	**Safe**
Illumin-ance	**Dark**	**Safe**	**Safe**	**Safe**	**Bright**	**Safe**	**Safe**

Figure 4.14 Safe Configuration Set Up

4.5 Illuminance

Halogen lighting consistently achieved illuminance levels closer to recommended standards across all coverage areas, outperforming both LED and balloon lighting in terms of meeting minimum safety thresholds. Balloon lighting, while commonly referenced in standards, exhibited a lower overall coverage area, which may limit its effectiveness in larger or irregularly shaped work zones. LEDs, on the other hand, produced extremely high brightness at the source, often exceeding optimal levels, but provided better uniformity across extended coverage areas. This characteristic makes LED lighting particularly advantageous for maintaining consistent illuminance across wider zones, though careful calibration is needed to avoid localized over-illumination. Figures 4.15 and 4.16 show the illuminance contour maps for a single LED and Halogen light tower

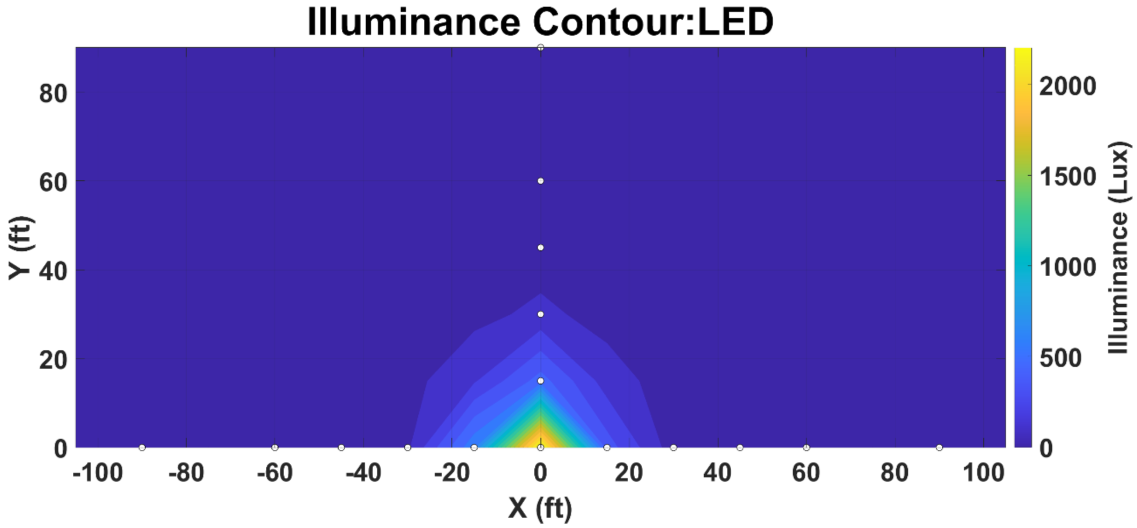


Figure 4.15 Illuminance For a Single LED Light Tower

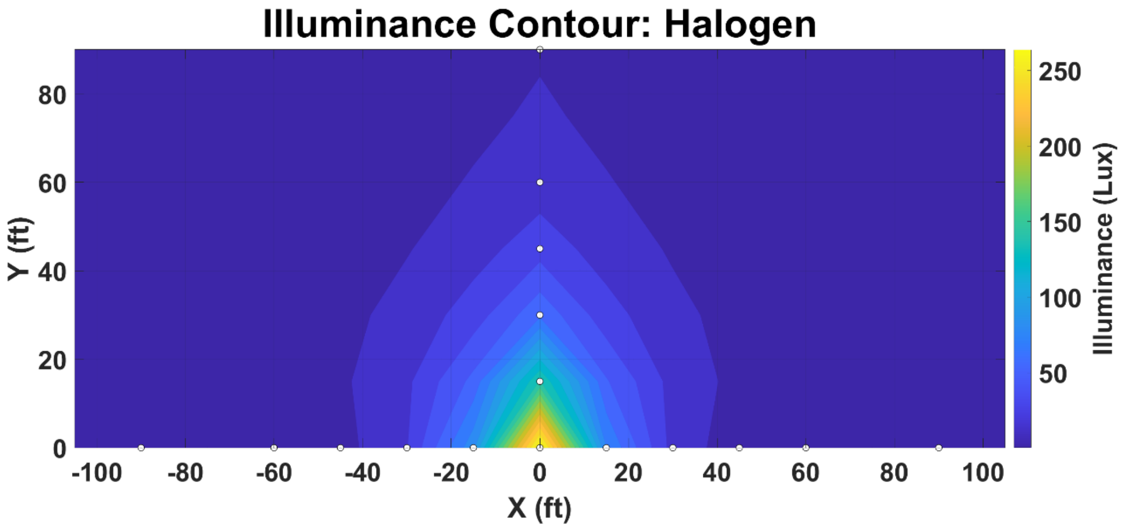


Figure 4.16 Illuminance For a Single Halogen Light Tower

4.6 Driver Glare

In terms of glare, LED lighting outperformed halogen and balloon lights, producing less visual discomfort for both workers and motorists. Although all three lighting types exhibited limited impact on glare, their performance allows for flexible field deployment, particularly when adjusting orientation and mounting height. Managing glare remains critical because excessive brightness or improper angles can compromise safety, even when illuminance levels meet recommended standards.

4.6.1 LED Glare

The glare performance of the LED luminaire was evaluated across multiple rotation angles (30° to 150°), mounting heights (12, 14, and 16 ft), observer distances, and aiming angles (15°, 30°, and 45°). Glare acceptability was assessed using the veiling luminance ratio (VL ratio), with values ≤ 0.30 considered acceptable, 0.30–0.40 marginally acceptable, and > 0.40 unacceptable.

4.6.2 Overall Trends

Across all test conditions, VL ratio increased systematically with luminaire rotation angle, indicating a strong sensitivity of glare to horizontal orientation. Configurations with rotation angles ≤ 60° were predominantly within the acceptable range, whereas angles ≥ 90° frequently exceeded the acceptable threshold and entered the unacceptable range. Mounting height and aiming angle were found to significantly influence glare outcomes, with higher mounting heights generally improving acceptability.

Low Rotation Angles (30°–60°)

At rotation angles of 30°, 45°, and 60°, the majority of VL ratios across all mounting heights and aiming angles fell within the acceptable (green) range. Average VL ratios at these orientations were consistently below 0.30, particularly at 14 ft and 16 ft mounting heights, indicating minimal veiling luminance contribution under forward-facing configurations.

Marginal (yellow) cases were occasionally observed at 12 ft mounting height with shallow aiming angles, but these were limited in magnitude and frequency. No persistent red (unacceptable) glare conditions were observed within this rotation range.

4.6.3 Moderate Rotation Angles (90°)

At a 90° rotation angle, glare performance degraded noticeably. While some configurations—particularly at higher mounting heights (16 ft) and longer observer distances—remained within or near the acceptable range, a substantial number of VL ratios entered the marginal (0.30–0.40) range.

Unacceptable glare conditions (VL ratio > 0.40) became evident at lower mounting heights (12 ft) and under steeper aiming angles, suggesting increased direct exposure of luminance toward the driver's line of sight.

4.6.4 High Rotation Angles (120°–150°)

Rotation angles of 120°, 135°, and 150° exhibited the poorest glare performance overall. Under these conditions, VL ratios frequently exceeded 0.40, indicating unacceptable glare levels (red) for a majority of scenarios.

Even at 16 ft mounting height, many configurations remained only marginally acceptable or unacceptable, especially for shorter observer distances and aiming angles of 15° and 30°. Average VL ratios at these rotation angles were consistently higher than at lower angles, confirming that extreme lateral or rear-oriented luminaire placement poses significant glare risks.

4.6.5 Influence of Mounting Height

Mounting height had a mitigating effect on glare across all rotation angles. Increasing the mounting height from 12 ft to 16 ft generally reduced VL ratios, shifting several marginal or unacceptable cases into the acceptable range at low and moderate rotation angles. However, at rotation angles ≥ 120°, the benefit of increased mounting height was insufficient to fully counteract the elevated glare potential.

4.6.6 Influence of Aiming Angle

For a given rotation angle and mounting height, larger aiming angles (45°) typically resulted in lower VL ratios compared to shallow aiming angles (15°). This trend was most pronounced at lower rotation angles, where appropriate aiming effectively controlled direct luminance toward the observer. At higher rotation angles, however, aiming adjustments alone could not prevent unacceptable glare levels in many cases.

4.6.7 Key Findings

- Acceptable glare performance (VL ≤ 0.30) is generally achieved at rotation angles ≤ 60°, particularly when combined with mounting heights ≥ 14 ft.

- Marginal glare (0.30–0.40) becomes common at 90° rotation, especially at lower mounting heights.
- Unacceptable glare (VL > 0.40) predominates at rotation angles ≥ 120°, regardless of mounting height or aiming angle.
- Increasing mounting height and aiming angle reduces glare but cannot fully compensate for excessive rotation angles.

4.7 Halogen Glare

The glare performance of the halogen headlamp system was evaluated for a range of rotation angles (30° to 150°), mounting heights (12, 14, and 16 ft), observer distances, and aiming angles (15°, 30°, and 45°). Glare acceptability was assessed using the veiling luminance ratio (VL ratio). Values ≤ 0.30 were considered acceptable, values between 0.30 and 0.40 marginally acceptable, and values > 0.40 unacceptable.

4.7.1 Overall Glare Trends

Evaluation results indicate that rotation angle was the primary factor influencing halogen glare performance. Acceptable VL ratios were concentrated at low and some extreme rotation angles, while intermediate rotation angles resulted in a high frequency of unacceptable glare conditions. Across all configurations, more than half of the evaluated VL ratios exceeded the acceptable threshold, demonstrating the sensitivity of halogen glare performance to horizontal orientation. Variations in mounting height and aiming angle influenced VL ratio values but did not override the dominant effect of rotation angle.

4.7.2 Low Rotation Angles (30°–60°)

At a 30° rotation angle, all evaluated conditions produced VL ratios within the acceptable range, indicating minimal glare exposure under forward-facing configurations.

At 45° and 60° rotation angles, a notable reduction in glare performance was observed. Approximately 26–30% of VL ratios remained acceptable, while more than half of the evaluated conditions exceeded the unacceptable threshold. A limited number of marginal cases were observed, primarily at 45°, but these did not represent the dominant condition. These results indicate that even moderate deviations from forward-facing orientation can result in elevated glare levels for halogen headlamps.

4.7.3 Moderate Rotation Angle (90°)

At a 90° rotation angle, glare performance degraded substantially. Approximately three-quarters of VL ratios exceeded 0.40, indicating unacceptable glare under most evaluated configurations. Acceptable VL ratios were primarily associated with higher mounting heights and favorable aiming conditions. Marginal conditions were infrequent, suggesting a rapid transition from acceptable to unacceptable glare as rotational exposure increased.

4.7.4 High Rotation Angles (120°–150°)

At rotation angles of 120°, 135°, and 150°, glare performance remained generally poor. At 120°, nearly 75% of VL ratios were classified as unacceptable, with the remaining values primarily within the acceptable range and few marginal cases observed.

At 135° and 150°, a partial improvement in glare performance was observed relative to intermediate rotation angles. Approximately 55–60% of VL ratios met the acceptable criterion, while 40–45% remained unacceptable, indicating that glare reduction at extreme rotation angles was incomplete and configuration-dependent.

4.7.5 Effect of Mounting Height

Increasing mounting height from 12 ft to 16 ft generally resulted in reduced VL ratios across all rotation angles. At low and moderate rotation angles, increased mounting height shifted some conditions from unacceptable to acceptable ranges. However, at rotation angles ≥ 90°, the reduction in glare associated with increased mounting height was insufficient to consistently achieve acceptable VL ratios.

4.7.5.1 Effect of Aiming Angle

For a given rotation angle and mounting height, larger aiming angles (30° and 45°) generally produced lower VL ratios compared to shallow aiming angles (15°). This effect was most evident at low rotation angles. At higher rotation angles, adjustments to aiming angle alone were not sufficient to prevent unacceptable glare conditions in many cases.

4.7.6 Summary of Key Findings

- Acceptable glare performance (VL ≤ 0.30) was consistently observed at a 30° rotation angle.
- Intermediate rotation angles (45°–120°) produced the highest frequency of unacceptable glare, with 55–74% of VL ratios exceeding 0.40.
- Marginal glare conditions were infrequently observed, indicating limited transitional behavior between acceptable and unacceptable states.
- Increased mounting height and larger aiming angles reduced VL ratios, but did not fully mitigate glare at high rotation angles.
- Rotation angle was identified as the dominant factor governing halogen glare performance across the evaluated configurations.

4.8 Effect of Rotation and Height

Increasing the light tower height improves illumination uniformity and reduces localized areas of excessive brightness that may contribute to glare. When the tower height increases from 12 ft to 16 ft, the maximum measured illuminance decreases from approximately 1,986 lux to

1,114 lux, representing a reduction of about 44%. This indicates that greater mounting heights help distribute light more evenly across the work area.

Certain directional angles consistently produce higher illuminance levels regardless of tower height. The largest exceedances occur near 90°, 135°, 180°, 210°, 255°, and 270°. These directions remain the primary sources of over-bright areas across all tested heights; however, the magnitude of these peaks decreases as tower height increases.

The rotational angle of the light tower also influences lighting performance. At a fixed height, a 30° rotation produces the highest average horizontal illuminance across the measurement area. A 60° rotation produces the highest peak intensities at lower mounting heights, particularly near 135°. At 16 ft, the differences between the three rotations (30°, 45°, and 60°) become less pronounced, with peak values converging near 1,100 lux.

Overall hazard levels can be mitigated or increased depending on the mounting height and rotational angle of the lighting tower. The measurements showed that luminous flux is generally higher at lower mounting heights and decreases as the height increases.

Performance also varied by lighting type. LED lighting performed well at lower mounting heights, producing strong localized illumination and good coverage. Halogen lighting showed minimal change with variations in height or rotation, indicating limited adaptability under different configurations. Balloon lighting provided relatively consistent illumination coverage regardless of rotational angle, although it was less effective at producing higher illumination levels at increased mounting heights.

Compliance with the target illumination range (40–480 lux) remained relatively consistent across configurations, with approximately 50–63% of measurement points falling within the acceptable range. However, when the tower height was 16 ft, measurements exceeding the maximum threshold were closer to the allowable limit, indicating reduced glare severity compared with the 12 ft configuration.

Figures 4.17, 4.18, and 4.19 illustrate the effects of rotational angle and mounting height on illumination levels. In these figures, the red shaded areas represent measurements exceeding the recommended illumination range, while the green shaded areas represent measurements within the acceptable range.

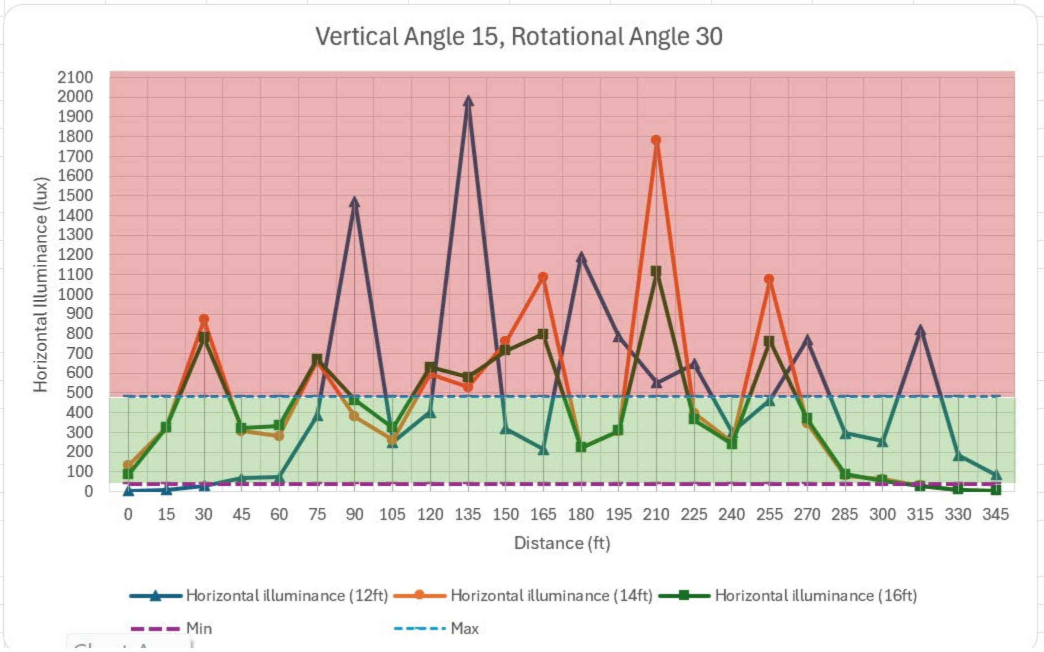


Figure 4.17 Horizontal Illumination changes across heights

This chart compares lighting performance at 12 ft, 14 ft, and 16 ft using the same rotational angle.

- 12 ft:
  - Peak near 135° (LED Perpendicular to traffic) (~1,986 lux).
  - Other peaks at 90° (LED toward traffic) and 180(LED away from traffic).

    - Highest overall variability in illumination.
- 14 ft:
    - Largest peak near 210° (LED away from traffic and Halogen towards traffic) (~1,779 lux).
    - Additional peaks near 165° and 255°.
- 16 ft:
    - Largest peak near 210° (~1,114 lux).
    - Most other values remain below ~800 lux.

Although the number of measurements exceeding 480 lux remains similar across heights, the magnitude of exceedances decreases significantly as the tower height increases.

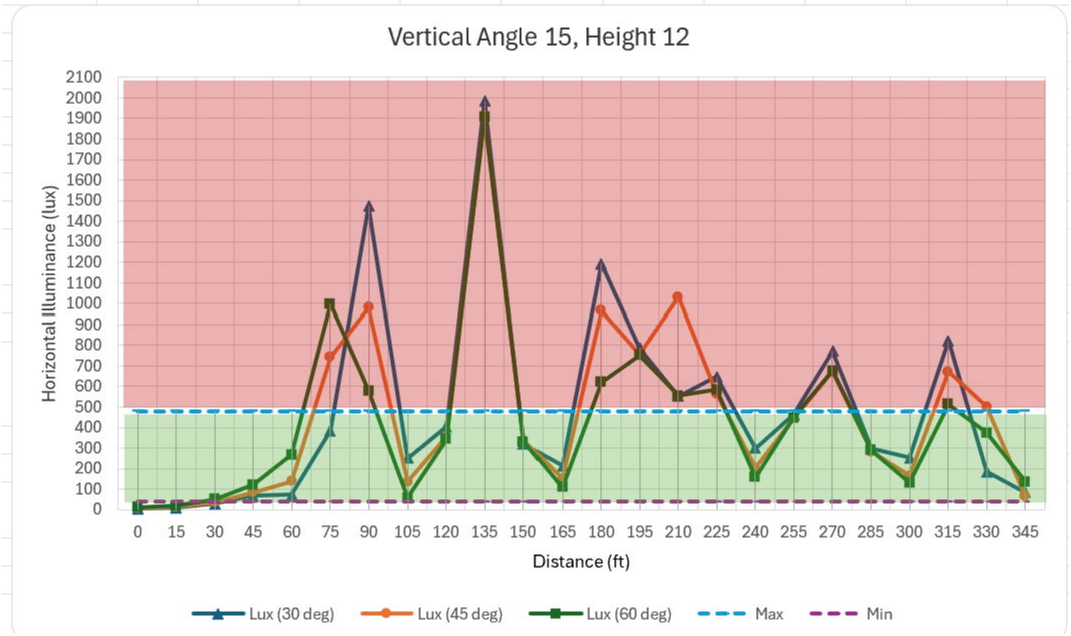


Figure 4.18 Lux Changes Across Rotational Angle Changes (Height 12)

At 12 ft, illumination levels become more uneven and peak intensities increase significantly.

Key over-bright areas include:

- 135° (LED perpendicular to traffic): ~1,900–1,986 lux.
- 90° (LED facing traffic): ~980–1,472 lux.
- 180° (LED facing away): ~620–1,194 lux.
- 210° and 270°: also frequently exceed 480 lux.

Approximately 46–54% of measurements fall within the recommended range, but many exceedances are far above the 480 lux limit, indicating a higher potential for glare. This suggests that lower mounting heights increase the risk of glare and uneven lighting.

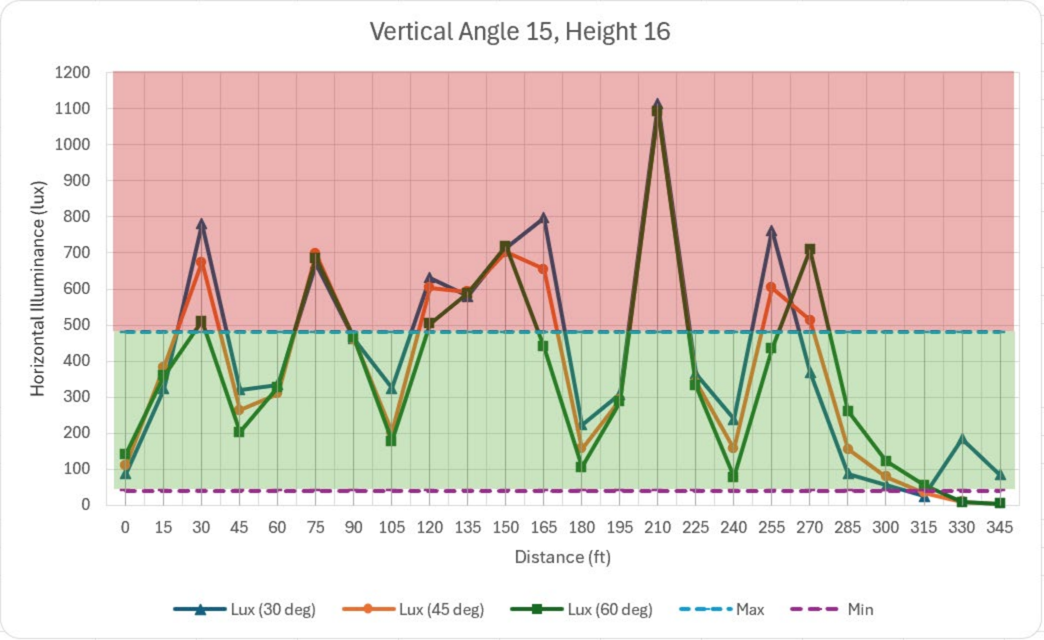


Figure 4.19 Lux Changes Across Rotational Angle Changes (Height 16)

At 16 ft, illumination is more evenly distributed and peak intensities are lower compared with the 12 ft configuration.

- Average illumination ranges from 359–410 lux depending on rotation.
- The largest peak occurs near 210°, reaching approximately 1,100 lux for all rotations.
- Secondary peaks occur around 150–165° and 255–270°, typically between 700–800 lux.
- About 50–63% of measurements fall within the recommended range.

Overall, raising the tower height improves uniformity and reduces extreme brightness levels.

4.9 Consistency of Results

Measurements from motorists' perspectives closely mirrored those at workers' ground-level positions, indicating strong consistency in lighting performance across the site. This alignment suggests that glare will be a critical factor in overall safety: if both driver and worker illuminance meet the required thresholds, glare becomes the limiting factor in safe operations. Figure 4.20 visually shows this result pattern when vertical illuminance and horizontal illuminance for both worker and driver are graphed over each other.

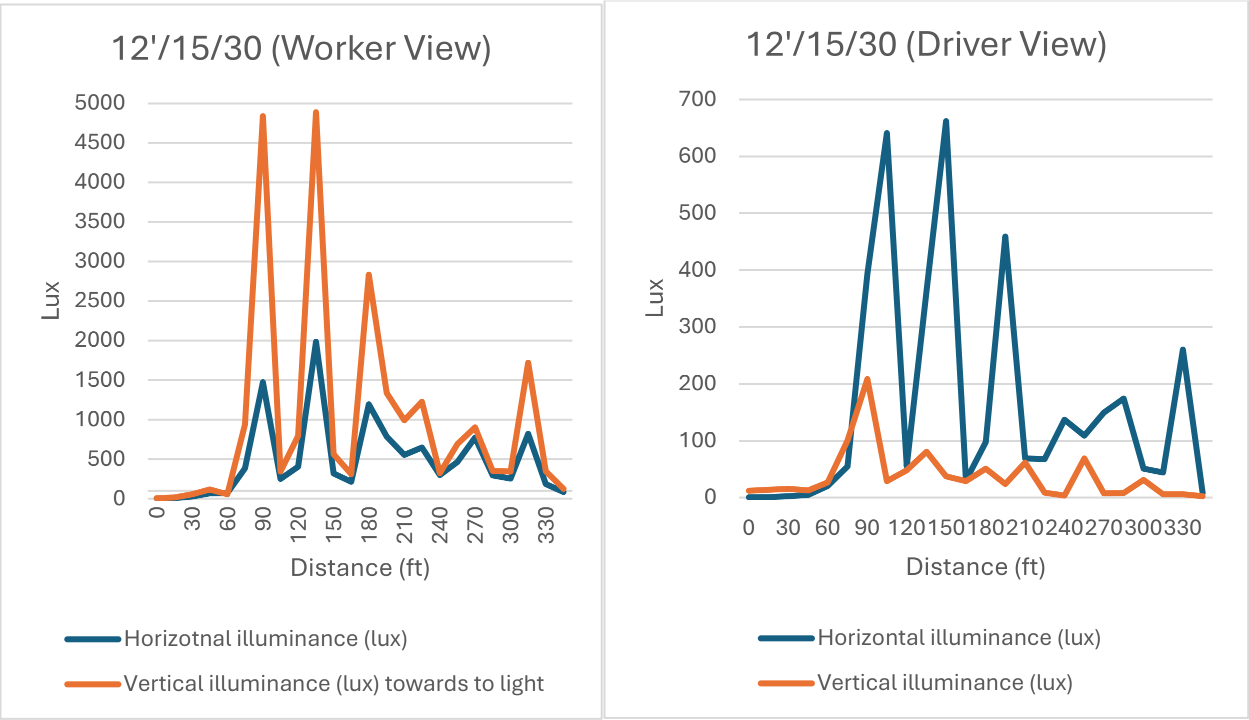


Figure 4.20 Horizontal and Vertical Lux for Driver vs. Worker

Note: the title 12’/15/30 in Figure 4.20 left represents height 12, vertical angle 15 and rotational angle 30.

4.10 Summary

Overall, LED lighting offers superior flexibility and coverage, especially at lower mounting heights, while halogen lighting is more reliable for meeting standard illuminance levels but offers limited adaptability. Balloon lighting remains a consistent option but is constrained by its smaller effective coverage area. For field deployment, careful consideration of mounting height, rotation angles, and type of light tower is essential to optimize both illuminance and glare, ensuring safety for workers and motorists alike. Table 4.1 below highlights the summary of the differences in lighting sources to help aid decision making when trying to determine which lighting source is best for a project.

Table 4.4 Summary Table of Lighting Sources

Lighting Type	Illuminance Performance	Glare	Coverage Area	Effect of Mounting Height	Rotation/Angle Flexibility	Notes
LED	Bright at source; better uniformity across coverage areas; sometimes exceeds optimal brightness	Lowest glare among all types	Good coverage, especially at lower heights	Highest flux at lower heights; decreases with height	Highly flexible; rotation angles significantly affect hazard visibility	Best overall for adjustable field deployment; careful calibration needed to avoid localized over-illumination
Halogen	Closest to standards across all coverage areas	Moderate glare	Moderate coverage	Minimal improvement with height adjustments	Limited effect on hazard visibility with rotation	Reliable for meeting standard illuminance, but less adaptable than LEDs
Balloon	Constant per standards but lower overall illuminance	Moderate glare	Limited coverage compared to LED and Halogen	Consistent across heights but lower flux at elevated positions	Rotation has minor effect	Consistent and predictable; best for small areas but less effective for large zones

4.11 Recommended Safest Configuration

Based on the combined evaluation of worker horizontal illuminance, glare performance, coverage uniformity, and deployment robustness, several configurations were identified as suitable for safe field deployment. These configurations consistently maintained worker horizontal illuminance within the target 40–480 lux range while also meeting the glare acceptability criterion of VL Ratio ≤ 0.30.

For LED light towers, the strongest and most reliable performance was observed for the following configurations:

- LED, 14 ft mounting height, 30° vertical aiming angle, 30° rotation
- LED, 14 ft mounting height, 30° vertical aiming angle, 45° rotation
- LED, 16 ft mounting height, 30° vertical aiming angle, 45° rotation
- LED, 16 ft mounting height, 30° vertical aiming angle, 60° rotation

These configurations produced consistent and uniform illuminance across worker locations without excessive peak brightness and maintained acceptable glare levels across the evaluated observer geometry.

For halogen light sources, acceptable performance was limited to a narrower set of conditions. The most reliable halogen configurations were:

- Halogen, 16 ft mounting height, 30° vertical aiming angle, 30° rotation, oriented away from traffic
- Halogen, 14 ft mounting height, 30° vertical aiming angle, 45° rotation, oriented away from traffic

Even under these configurations, halogen systems exhibited greater sensitivity to geometric changes than LEDs, but they satisfied both the illuminance and glare criteria more consistently than other halogen arrangements.

Configurations employing 15° vertical aiming angles or rotation angles ≥ 90°, while occasionally meeting glare thresholds or producing high illuminance at isolated points, were not retained as recommended solutions due to inconsistent illuminance compliance, increased susceptibility to over- or under-illumination, and reduced robustness to changes in worker position.

4.12 Tolerant Configurations

- LED systems demonstrated a high degree of tolerance across moderate rotation angles when paired with a 30° vertical aiming angle and mounted at 14–16 ft. Rotation angles between 30° and 60° provided the best balance between coverage and glare control when oriented toward or perpendicular to traffic. Steeper vertical aiming angles (≥ 45°) frequently resulted in over-illumination, while shallow vertical angles (≤ 15°) did not reliably meet illuminance requirements.
- Halogen systems exhibited greater sensitivity to both vertical aiming and rotation angle. Acceptable performance was achieved only at higher mounting heights (14–16 ft) with vertical aiming near 30° and rotations ≤ 45°, particularly when luminaires were oriented away from traffic. Higher rotation angles did not consistently reduce glare and often degraded illuminance uniformity.

4.13 All Safe Considerations

All LED and halogen configurations were evaluated using two criteria:

1. Worker horizontal illuminance compliance, defined as the percentage of measurements within the target range of 40–480 lux, and
2. Worker glare acceptability, defined as VL Ratio ≤ 0.30.

Illuminance data were drawn from the vertical-angle (15°, 30°, and 45°), mounting-height (12, 14, and 16 ft), and rotation-angle experiments, while glare values were obtained from the companion glare-evaluation workbooks. Each configuration was matched by light type, mounting height, vertical aiming angle, and horizontal rotation angle, then screened for compliance with both criteria.

Although six configurations were initially highlighted in the comparative analysis, further screening demonstrated that only a subset consistently satisfied both illuminance and glare requirements across worker locations. The final recommended configurations listed below in table 4.5 represent those combinations that provided adequate task lighting, acceptable glare levels, and robust performance under varying geometric conditions. These configurations are therefore best suited for safe and repeatable work-zone deployment.

Table 4.5 All Recommended Safe Considerations

Light Type	**Height (ft)**	**Aiming Angle (Vertical)**	**Rotational Angle (Horizontal)**
LED	14	30	30
LED	14	30	45
LED	16	30	45
LED	16	30	60
Halogen	14	30	135
Halogen	16	30	120

Chapter 5 Conclusion

This research evaluated nighttime work-zone lighting systems to identify lighting configurations that provide adequate worker visibility while minimizing glare-related impacts to motorists, consistent with FHWA and NDOT guidance for nighttime work-zone safety. Results from the industry survey and controlled field experiments indicate that lighting performance is governed primarily by configuration parameters—including mounting height, vertical aiming angle, and horizontal rotation—rather than lighting type alone. Uneven illumination, localized over-illumination, and glare directed toward approaching traffic were identified as the principal factors degrading work-zone safety.

Field measurements demonstrated that achieving concurrent compliance with FHWA-recommended worker illuminance levels (40–480 lux) and IES RP-8-22 glare acceptability criteria (VL Ratio ≤ 0.30) is feasible but limited to a constrained range of lighting configurations. While multiple configurations satisfied one performance criterion in isolation, fewer configurations consistently satisfied both illuminance and glare thresholds across worker locations and observer geometries. This finding underscores the narrow tolerance for acceptable nighttime lighting performance and the importance of controlled setup practices.

Based on measured horizontal illuminance compliance and glare performance, the following configurations are identified as recommended for nighttime work-zone deployment:

Recommended LED Lighting Configurations:

- LED light towers mounted at 14 ft, with a 30° vertical aiming angle and 30° horizontal rotation
- LED light towers mounted at 14 ft, with a 30° vertical aiming angle and 45° horizontal rotation

- LED light towers mounted at 16 ft, with a 30° vertical aiming angle and 45° horizontal rotation
- LED light towers mounted at 16 ft, with a 30° vertical aiming angle and 60° horizontal rotation

These configurations consistently produced worker horizontal illuminance within the 40–480 lux target range and maintained acceptable veiling luminance ratios for motorists, demonstrating stable performance across evaluated distances and worker positions.

Conditionally Acceptable Halogen Lighting Configurations

- Halogen light towers mounted at 16 ft, with a 30° vertical aiming angle and 30° horizontal rotation, oriented away from traffic
- Halogen light towers mounted at 14 ft, with a 30° vertical aiming angle and 45° horizontal rotation, oriented away from traffic

These halogen configurations met both illuminance and glare criteria more reliably than other halogen arrangements; however, performance was more sensitive to changes in geometry and orientation when compared to LED systems.

Lighting configurations employing shallow vertical aiming angles ($\leq$ 15°) or high rotation angles ($\geq$ 90°) were not retained as primary recommendations. Although such configurations occasionally met glare thresholds or produced high localized illuminance, they did not consistently maintain compliance with the target illuminance range and exhibited increased sensitivity to worker position and site geometry.

Overall, the findings emphasize the need for standardized configuration guidance, contractor and worker training, and field verification of lighting setups, consistent with FHWA and NDOT best practices. Incorporation of the recommended configurations into NDOT guidance and contractor deployment procedures can improve lighting consistency, reduce glare-related risk, and enhance safety for workers and motorists in nighttime work zones. Future work should focus on validation of these configurations under active work-zone conditions and on refinement of acceptable configuration ranges to support statewide implementation across varying roadway environments.

References

Ahmed, A., Mohammed, H. A., Gambatese, J., & Hurwitz, D. (2021). *Effects of flashing blue lights mounted on paving equipment on vehicle speed behavior in work zones*. **Journal of Construction Engineering and Management, 147**(9), 04021101. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002133

American Road & Transportation Builders Association. (n.d.). Posters. Work Zone Safety Information Clearinghouse. Retrieved March 2, 2026, from https://workzonesafety.org/public-awareness/outreach-posters/

American Traffic Safety Services Association. (2013). *Nighttime lighting guidelines for work zones: A guide for developing a lighting plan for nighttime work zones* (supported by Federal Highway Administration under Grant No. DTFH61 06 G 00004). https://workzonesafety-media.s3.amazonaws.com/workzonesafety/files/documents/training/fhwa_wz_grant/night_lighting_guide-508.pdf

Arditi, D., Lee, D.-E., & Polat, G. (2007). *Fatal accidents in nighttime vs. daytime highway construction work zones*. **Journal of Safety Research, 38**(4), 399–405. https://doi.org/10.1016/j.jsr.2007.04.001

Bhagavathula, R., & Gibbons, R. B. (2017). *Effect of work zone lighting on drivers' visual performance and perceptions of glare*. **Transportation Research Record: Journal of the Transportation Research Board, 2617**(1), 44–51. https://doi.org/10.3141/2617-06

Bryden, J. E., & Mace, D. J. (2002). *Guidelines for design and operation of nighttime traffic control for highway maintenance and construction* (Vol. 476). Transportation Research Board.

Centers for Disease Control and Prevention. (2024, November 7). Construction equipment visibility (National Institute for Occupational Safety and Health). U.S. Department of Health and Human Services. Retrieved March 2, 2026, from https://www.cdc.gov/niosh/motor-vehicle/constructionequipmentvisibilitydiagram/index.html

El-Rayes, K., & Hyari, K. (2003). *Lighting design requirements for highway nighttime construction*. In *Construction Research Congress* (Reston, VA). ASCE.

El-Rayes, K., & Hyari, K. (2005). *Optimal lighting arrangements for nighttime highway construction projects*. **Journal of Construction Engineering and Management, 131**(12), 1292–1300. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:12(1292)

El-Rayes, K., & Hyari, K. (2006). *Lighting requirements for nighttime highway construction*. **Journal of Construction Engineering and Management, 132**(5), 435–443. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:5(435)

El-Rayes, K., Hyari, K., Liu, L., Soibelman, L., Rebholz, F. E., Al-Kaisy, A., & Nassar, K. (2003). *Nighttime construction: Evaluation of lighting for highway construction operations in Illinois* (Technical Rep. No. ITRC FR 00/01, 2).

Ellis, R. D., Amos, S., & Kumar, A. (2003). *Illumination guidelines for nighttime highway work* (NCHRP Report 498).

Federal Highway Administration. (n.d.). Chapter 6D. Pedestrian and worker safety (Manual on Uniform Traffic Control Devices, 2003 ed.). U.S. Department of Transportation. Retrieved March 2, 2026, from https://mutcd.fhwa.dot.gov/htm/2003/part6/part6d.htm

Fotios, S., & Kent, M. (2020). *Measuring discomfort from glare: Recommendations for good practice*. **LEUKOS, 17**. https://doi.org/10.1080/15502724.2020.1803082

Hyari, K., & El-Rayes, K. (2006). *Lighting requirements for nighttime highway construction*. **Journal of Construction Engineering and Management, 132**(5), 435–443. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:5(435)

Illinois Department of Transportation. (2009). *Research pays off: Safety reports and statistics* (TR News No. 260). Illinois Department of Transportation. https://idot.illinois.gov/content/dam/soi/en/web/idot/documents/transportation-system/research/success-stories/research-pays-off--safety-reports-and-statistics.pdf

Mostafavi, A., Valentin, V., Abraham, D. M., & Louis, J. (2012). *Assessment of the productivity of nighttime asphalt paving operations*. **Journal of Construction Engineering and Management, 138**(12), 1421–1432. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000531

Nafakh, A. J., Davila, F. V., Zhang, Y., Fricker, J. D., & Abraham, D. M. (2022). *Work zone lighting and glare on nighttime construction and maintenance activities* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP2022/16). Purdue University. https://doi.org/10.5703/1288284317379

NIOSH. (2022). *Behind the wheel at work* (Vol. 7, No. 1). National Institute for Occupational Safety and Health.

Nnaji, C., Jafarnejad, A., & Gambatese, J. (2020). *Effects of wearable light systems on safety of highway construction workers*. **Practice Periodical on Structural Design and Construction, 25**(2), 04020003. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000469

Odeh, I., El-Rayes, K., & Liu, L. (2009). *Field experiments to evaluate and control light tower glare in nighttime work zones*. **Journal of Construction Engineering and Management, 135**(9), 911–919. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000054

OSHA (Occupational Safety and Health Administration). (2015). *Safety and health regulations for construction*. Washington, DC: U.S. Department of Labor.

Shehab, T., & Phu, L. (2015). *Accident patterns in road construction work zones*. **The Professional Constructor: Journal of the American Institute of Constructors, 39**(2).

https://www.researchgate.net/publication/350291101_Accident_Patterns_in_Road_Construction_Work_Zones

United States. Federal Highway Administration (2008). Field Guide on Installation and Removal of Temporary Traffic Control for Safe Maintenance and Work Zone Operations.

Work Zone Barriers. (2025, September 15). *Work zone crash facts: Work zone fatalities, injuries, & crashes*. WorkZoneBarriers.com. https://www.workzonebarriers.com/work-zone-crash-facts.html

Wood, J. M. (2020). *Nighttime driving: Visual, lighting and visibility challenges*. **Ophthalmic & Physiological Optics, 40**(2), 187–201. https://doi.org/10.1111/opo.12659

Appendix A Nighttime Work Zone Lighting Questionnaire

NDOT Lighting Project

Questionnaires

Name

Title

Organization

Phone Number

Email address

1. This study aims to evaluate the effect of lighting on work zone safety, taking the perspecti vs of construction workers and motorists into consideration for nighttime lighting arrangements, including:
    - The effect of lighting (i.e., glare/luminance/visibility) on the visual performance of construction workers.
    - The effect of orientation and placement of light towers on the perception of construction workers and motorists.
    - The identification of unsafe conditions due to inadequate lighting arrangements at nighttime work zones.

2. Rate the adequacy of lighting in your current nighttime work zones.
    - Superior
    - Adequate
    - Neutral

- Inadequate
- Unacceptable
- No Opinion

3. What types of lighting fixtures are most commonly used in your nighttime work zones?
    a. Portable light towers
    b. Fixed overhead lights
    c. Vehicle-mounted lights
    d. Handheld lights
    e. Other (please specify)
    f. N/A

4. Please select the option that best describes how lighting affects visibility in your nighttime work zone:
    a. Significantly improves (e.g., all areas are clearly visible)
    b. Moderately improves (e.g., most areas are visible, some remain dim)
    c. No impact (e.g., visibility is unchanged)
    d. Moderately reduces (e.g., shadows or glare occasionally obscure visibility)
    e. Significantly reduces (e.g., frequent shadows or glare severely impair visibility)
    f. N/A (Not applicable)

5. How effectively does the lighting that you are using contribute to the prevention of worker personal injuries in nighttime work zones?

   a. Very Effective
   b. Effective
   c. Neutral
   d. Ineffective
   e. Unacceptable

6. Do workers receive training on the importance of proper lighting and how to install, operate, and maintain it in nighttime work zones?
   a. Yes, comprehensive training
   b. Yes, basic training
   c. No, but planning to implement
   d. No training provided

7. What improvements would you suggest for enhancing lighting conditions in nighttime work zones?
   a. Increased lighting intensity
   b. More evenly distributed lighting
   c. Use of advanced lighting technologies (e.g., OLED or drone lighting
   d. Better maintenance practices
   e. Other (please specify)
8. Have you had reports that the lighting systems you are currently using adversely impact the traveling public? (e.g. glare)
   a. Many

   b. Several
   c. Some
   d. Few
   e. None

9. How satisfied are you with the overall safety of workers in your nighttime work zones considering the lighting you are currently using?
   a. Very Satisfied
   b. Satisfied
   c. Neutral
   d. Dissatisfied
   e. Very Dissatisfied

10. What measures are in place to ensure proper lighting in nighttime work zones? (Please mark all that apply.)
    a. Regular inspections
    b. Use of high-quality lighting equipment
    c. Worker feedback
    d. Adherence to safety standards
    e. Contract requirements
    f. Other (please specify)

11. if you selected Adherence to safety standards, could you provide standards/guidelines your agency has used?

12. Do you have experience with nighttime work zones?

    a. yes
    b. no